Observation of a Severe Wind Case Caused by Gust Front and Its Boundary Layer Structures Characteristics

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Abstract. Based on Doppler radar 3D-composited reflectivity, wind profiler radar, boundary layer Tianjin tower of 255m as well as intensified automatic surface observation data, the evolution of the boundary layer associated with two successive gust front processes in the evening of 10 June 2016 and the intensity of the related disastrous surface high wind were analyzed. The results shown as follows: (1) To the same storm cell, the wind intensity caused by the outflow boundary in the main body was stronger than the wind caused by the gust front. The intensity of the disastrous high wind was related to the maximum descending velocity in the boundary layer and the associated height. The stronger the maximum descending velocity and the lower the level, the stronger the disastrous high wind was. (2) The tower data indicated, as the approaching of the gust front, convergence fluctuations first emerged at low(20m) and middle(120m) levels of the tower, leading the emergence of disastrous high wind by 8 minutes. When the gust front passed over, the maximum variations of cooling and the wind velocity were in pace with each other.

1 Introduction

The meso-scale boundary, i.e. gust front or outflow boundary, is formed at the interface between the sinking cold air that reaches low level in the convective storm and the warm wet air at low level. During its passage, the temperature drops, the pressure jumps, and the wind direction shifts. The gust front is actually the boundary between sinking cold air inside the convection and the warm environmental air near the storm. Except elevated convection, the factors that determine local emerging and developing of the convective storm are in the boundary layer, while the gust front is one of the major types of the convergence lines in the boundary layer. Surface divergence(convergence) is obvious behind (before)the gust front, and obvious updraft is observed near the gust front^[1,2].

In recent years, studies on the structures of gust front and the related initiation mechanisms using intensified automatic surface observation data and Doppler radar data increased. Wu et al.^[3] analyzed the evolution characteristics of the gust front and the high wind behind it, pointed out that strong rear inflow favored stronger sinking in the rear storms, and then produced stronger downburst and gust front in the surface. Additionally, strong convective cells emerged when two gust fronts moved heading toward each other^[4].

Primary studies on the relationship between cold gust velocity and descending speed had many results. However, the relevance between the descending speed of

the gust accompanied by the gust front in the boundary layer and the instantaneous high wind was less studied. The fine resolution data, such as the Doppler radar data^[5,6], wind profiler radar data^[7] and the tower data in boundary layer^[8,9], are important to have detailed and quantitative investigations on the related issues in the boundary layer. Utilizing the multi-data in the boundary layer of wind profiler radar data, the meteorological boundary layer tower data and the intensified automatic surface observation data, combined with 3D-composited reflectivity fields based on the four Doppler radars, a disastrous high wind caused by a quasi-line meso-scale convective system on 10 June 2016 was studied. The relationship between the downdraft speed of the surface high wind caused by the gust front in the boundary layer and the instantaneous high wind was investigated to reveal the vertical structures of meteorological elements in the boundary layer accompanied with high wind, and will help to improve the forecasting and warning for the intensity of the surface high wind induced by the gust front.

2 Weather state and environmental conditions

2.1 Case description

In the evening of 10 June 2016, a wide range of thunderstorm high wind emerged in

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Beijing-Tianjin-Hebei region, the maximum velocity reaching 10 grade ($26.0 \text{ m}\cdot\text{s}^{-1}$) appeared in Qingxian Hebei province. Figure 1 shown the distribution of national automatic stations in Beijing-Tianjin-Hebei region where the real state of wind speed $\geq 17.0 \text{ m}\cdot\text{s}^{-1}$ from 14:00 10 June to 02:00(Beijing time without special instructions) 11 June, and the velocity as well as the time with instantaneous wind speed ≥ 9 grade ($20.8 \text{ m}\cdot\text{s}^{-1}$) were indicated in the figure.

Fig.1. High wind in Beijing-Tianjin-Hebin region from 14:00 BJT 10 June 2016 to 02:00 BJT 11 June 2016(★ indicate the location of the wind profiler radar, ● indicate the location of the Doppler radar, ▲ indicate the location of Tianjin tower)

2.2 Synoptic background

The Mongolia cold vortex maintained at 08:00 10 June 2016 (figure omitted) and Beijing-Tianjin-Hebei region was to the southeast of the cold vortex. The quasi-line convective system initiated over the border in head of the warm center and to the front left of the southwest low level jet at 850hPa (figure omitted). The cold-dry air intruded at middle level was over the low level warm-wet air which led the temperature differences between 850hPa and 500hPa to exceed 28°C . It indicated that the structure with cold-dry air at high level and warm-wet air at low level was obvious, increasing static instability. Cyclonic vortex occurred in southern part of Hebei at 14:00 on surface chart (figure omitted), accompanied by the strong warm wet center which produced a belt of large temperature gradient with the cold center in eastern Tianjin, benefited the development of the storm.

2.3 Environmental conditions

The data of Beijing radiosonde station at 08:00 10 June indicated that 850-1000hPa was the wet level and 800-500hPa was the dry level. The greater the value the drier the air was or the thicker the dry level was, favoring the intense downdraft inside the storm [10]. The intensity of dry air was 20°C at mid-high troposphere, the dry level was clear. DCAPE (commenced at 600hPa) reached $1153.9 \text{ J}\cdot\text{kg}^{-1}$ with great potential associated with severe downdraft and high wind. CAPE increased from $365 \text{ J}\cdot\text{kg}^{-1}$ at 08:00 to $2179 \text{ J}\cdot\text{kg}^{-1}$ at 14:00. Both the amplification of CAPE and the CAPE at 14:00 were big, leading the development of instable convective system. The temperature difference between 850hPa and 500hPa was used to stand for the static stability and it reached 27°C at 08:00 10 June. The vertical shear was $22.8 \text{ m}\cdot\text{s}^{-1}$ in

0-6km at 08:00 10 June typed as a severe vertical shear [11].

3 The evolution characteristics of the gust front

The ‘6.10’ disastrous high wind in Tianjin and southern Hebei were affected by two gust fronts in sequence. The first gust front (marked as gust front 1) emerged at 15:42 in Daxing, Fangshan of Beijing, and disappeared around Huanghua, Haixing of southeastern Hebei at 21:12. The second gust front (marked as gust front 2) arose at 20:24 in Hejian of Hebei province, and disappeared around Yangxin, Binzhou of Shandong province. Based on the maximum velocities caused by the gust front measured by automatic stations, the life of the gust front can be divided into three stages: the evolution stage, the mature stage and the dissipating stage.

3.1 Gust front 1

3.1.1 The evolution stage (15:42-17:30)

The convective storm cell moved into the adjacent area of Beijing-Tianjin-Hebei region at 16:36 10 June, the structure of the convective system was similar to the individual cells (CCs) [12]. Surface convergence line formed by the northeasterly and southwesterly was to the southwest of the convective cell. According to the radar reflectivity at low elevation angles, to the south of the cell existed a narrow bow echo which denoted the gust front 1 with the maximum wind speed up to $14.9 \text{ m}\cdot\text{s}^{-1}$ at 16:04. The Position of surface convergence line detected by every 5min surface wind direction observation agreed with the position observed by radar echo, confirming the exact position of the gust front. The adjacent area of Beijing and Tianjin was affected by convective cell at 17:00, forming cold pool (surface temperature $20-23^\circ\text{C}$), temperature decreased at $6^\circ\text{C}\cdot(10\text{min})^{-1}$ near the high wind areas. Most part of Tianjin was controlled by high temperatures greater than 31°C . Based on the wind distribution, the gust front produced by the convergence of cold pool outflow and environmental southeasterly was associated with surface convergence line and weak narrow echo. Additionally, a convergence line of southwesterly and southeasterly was in northeastern Tianjin. In terms of the distribution of temperature and dew-point temperature, this convergence line corresponded with the gradient between cold-wet and warm-dry air, which was known as sea-breeze front (Figure 2a).

Boundary layer wind could be analyzed in detail through wind profiler radar data with high spatial and temporal resolutions. Gust front 1 began to influence the border of Beijing and Tianjin at 15:30 with wind speed lower than $8 \text{ m}\cdot\text{s}^{-1}$ in the boundary layer and ascending movement under 700m. At 15:48, the boundary layer was dominated by descending air. After the gust front passed, convergence fluctuation arose under 700m (figure omitted). At 16:18, the maximum downdraft velocity

reached $0.5 \text{ m}\cdot\text{s}^{-1}$ and high wind appeared in Xianghe station 7 minutes later.

Fig.2. Composite reflectivity of convective systems(shading, units: dBZ), surface temperature (red isolines, units: $^{\circ}\text{C}$), surface pressure (black contours, unit: hPa) and surface wind from ground-based automatic stations on 10 June 2016. XH is the abbreviation of Xianghe, LF: Langfang, XQ: Xiqing, DG: Dagang, QX: Qingxian, HH: Huanghua, MC: Mengcun (black dashed lines: meso-scale surface convergence line, G: the center of thunderstorm high, N: warm center, L: cold center)

3.1.2 The mature stage (17:30-20:00)

At 17:30, the convective system was the broken lines (BLs) structure^[12], the surface temperature and pressure gradients became intenser associated with gust front 1 in the head of the storm cell. This was the strongest period of gust front 1 when the temperature gradient along the front was $2.7 \text{ }^{\circ}\text{C}\cdot(10\text{km})^{-1}$ and the pressure gradient reached $8.8 \text{ hPa}\cdot(10\text{km})^{-1}$. At 18:18, the convective cell moved southeastward, the cold pool advanced southeastward, and the surface temperature dropped to $22-24 \text{ }^{\circ}\text{C}$. The high temperature center weakened comparing to the one at 17:00. Wind propagated southeastward accompanied by the gust front. At 18:18, the gust front met the westward sea-breeze front in Dongli Tianjin, intensified into a stronger convergence belt which was coincidence with the simulation results of Wang et al.^[13]. The gust front brought 7 grade high wind of $17.0 \text{ m}\cdot\text{s}^{-1}$ in Xiqing. Strong updraft emerged in the boundary layer and lower troposphere, triggered convective cell, and caused the convective cell to grow rapidly.

According to the horizontal wind profiler radar data in Xiqing (figure omitted), when gust front 1 passed, the environmental wind was dominated by warm-wet southwesterly of $8-12 \text{ m}\cdot\text{s}^{-1}$, stronger than in the evolution stage. Ascending movements were in the boundary layer and lower troposphere above 870m, whose maximum value was up to $1.0 \text{ m}\cdot\text{s}^{-1}$ around 2.3 km. During this stage, the horizontal and vertical velocity were stronger than in the first stage in the boundary layer and lower troposphere when the gust front passed by.

3.1.3 The dissipating stage (20:00-21:12)

After 20:00, the maximum wind speed associated with gust front 1 decreased to $16.2 \text{ m}\cdot\text{s}^{-1}$. And the temperature gradient and pressure gradient along the gust front reduced to $1.2 \text{ }^{\circ}\text{C}\cdot(10\text{km})^{-1}$ and $2.0 \text{ hPa}\cdot(10\text{km})^{-1}$, respectively. With the horizontal wind profiler radar data in Huanghua, the gust front was in the dissipating stage, strong convergence fluctuation occurred under 1.5km in the boundary layer, the wind maximum larger than $22 \text{ m}\cdot\text{s}^{-1}$ was around 0.8-1.4 km. Accompanied by the passage of the gust front, the wind maximum and convergence fluctuation descended to the near-surface. The northwest high wind maximum was coherent with the strong downdraft. After 21:12, gust front 1 disappeared in southeastern Hebei province.

3.2 Gust front 2

3.2.1 The evolution stage (20:24-21:12)

The convective storm A moved to the border between southern Tianjin and Hebei, the storm cell B to the rear of A travel direction developed into bow echo (Figure 3). The whole gale of $26.0 \text{ m}\cdot\text{s}^{-1}$ in Qingxian occurred at the apex of the bow echo. On the southeast flank of the moving direction of storm cell B emerged gust front 2, of which maximum wind was less than $18.0 \text{ m}\cdot\text{s}^{-1}$ at this stage.

3.2.2 The mature stage (21:12-22:00)

The convective systems further developed into bow echo (BE), the intensity of thunderstorm high reached 1007.5 hPa , and the corresponding center of cold pool was $18 \text{ }^{\circ}\text{C}$ (Figure 2e). The intensity of the high pressure and the cold pool reached the maximum during the entire process. The storm cell B moved southeastward and approached cell A. The two cells merged into the inverted-Y echo, the outflow boundary in the echo adjacent area caused the disastrous 10 grade disastrous wind of $24.9 \text{ m}\cdot\text{s}^{-1}$ in Huanghua station. As seen from the radar echo observation, the string or narrow belt weak echo along the outflow boundary was not obvious when mixed with ground clutter or clear air echo^[14].

Different from gust front 1, during the mature stage, downdraft dominated the boundary layer of gust front 2 whose maximum was around 900m reaching $0.8 \text{ m}\cdot\text{s}^{-1}$. Northeasterly was under 700m, and above 700m was

southwesterly. As the strong echo passed Huanghua, it switched into northerly flow in the boundary layer and lower troposphere, and the maximum wind above 16 $\text{m}\cdot\text{s}^{-1}$ emerged under 900m. Gust front 2 in front of the bow echo brought 9 grade wind of $21.0 \text{ m}\cdot\text{s}^{-1}$ to Mengcun. Compared to the high wind initiated by the outflow boundary which did not split from the main body, the intensity of high wind associated with the gust front was relatively weak (Table 1). The maximum pressure gradient and temperature gradient along the gust front were $13.2 \text{ hPa}\cdot(10\text{km})^{-1}$ and $2.5 \text{ }^{\circ}\text{C}\cdot(10\text{km})^{-1}$, respectively.

3.2.3 The dissipating stage (22:00-23:00)

After 22:00, the left branch of the inverted-Y echo dissipated due to the vanishing of surface convergence line, the inverted-Y echo structure faded away. The wind related to gust front 2 decelerated significantly, the surface maximum velocity was below $17 \text{ m}\cdot\text{s}^{-1}$, and the pressure and temperature gradients weakened. The gust front dissipated accompanied by the system moved eastward to the sea around 23:00.

Table 1. Disastrous high wind characteristics in the representative stations of Tianjin-Hebei region

Causes of disastrous wind	Gust front 1	Gust front 2	
		In main body	Off main body
Representative stations	Xiqing	Huanghua	Mengcun
Wind intensity ($\text{m}\cdot\text{s}^{-1}$)	17.0	24.9	21.0
Occurrence time	18:23	21:28	21:42
Maximum descending velocity in boundary layer ($\text{m}\cdot\text{s}^{-1}$)	0.4	0.8	0.7
The height occurred maximum downdraft(m)	270	870	990
Time of the maximum downdraft	18:12	21:18	21:24

4 Boundary layer characteristics of gust front

The Tianjin Tower in the boundary layer recorded the variations of synoptic elements during this gust front with high wind process, all the data were 1-min averaged with good quality. Gust front 1 affected the entire level of the front tower with the southerly not exceed $5.5 \text{ m}\cdot\text{s}^{-1}$. At 18:15, fluctuations first emerged at 20m and 120m (Figure 3a), leading the emergence of disastrous high wind by 8 minute. At 18:24, the wind over the entire tower switched to the northerly, wind speed under 40m accelerated rapidly with the velocity of $8.5 \text{ m}\cdot\text{s}^{-1}$ at 30m. At 18:25, maximum variations of cooling center with $3.1 \text{ }^{\circ}\text{C}\cdot\text{min}^{-1}$ and wind velocity with $7.2 \text{ m}\cdot(\text{s}\cdot\text{min})^{-1}$ occurred at 30m and 60m, respectively. Afterward the high wind level lifted. Surface instantaneous maximum

high wind of $8.1 \text{ m}\cdot\text{s}^{-1}$ occurred at 18:30 while the wind at lower tower level decelerated and mid-high level wind accelerated above 60m. At 18:39, the wind velocity reached $15.5 \text{ m}\cdot\text{s}^{-1}$ at 220m.

Fig.3. Meteorological per minute elements evolution observed by Tianjin tower at 18:00-19:00 10 June 2016 (a) shading: wind speed (units: $\text{m}\cdot\text{s}^{-1}$), wind-direction shaft; time interval: 2 min; brown ellipses denote convergence perturbation. (b) shading: relative humidity (units: %), contours: temperature (units: $^{\circ}\text{C}$), denote the moment with maximum wind speed, black dashed lines denote the time when the gust front passed by

Based on the analysis above, the conceptual diagram of the vertical structure with the two gust fronts in the boundary layer was built (Figure 4). During the evolution stage, the vertical velocities of the two gust fronts were of little difference. Gust front 1 and 2 were associated with surface southwesterly and northeasterly, respectively. During the mature stage, updraft was at mid-high level of the boundary layer associated with gust front 1 while downdraft was dominant in the boundary layer related to gust front 2, this was one of the reasons why surface wind was stronger as caused by gust front 2 than gust front 1. During the dissipating stage, northerly dominated boundary layer associated with the 2 gust fronts. Additionally, extremely strong wind exceeded $20 \text{ m}\cdot\text{s}^{-1}$ was at middle level.

Fig.4. The conceptual diagram of vertical structure of the gust front on 10 June 2016 (The 3D structures of horizontal and vertical velocities. Black represent gust front 1 and grey represent gust front 2. The upward and downward arrows denote updraft and downdraft, respectively)

5 Conclusions and discussion

Based on Doppler radar 3D-composited reflectivity data, wind profiler radar data, boundary layer Tianjin tower data and intensified automatic surface observation data in Beijing-Tianjin-Hebei region, the evolution of the

boundary layer related to two successive gust front processes in the evening of 10 June 2016 and the intensity of the related disastrous high wind were analyzed. The main conclusions are as follows:

(1) The intensity was not proportional to the last time of the instantaneous wind caused by the gust front. The duration of the gust front in front of the bow echo was the shortest while the wind intensity caused by the gust front was the strongest. To the same storm cell, the wind intensity caused by the outflow boundary in the main body was stronger than the wind caused by the gust front. The intensity of the disastrous high wind was related to the maximum downdraft in the boundary layer and the associated height. The stronger the maximum downdraft and the lower the level, the stronger the disastrous high wind was.

(2) It was indicated by the tower data, as the approaching of the gust front, it emerged convergence fluctuations at low (20m) and middle (120m) levels of the tower, leading the emergence of disastrous high wind by 8 minutes. When the gust front passed over, the wind direction over all levels of the tower switched into northerly. The maximum variations of cooling and the wind velocity basically kept in pace with each other. The maximum cool reached $3.1^{\circ}\text{C}\cdot\text{min}^{-1}$, and the drastic changes of velocity and temperature lasted for 2 minutes and 4 minutes, respectively.

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