Multi-source observations and high-resolution numerical model applied on the analysis of a severe convective weather affecting the airport

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Abstract
In order to explore the application of multi-source data from different observational systems (including meteorological stations, radar, and airport observational reports) and high-resolution numerical model results in the analysis of severe convective weather affecting airports, a local severe convective weather event that affected Beijing Capital International Airport (ZBAA) on 26 June 2018 was studied in this work. Although there was no significant triggering of synoptic systems, the process produced a violent thunderstorm with strong wind gusts, poor prevailing visibility, and hail in just a 30-min period, resulting in severe impacts on the airport operations. In addition to the routine analysis of weather using observations from meteorological stations and radar, high spatial and temporal resolution data from instruments at the airport were used to reveal the fine-scale characteristics of the development and evolution of various associated meteorological parameters, which demonstrably served as a useful auxiliary dataset for the analysis of this event. Furthermore, the reliability of the high-resolution numerical (Weather Research and Forecasting) model simulation was evaluated by using these 1-min-scale airport observations. Based on what was judged to be a reliable simulation of the meteorological variables by the model, the trigger and strengthening mechanisms of the storm formed in this region of complex topography, as well as the interaction with another cell, were explored. The model results suggested that convections were initially triggered by the interaction of southerly flow from the plain and northwesterly flow from the mountains, in conjunction with the effect of orographic uplift. The outflow of the cold pool from the former cell prevented the later cell (affecting ZBAA) from moving east. Due to the strong vertical wind shear in the lower levels, the echo tilted to a certain extent and formed an inner secondary circulation, contributing to the maintenance and strengthening for the storm.

KEYWORDS
airport, dense observation, model, severe convective weather

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1 | INTRODUCTION

Meso- and microscale severe convective weather analysis is used to assess a variety of disastrous weather phenomena, including short-duration heavy rain, gusty wind, hail, and squall lines, etc., all of which usually possess great destructive power (Fu et al., 2011; Wan & Liu, 2018; Xue et al., 2019; Yu et al., 2012; Q. H. Zhang et al., 2017). Such severe convective weather is a particular problem for the aviation sector, where it is more likely to cause high levels of economic loss and pose relatively greater threats to the safety of the people involved. With the growth of this sector, the need for forecasting meteorological phenomena that pose such threats has increased significantly (Chun et al., 2017; Goodman & Small Griswold, 2019; Ozdemir & Deniz, 2016). Forecasting for the aviation sector is slightly different from traditional weather forecasting, as it requires an extremely high degree of accuracy for both meteorological variables and in terms of the temporal resolution (down to 1 min), in line with the Civil Aviation Forecast Specification (http://www.caac.gov.cn). Moreover, the forecasting of convective weather affecting airports is particularly challenging because temporal resolutions of meteorological observations are currently too coarse, observational data of meteorological variables are not comprehensive enough, and the fact that automatic weather stations do not provide sufficiently complete coverage of airport sites. Indeed, there have only been a few studies of convective weather affecting airports published, most of which merely used observational data from nearby meteorological stations—including radar stations, automatic weather stations, sounding stations, etc.—complemented by numerical weather prediction models, to analyse the convective weather. For instance, Young (2007) examined the evolution of a severe thunderstorm that led to the closure of Bristol International Airport in England by using satellite and radar images; and Liu (2008), based on model simulation, discovered that the lifting of air provided by cold front and terrain promoted the formation and development of a squall line that affected Baiyun International Airport in China. There have also been some related studies that focused on the application and evaluation of the convective products available for the aviation sector (Morris et al., 2020; Smith et al., 2016), and on the development of a nowcasting guidance system (James et al., 2018). Despite these studies being helpful towards a deeper understanding of convective weather affecting airports, finer spatiotemporal resolutions and more meteorological data are needed to better analyse the development and evolution of these events. Chinese airports operate manned stations, which issue observations as Meteorological Terminal Aviation Routine Weather (METAR), SPECI (which is an extraordinary [special] report issued when some meteorological criteria have been meet), and 1-min Automated Weather Observing System (AWOS) surface data. However, these airport observational data have rarely been applied in scientific studies (Ozdemir & Deniz, 2016).

High-resolution numerical weather prediction models (HNMs) are playing an increasingly important role in severe convective weather analysis and prediction (Qi, 2015), as well as in the aviation sector. An HNM can provide physical arguments and refined guidance products for convective weather occurring at airports. Therefore, it is particularly important to assess the reliability of HNMs. In this respect, a variety of verification methods have been used for the systematic evaluation of HNMs, such as the traditional pixel-versus-pixel threat score (L. P. Huang et al., 2017; Zhou et al., 2011), and the more recent spatial verification methods (Tang et al., 2018; X. W. Zhang et al., 2020). However, the results of such systematic assessments provide limited guidance for individual cases. Therefore, before further exploring severe convective weather more holistically, we need to evaluate individual simulation cases. Thus far, such individual case evaluations of HNMs have mostly been in the form of accumulated precipitation, radar echoes, etc. (Avolio et al., 2020; Kain et al., 2006; Sun & Fang, 2013). By contrast, assessments of the evolution and development of such weather processes have rarely been documented.

The local (surrounding) orography of individual airports can be an important impact for hazard in the risk of severe convective storms. The topography surrounding Beijing is complex, owing to its higher elevation in the west and north than in the east and south (Figure 1a). According to statistical data on the sources of convective storms in Beijing during 2003–2005, the proportion of storms triggered in the northwest mountains was approximately 95% (R. Huang, 2012). Thunderstorms are frequently initiated over mountains, and under certain weather conditions these storms can grow and propagate to the southeast where they can ultimately threaten Beijing Capital International Airport (ICAO: ZBAA), while at other times they will dissipate before reaching the airport. Therefore, the northwest mountains are regarded as a key area to forecast whether or not thunderstorms propagating from the northwest to the southeast will intensify or dissipate as they move to the plains (Xiao et al., 2015)—an aspect that greatly increases the difficulty for nowcasting at ZBAA. Previous research has suggested that the low-level heat and dynamic instability, along with the mid- and low-level vertical wind shear, are import factors determining whether or not storms will successfully propagate to the plains (Chen & Wang, 2012; Roberts et al., 2011; Wilson et al., 2004, 2005, the proportion of
In this study, the storm intensified after descending mountains and eventually affected ZBAA. Taking this case as an example, the use of multi-source observations to analyse a severe weather in a synergistic way and evaluate the reliability of HNM is representative for ZBAA, and the trigger and strengthening mechanisms of the storm are also worth to explore. Besides, before the storm affecting ZBAA was triggered, another storm was triggered over the mountains and developed strongly but did not affect ZBAA, thus providing an interesting opportunity to explore the interaction between the two storms.

Therefore, the purpose of the present paper is threefold:

i. Multi-source observations from meteorological stations, radar, and the airport are used to analyse a severe convective weather event that affected ZBAA: the aim being to gain a deeper understanding of the characteristics of the development and evolution of such severe convective weather processes.

ii. Using the 1-min-scale observations available from the airport, we evaluate the ability of an HNM to simulate the evolution of a range of meteorological variables during this weather process.

iii. Based on the reliability of the HNM, we then investigate the trigger and strengthening mechanisms of the storm, including any possible interactions with other cells that formed in the same area, but did not affect the airport.

Despite this being a study of only a single case, we nonetheless hope that it can serve as an example to provide valuable information for the further study of convective weather affecting airports under similar synoptic conditions.

The rest of the paper is structured as follows: Section 2 describes the datasets and methods. Section 3 begins with a brief introduction to the severe convective weather affecting ZBAA, then describes the synoptic environment of the storm, and uses multi-source observation data from meteorological stations, radar, and the airport to present the fine-scale characteristics of the storm’s development and evolution. Section 4 evaluates the HNM simulation, followed by preliminary findings regarding the trigger and intensification mechanisms of the storm in this area of complex topography, as well as the interaction with the former storm that did not affect ZBAA. The paper closes with a summary and some further discussion in section 5.

2 | DATASETS AND METHODS

2.1 | U.S. National Centers for Environmental Prediction final data

Data on the large-scale atmospheric conditions of this case study were taken from the final (FNL) global reanalysis dataset released by the U.S. National Centers for Environmental Prediction (NCEP). The horizontal spatial and temporal resolutions of the FNL data are...
100 km and 6 h, respectively. The specific data selected were those nearest to the time when the convection occurred in this case (0600 UTC 26 June 2018).

2.2 | Radar data

MaxEcho maps from the six Beijing–Tianjin–Hebei region’s radars (including Daxing meteorological radar; in black Figure 1c), with a temporal and horizontal spatial resolution of 6 min and 1 km, respectively, were used in this study. The meteorological radar at Daxing is an S-band single-polarization Doppler radar facility, located to the south of ZBAA. The horizontal spatial resolution of Daxing radar’s echo top and liquid water content (LWC) is 1 km, and the horizontal spatial resolution of its velocity is 250 m.

2.3 | Runways and airport observations

ZBAA is located in the northeastern suburbs of Beijing (Figure 1a), China. Its altitude is 30.4 m, and the airport has three parallel runways (Figure 1b): 18R/36L—west runway; 18L/36R—middle runway; and 01/19—east runway. The distance between the two outermost runways is 3.5 km. The airport issues METAR every half an hour and SPECI when it is necessary, while AWOS data are available every minute. The meteorological variables and evolutionary characteristics of the storm were analysed in this study using these observational data from METAR, SPECI, and AWOS.

2.4 | High-resolution Weather Research and Forecasting simulation

Weather Research and Forecasting (WRF) version 3.9.1.1 (Skamarock et al., 2008; https://www2.mmm.ucar.edu/wrf/users/citing_wrf.html) was used to analyse this storm, which occurred on 26 June 2018. The FNL data (horizontal spatial resolution: 100 km) released by the NCEP were chosen for the analysis and six-hourly-updated boundary conditions for the model. The start time was 0000 UTC 26 June and the total forecast time was 12 h.

The model set-up consists of a triple bidirectional nesting scheme (Figure 1d). The horizontal grid-spacing was 9 km × 9 km in domain 1, covering almost all of central-eastern China. In domain 2, the horizontal grid-spacing was 3 km × 3 km. While it was 1 km × 1 km in domain 3, covering Beijing–Tianjin–Hebei region. The output time-step of domain 3 was 10 min. The physical options used in each domain were roughly the same, except for the cumulus parameterization: the Kain–Fritsch eta scheme (Kain, 2004) was used in domain 1, while no cumulus parameterization scheme was used in domain 2 and domain 3. Other physical options were as follows: the WSM6 scheme (Hong & Lim, 2006) was used for microphysics; the RRTMG scheme (Iacono et al., 2008) was used for longwave and shortwave radiation; and the MYJ scheme (Janjic, 2002) was used for the planetary boundary layer.

3 | OBSERVATION AND ANALYSIS

3.1 | Severe convective weather situation

Statistics data on thunderstorms affecting ZBAA show that, during the thunderstorm season in 2018, there were 32 days of thunderstorms (average of 31.2 days recorded from 2000 to 2018) and 45 thunderstorm events were recorded. Seven days of thunderstorms occurred in June, during which the most violent storm occurred on 26 June 2018, characterized by hail and gusty winds and poor prevailing visibility of 600 m. This process produced significant impacts on inbound and outbound flights at the northern terminal, resulting in the cancellation of 127 flights and the diversion to other airports of 21 flights.

This storm caused widespread precipitation across southwest and northeast Beijing, while there was almost no precipitation in the urban area (not shown). In total, this process brought 12 mm of precipitation to ZBAA. More specifically, the timing of the severe convective weather was as follows: 39 min of thunderstorms from 14:36 to 15:15 (local time, which is UTC −8 h); 24 min of precipitation from 14:47 to 15:11, which includes 16 min of hail from 14:50 to 15:06. Based on data during 2001–2004, Zhuo et al. (2016) classified thunderstorms affecting ZBAA into eight different types according to their characteristics—namely, weak precipitation, heavy-rainfall, dry-convective, wet-convective, weak-hail, strong-hail, mixed-convective, and hail-with-gale thunderstorms. The proportion of hail-with-gale thunderstorms (strong hail and gales) only accounted for 0.6%, but this was the type that occurred on 26 June 2018. Such cases of multiple disastrous weather phenomena produced in such a short period are relatively rare at ZBAA, and relatively more challenging for nowcasting.

3.2 | Synoptic environment

To examine this severe storm case at ZBAA, we started by investigating the synoptic environment. At 0600 UTC
26 June 2018, ZBAA was under a relatively straight westerly flow at the bottom of a northeastern cold vortex, with weak cold air at upper levels (Figure 2a). Therefore, this case occurred under a relatively weak large-scale forcing environment against a cold vortex weather background. Meanwhile, weak mesoscale convergence (a convergence line of wind direction apparent at the surface; not shown) existed near the airport, and the low-level wind speed was feeble (Figure 2c). From the surface pressure field shown in Figure 2b, it is clear that the airport was in a weak pressure gradient area, located at the periphery of Mongolian high pressure. The nearby dew point temperature was between 18°C and 20°C, indicating moderately moist conditions. Figure 2d shows that ZBAA was located in the negative gradient area of the Best Lift Index and the Convective Available Potential Energy (CAPE) values nearby exceeded 1000 J/kg, indicating favourable convective instability. The temperature difference between 850 hPa and 500 hPa exceeded 28°C, revealing strong thermal instability. The middle-layer airmass was very dry, and the 0–6-km vertical wind shear was relatively strong (exceeding 20 m/s) (Figure 2c,d).

Based on previous experience of severe weather forecasts, it is difficult for the dynamic conditions, water vapour and thermal conditions to meet all the standards of severe weather. Therefore, for this case, although no significant trigger of synoptic systems was apparent, the convective and thermal instability formed a preferable convective potential and accumulated energy for severe weather.

3.3 | Fine-scale analysis from radar data

Using MaxEcho maps from the Beijing–Tianjin–Hebei region's radars, it is possible to see that the onset of convection took place in the northwest mountains area starting at noon (not shown), local time. A cell (arrow A in Figure 3a) moved eastwards, strengthening all the way, and ultimately developed to its maximum extent at 0530 UTC. Then, it continued to move eastwards and gradually dissipated (not affecting ZBAA). Furthermore,
another new cell (arrow B in Figure 3a) also initiated from the mountains (at 0512 UTC, not shown), moving southeast. It strengthened rapidly (Figure 3b) and eventually evolved into a strong storm moving over ZBAA at 0630 UTC (Figure 3c). The maximum composite reflectivity of the storm exceeded 65 dBZ, leading to the occurrence of severe convective weather at ZBAA.

Studying from characteristic products of Daxing meteorological radar at 0630 UTC (Figure 4), a three-body scatter spike (TBSS) echo and hail, with a diameter of 67.8 mm, was also clearly recognizable in the composite reflectivity image at an elevation angle of 4.4°, and the largest LWC exceeded 70 kg/m². The echo top of the storm extended to 9–12 km. Because the heights of the 0°C and −20°C layers at ZBAA were about 600 hPa and 400 hPa (obtained from the FNL data), the indication was that a deep hail accumulation area had been generated in the convective cloud. In addition, a convergence zone was apparent in the velocity image, and a gust front along with the echo could be seen from the airport’s C-band double-polarization Doppler radar at an elevation angle of 0.5° from 0623 UTC (not shown). All of these related characteristics indicate that the convective cell was in a period of rapid development, accompanied by clear hail and gusty wind features.

3.4 METAR, SPECI, and AWOS observations

Based on METAR and SPECI observations obtained from ZBAA, a more refined peak period of the storm could be analysed (Table 1). The ground-wind speed was 3 m/s from 120°, with no notable weather phenomena at 0630 UTC. A thunderstorm began after 6 min. At 0647 UTC, the wind direction changed from southeast to north (from 120° to 360°). Meanwhile, the wind speed started to increase rapidly to 7 m/s, with gusts of 14 m/s, along with thunderstorm and moderate rain. Three minutes later, the gust velocity increased to 23 m/s (according to the Civil Aviation Forecast Specification, gusts exceeding 20 m/s are a serious threat to the safety of flights), with heavy rain and hail, and the prevailing visibility dropped from 3000 m to 800 m, posing severe risk to flights. The thunderstorm could still be observed at 0705 UTC, but the wind direction had changed back from north to southeast, and was still gusty. Soon afterwards, the wind gusts disappeared, the prevailing visibility increased to at least 10 km, and the storm started to dissipate. In summary, the process delivered a violent thunderstorm of short duration, with poor prevailing visibility, gusty winds, hail, and rain.
One-minute-scale observational wind data were also recorded by AWOS devices at the three runways of ZBAA between 0630 UTC and 0728 UTC. The sequential variation of surface wind speed (Figure 5a) showed that the initial wind speed maintained at 2–4 m/s between 0630 UTC and 0635 UTC, and then increased sharply from 3 m/s to 14 m/s between 0635 UTC and 0655 UTC at runway 18R, before reaching a peak at each runway successively. A few minutes later, the wind speed decreased to 6 m/s between 0650 UTC and 0700 UTC and started to stabilize. Furthermore, although the evolution of wind speed at each runway was roughly the same, the timing of each peak still differed slightly. The wind-speed variation for 18R-west runway was always a few minutes ahead of the other runways, due to the fact that the storm swept across the terminal area of ZBAA from northwest to southeast.

**FIGURE 4** Images of Daxing meteorological radar at 0630 UTC 26 June 2018 showing (a) composite reflectivity at an elevation angle of 4.4° (unit: dBZ), (b) velocity (unit: kts), (c) echo top (unit: kft), (d) liquid water content (units: kg/m²). Daxing meteorological radar is located on the southwest corner, outside the map. The location of ZBAA is represented by the red frame.

| METAR and SPECI reports between 0630 UTC and 0730 UTC |
|-----------------------------------------------|
| Time (UTC) | Wind (degrees/MPS) | Weather phenomena | Prevailing visibility (m) | Cloud base (m) | Temperature T (°C)/Td (°C) | Pressure QNH (hPa) |
|----------|-------------------|-------------------|--------------------------|----------------|--------------------------|-----------------|
| 06:30    | 120/03 HZ         |                   | 4400                     |                | 32/22                    | 1000            |
| 06:36    | 130/03 TS, HZ     |                   | 4400                     | 1500CB         | 32/22                    | 1000            |
| 06:47    | 360/07G14 TSRA, HZ|                   | 3000                     | 1200CB         | 32/22                    | 1000            |
| 06:50    | 350/11G23 +TSRAGR |                   | 800                      | 1200CB         | 29/22                    | 1001            |
| 06:53    | 340/13G2 +TSRAGR  |                   | 600                      | 1200CB         | 23/19                    | 1002            |
| 07:00    | 210/7G23 +TSRAGR  |                   | 2000                     | 1200CB         | 21/19                    | 1001            |
| 07:05    | 140/05G16 −TSRA   |                   | ≥10,000                  | 1500CB         | 21/20                    | 1000            |
| 07:30    | 160/07           |                   | ≥10,000                  | 1500CB         | 26/18                    | 999             |

Abbreviations: −, intensity: slight, +, intensity: severe; CB, cumulonimbus; G, gust; HZ, haze; QNH, sea level pressure; TS, thunderstorm; TSRA, thunderstorm with rain; TSRAGR, thunderstorm with rain and hail.
Similarly, the 1-min-scale change of wind direction is shown in Figure 5b. The variation of wind direction for the runways could also be roughly divided into three stages: the prevailing wind direction being east to southeast (90°–150°) between 0630 UTC and 0646 UTC; then a sudden change of wind direction from northwest to north (300°–360°) between 0637 UTC and 0657 UTC; and lastly return from southeast to southwest (150°–220°) between 0651 UTC and 0728 UTC. In summary, striking wind speed and directional shear were generated during this process, posing a serious threat to flights.

More meteorological parameters involving temperature, dew point temperature, and corrected sea-level pressure recorded by AWOS every minute between 0630 UTC and 0728 UTC are shown in Figure 5c–e. With the arrival of the storm, the meteorological parameters for 18R-west runway changed first at 0636 UTC: the temperature fell, the dew point temperature followed a fluctuating decline, and the corrected sea-level pressure began to rise a few minutes later. At the moment of 0655 UTC, the temperature and the dew point temperature decreased to their lowest points, while the corrected sea-level pressure reached its peak. In a 19-min period, meteorological parameters had changed drastically, including a temperature drop of 12°C, a dew point temperature drop of 4°C, and a corrected sea-level pressure increase of 3 hPa.

Taking this case as an example, we have demonstrated that, with the supplement of airport reports and 1-min-scale observations, the dramatic and fine-scale characteristics of the development and evolution of weather phenomena and various meteorological parameters can be clearly exhibited, i.e., airport observations enable a high-quality auxiliary analysis for severe weather. Moreover, the eruption of multiple types of severe weather in such a short period had a significant impact on the operations of ZBAA. Nowcasting severe
Weather under a weakly synoptic-forced system is difficult for forecasters, and so the trigger and strengthening mechanisms are certainly worthy of exploration. Besides, from the observations, we uncovered an interesting fact that two cells generated successively in the mountains area, with one moving eastwards, but the other southeastwards to ultimately affect ZBAA. Did the former cell perhaps have an impact on the later cell? These aspects are discussed in the next section by examining the results from the WRF model.

4 | Trigger and Strengthening Mechanisms

4.1 | Evaluation of HNM experiment

We used the WRF model to simulate the event. In general, the simulation captured the triggering, propagation, and evolution of the convective cell well (Figure 3d-f): echoes generated from the northwest mountains area of Beijing from 0400 UTC. Two isolated echoes were clearly visible at 0530 UTC, one of which moved eastwards and dissipated after 0620 UTC (not shown), and the other moved southeastwards to ultimately affect ZBAA. However, the simulation slightly lagged behind the observation. In addition, the model basically captured the area of hourly accumulated precipitation during this process, but the precipitation forecast was weaker than observed and the simulated area of accumulated precipitation was slightly smaller (not shown). Similar conclusions were reached in Wan and Liu (2018) in the case of severe weather in lower-level weak convergence in East China from March to August 2016. Specifically, the location of the accumulated precipitation simulated by WRF was roughly the same as observed, while the simulated area of accumulated precipitation was slightly smaller than the observed.

To further verify the reliability of the WRF simulation, the evolution of reflectivity and various meteorological parameters at ZBAA were compared between the simulation and observations during this process (Figure 6). Since the temporal resolutions of the simulation and observations were different, we focus more on comparing the evolutionary trend. The simulated echo affected ZBAA during 0630 UTC to 0700 UTC, which was close to the observational time. However, the intensity of the simulated echo was obviously weaker than that of the observation, and the maximum reflectivity difference at the strongest point in time was about 25 dBZ. Moreover, the simulated 10-min-averaged wind speed, temperature, and relative humidity were compared with the 1-min-scale data from AWOS devices. It was found that the evolutionary trend of the 10-min-averaged wind speed was captured well by the model, with some slight differences in magnitude and timing.

![Figure 6](image-url) Time series of Weather Research and Forecasting (WRF)-simulated and observed (a) MaxEcho (unit: dBZ) observed by radar between 0600 UTC and 0700 UTC, (b) MaxEcho (unit: dBZ) simulated by WRF between 0600 UTC and 0700 UTC, (c) WRF-simulated 10-min-averaged wind speed (units: m/s) between 0630 UTC and 0730 UTC, (d) WRF-simulated 10-min-averaged temperature (unit: °C) between 0630 UTC and 0730 UTC, and (e) WRF-simulated 10-min-averaged dewpoint temperature (unit: °C) between 0630 UTC and 0730 UTC, at ZBAA on 26 June 2018.
speed in the WRF simulation was nearly the same as that of the 1-min-scale wind speed from AWOS devices at the 36R-middle runway, albeit the simulated peak value was about 4 m/s smaller than observed. The timing of the simulated minimum temperature was almost the same as observed, and the simulated evolutionary trend was the same, but obviously higher than observed. The simulated dew point deficit was obviously larger than observed, meaning that the model underestimated the surface moisture. This may be one of the reasons for why the model underestimated the intensity of echo at ZBAA.

4.2 Trigger, strengthening, and propagation of the storm

Considering that the occurrence of severe weather under the weak forcing of synoptic-scale system and whether the downhill convection could strengthen (due to the complexity of the surrounding orography of Beijing) are difficult for forecasting, we need to further explore the trigger and strengthening mechanisms of the storm. The model evaluation results reported in the previous section show that the evolutionary trends of the surface wind, echo, and surface temperature were well simulated. Therefore, we mainly use these simulated meteorological variables for the analysis hereafter.

At noon (local time), warm and moist southerly flow dominated over the plain (Figure 7a). The southerly flow interacted with northwesterly flow from the mountains, in conjunction with the effect of orographic uplift (Figure 7c), forming the unstable environment that was conducive to the triggering of convection. Owing to the weak low-level wind speed, convection (the cell marked ‘A’ in Figure 3a) moved eastwards, mainly guided by the high-level wind. At 0530 UTC, cell A developed to a mature stage and cell B also initiated over the mountains (with the same trigger mechanism, Figure 3d). Two cold pools (Parker and Johnson (2000) and Xiao et al. (2015) used a temperature change of $-3^\circ$C as the cold pool limit) existed over the northwest of Beijing (Figure 7b), and the outflows of these two cold pools joined on the east side of cell B. Although the direction of movement of cell B was still mainly guided by the high-level westerly flow, the outflow of the cold pool from cell A prevented cell B from moving east, and ultimately caused cell B tend towards the southeast.

At 0600 UTC, as shown in Figure 8a, the impact of meso- and microscale systems weakened owing to the reduction in the scope of the cold pool, and the convective cell was mainly affected by the synoptic-scale environment. The echoes shown in Figure 8b tilted to a certain extent on account of moderate to strong vicinal low-level vertical wind shear (the 0–3-km vertical wind shear value was

![Figure 7](a, b) Meteorological filed at (a) 0400 and 0530 UTC 26 June 2018 simulated by Weather Research and Forecasting: 10-m wind field on the ground (vectors); potential temperature at 2 m (shaded, unit: $^\circ$C), surface 1-h temperature change (below $-3^\circ$C was indicated by red contour). (c) Terrain height along black line in (a).
about 16–18 m/s), and an inner secondary circulation of convergent updrafts and divergent downdrafts formed, jointly contributing to the maintenance and strengthening of the convective cell.

Figure 8e shows that the area-average (16.3°–116.5°E, 40.1°–40.3°N; shown by the box in Figure 3e) 0–3-km vertical wind shear surrounding the convection increased to a near maximum at 0650 UTC. The 0–3-km vertical wind shear sharply increased from 12 m/s to 19 m/s. Correspondingly, the convective cell developed into a storm with the maximum echo value exceeding 60 dBZ. The inclination of the storm further increased, and the echo top was almost 7 km (lower than the observed echo top); the echoes grounded and generated strong downward motion in the boundary layer (Figure 8c,d), resulting in surface wind close to 10 m/s.

5 | CONCLUSIONS AND DISCUSSIONS

5.1 | Conclusions

In this study, a local severe convective weather event that affected ZBAA on 26 June 2018 was investigated with the aid of multi-source observational data from meteorological stations, radar, and the airport itself. Taking this case as an example, we have shown that combining these multi-source data can help reveal more refined characteristics of the development and evolution of such weather phenomena and various associated meteorological parameters, thus serving as a useful reference for forecasters and other researchers. Moreover, 1-min-scale airport observations were used to evaluate the evolutionary
trends of various meteorological parameters simulated by the high-resolution numerical weather prediction model (namely, WRF). Also, based on what was judged to be a reliable simulation of the meteorological variables by the model, we then explored the trigger and strengthening mechanisms of the storm, and discussed the interaction of it with another cell.

This event delivered a violent thunderstorm, poor prevailing visibility, gusty winds, hail, and weak rain in a short duration of just tens of minutes, which resulted in serious impacts on the operations of ZBAA. Analysis of the synoptic environment indicated that, although without a significant trigger of the synoptic system, the convective and thermal instability conditions were favourable, and the 0–6-km vertical wind shear was relatively strong, together forming conditions that were potentially conducive to convection. Radar maps showed that convection was first triggered over the northwest mountains area of Beijing at noon, local time, with one cell moving eastwards, and another southeastwards, with the later strengthening rapidly to eventually evolve into a strong storm that affected ZBAA. In the peak period of the storm, hail and gusty winds were clearly identifiable from the data products of Daxing meteorological radar and the airport radar: there was a TBSS echo, hail with a diameter of 67.8 mm, a convergence zone, a gust front along with the echo, an echo top that extended to 9–12 km, and the largest LWC inside the storm exceeded 70 kg/m².

Meanwhile, we innovatively combined METAR, SPECI, and AWOS observations obtained from ZBAA to reveal a more refined view of characteristics of the development and evolution of the storm. Specifically, the wind speed increased rapidly from 3 m/s to 13 m/s, with gusts of 23 m/s; the wind direction varied from southeasterly to southerly; and the prevailing visibility fell from 3000 m to 600 m. The 1-min-scale airport observations also indicated that tremendous changes in surface wind speed and direction were generated in just tens of minutes at each of the three runways. Besides, other meteorological data from the 1-min-scale observation showed that, in just a 19–min period, the temperature fell by 12°C, the dew point temperature fell by 4°C, and the corrected sea level pressure increased by 3 hPa. Such observations with high temporal resolution can clearly provide important guidance for the security of flights.

In order to reveal the trigger and strengthening mechanisms of the storm, as well as the nature of its interaction with the other storm, we analysed the results from a high-resolution WRF simulation. First, we evaluated the reliability of the model. The results showed that the WRF simulation captured the triggering, propagation, and evolution of the convective cell well, and basically captured the area of hourly accumulated precipitation (albeit the precipitation forecast was weaker). Moreover, by comparing with the 1-min-scale airport observations, we found that the period during which the simulated echo affected ZBAA was close to the observation, but the model underestimated the intensity of the echo at ZBAA. The simulated evolutionary trends of the surface wind and temperature were reliable, but the model seriously underestimated the surface moisture, which may be one of the reasons for why it underestimated the intensity of the echo at ZBAA.

Warm and moist southerly flow from the plain interacted with northwesterly flow from the mountains and, in conjunction with the effect of orographic uplift, triggered the convection at noon. The former cell moved east, mainly guided by the high-level winds. The outflows of two cold pools (generated from the former cell and the later cell) joined on the east side of the later cell and the cold pool from the former cell prevented the later cell from moving east. Influenced by moderate to strong vinal low-level vertical wind shear, the echo of the storm tilted to a certain extent and formed an inner secondary circulation of convergent updrafts and divergent downdrafts, jointly contributing to the maintenance and strengthening of the storm. In the peak period of the storm, the echo grounded and generated a strong downward motion in the boundary layer, resulting in surface wind close to 10 m/s.

5.2 | Discussions

Although some rough conclusions have been obtained from this study, there are still a few remaining questions that need to be further explored. It is well known that analysing the mechanisms of meso- and microscale convection is a complex issue, due not only to the influence from synoptic systems but also the interaction between meso- and microscale systems, which can also contribute to the maintenance and development of the convection. In the current work, we found that the model underestimated the intensity of this event, and preliminarily revealed that the underestimated surface moisture may be one of its reasons. It is worth to do more in-depth research on the reasons of the model failure, such as data assimilation and parameterizations. In addition, the effect of environmental vertical wind shear and the cold pool was studied for a single case, but more cases and sensitivity tests should be studied to further verify the conclusions. Meanwhile, terrain is also an important factor of influence for meso- and microscale convection. The impact of the northwest mountain areas in Beijing on the triggering of storms has been discussed here.
However, in more details, these mountains are in fact composed of two mountain ranges with different orientations, and a low-lying area (reservoir) between the mountains can replenish the water vapour of storms, which are clearly some further aspects worthy of more in-depth research.

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