

Observation of a Straight-Line Wind Case Caused by a Gust Front and Its Associated Fine-Scale Structures

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ABSTRACT

A straight-line wind case was observed in Tianjin on 13 June 2005, which was caused by a gust front from a squall line. Mesoscale analyses based on observations from in-situ surface stations, sounding, and in-situ radar as well as fine-scale analyses based on observation tower data were performed. The mesoscale characteristics of the gust front determined its shape and fine-scale internal structures. Based on the scale and wavelet analyses, the fine-scale structures within the gust front were distinguished from the classical mesoscale structures, and such fine-scale structures were associated with the distribution of straight-line wind zones. A series of cross-frontal fine-scale circulations at the lowest levels of the gust front was discovered, which caused a relatively weak wind zone within the frontal strong wind zone. The downdraft at the rear of the head region of the gust front was more intense than in the classical model, and similar to the microburst, a series of vertical vortices propagated from the rear region to the frontal region. In addition, strong tangential fine-scale instability was detected in the frontal region. Finally, a fine-scale gust front model with straight-line wind zones is presented.

Key words: straight-line wind, gust front, fine scale, squall line

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1. Introduction

A gust front is the leading edge of an outflow from a thunderstorm (either single or multiple cell), a more complex system such as a squall line (quasi-linear convective system, QLCS), or other mesoscale convective systems (MCSs). A gust front is often associated with strong and damaging winds (straight-line winds) and severe convective weather. This is because it is a type of mesoscale front with a significant pressure gradient across the front line. On the mesoscale (horizontal scale from 2 to 200 km; Orlanski, 1975) and fine-scale (horizontal scale less than 2 km; Orlanski, 1975), and with high-resolution data, strong inconsistency in wind direction, wind speed (both horizontal and vertical), pressure, and temperature is often observed (Shapori, 1985). However, due to limited obser-

vations, such a phenomenon has not been recorded to a satisfactory level in China. There have been many studies published on gust fronts (Wang et al., 2006; Liao et al., 2008), but few on the frontal structure of gust fronts. Wang et al. (2006) observed an inconsistent pattern within the frontal region of a gust front; however, their analysis lacked in detail, without examination of fine-scale characteristics.

Although the classical structure of a gust front was described by Drogemeier and Wilhelmson (1987), later observations have shown different types of gust fronts with different amounts of surges after the head of the gust front. These features also contribute to the shape of the top of the planetary boundary layer (PBL) (May, 1999) and affect the propagation of gravity waves triggered by the instability from the head of the gust front, and by the range of damaging wind

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zones and the initialization of secondary convective cells (Weckwerth and Wakimoto, 1992), both of which are revealed based on examination of fine-scale structures.

The different shapes of gust fronts are to some degree related to environmental parameters, especially the buoyancy and vertical wind shear near the top of the PBL. This is because the surge of a gust front is caused by the backward propagation of the Kelvin–Helmholtz (K–H) wave triggered by the K–H instability at the head of the gust front. The K–H instability is strongly linked to the environmental Richardson number, which is the ratio of buoyancy and vertical wind shear, and for a K–H instability to develop, this ratio should be not more than 0.25. The conditions of the environment may also contribute to the characteristics of initialized secondary cells along the instability, which affect the intensity of the surface wind.

The lowest levels of the gust front structure can be observed based on the PBL observation towers (Goff, 1976; Zhao et al., 1982) with the height below 500 m. Meanwhile, with the development of Doppler radar, radar data together with sounding data are now helping to provide descriptions of the upper-level structure of gust fronts (Wakimoto, 1982; Uyeda and Zrnic, 1986; Kirsten and Schroeder, 2007). However, in such studies, the fine-scale distribution of damaging winds is not delineated well, because the turbulent process is not analyzed down to this level in detail. There is also a lack of insight into the contribution of turbulent fluctuation and transfer of momentum and energy to the damaging winds. In-situ Doppler radar measurements are always used in such analyses, but it nevertheless remains challenging to describe the development of meso- γ -scale or fine-scale systems by merely applying in-situ radar data. Data from observation towers can only reach the lower levels of a gust front, and no radar-based velocities can be derived for this part of the profile because the lowest two elevations for Doppler radar are 0.5 (350 m above ground level) and 1.5 (1200 m above ground level), but the height of the gust front is approximately 600 m. On the other hand, the fine-scale structures within a downburst propagate outwardly near the surface, with the

maximum at about 170–300 m (Fujita, 1981). Thus in this paper, only the fine-scale structures within the lowest part of the gust front are analyzed.

In this paper, we analyze a straight-line wind case that occurred on 13 June 2005 in Tianjin, China. The event was caused by a gust front from a squall line. The front happened to pass over a PBL observation tower in Tianjin, thus providing us with valuable data to examine the internal structures of the outflow. The data from the observation tower are used to scrutinize the structure of the gust front, in order to distinguish the fine-scale structures within the gust front from the classical mesoscale structures, and to understand their characteristics and causes. The fine-scale structures determine the straight-line wind distribution within the traditional strong wind zone. The data used in the study are described in Section 2. In Section 3, the mesoscale surface observation data are used to examine the environmental conditions to determine how the gust front formed. The fine-scale tower observations are analyzed in Section 4. Section 5 provides a scale analysis, separates the fine-scale structures from the mesoscale structures, and describes the characteristics and causes of these fine-scale structures. Section 6 presents a new gust-front model that includes fine-scale structures.

2. Data and method

Four main sets of data are used in the observational analysis: in-situ surface observations in the Beijing-Tianjin area; the sounding data from Beijing station (used to represent the soundings at Tianjin station); in-situ Doppler radar data from Tanggu station; and observation tower data in Tianjin, with per-minute pressure data supplied by an automatic weather station (AWS). Quality check on some of the data were conducted before further data analysis.

2.1 *In-situ surface station and Doppler radar observations*

In-situ surface observations in the Beijing-Tianjin area were selected. The closest observation time around the case was 0900 UTC 13 June 2005. The time 0900 UTC was not the standard observation time

in 2005, and the AWS network was to be established. Thus, the number of stations with observations in that area was 20.

The in-situ Doppler radar resides at Tanggu station, 41 km to the southeast of Tianjin station. The radar provides reflectivity and radial velocity data at elevation angles of 0.5° , 1.5° , 2.4° , 3.6° , etc., with an interval of 6 min.

2.2 Sounding data

Beijing station is the only sounding station within the Beijing-Tianjin area. The sounding profile of Beijing station is usually used as a proxy for Tianjin station, together with the surface stationary observation data of Tianjin. This is because in many cases the mid-to-upper atmospheric fields of Beijing and Tianjin are homogeneous (Liu, 2010). In the present case, the wind direction of the Beijing-Tianjin area at both 500- and 700-hPa layers was northwest, and Tianjin is to the southeast of Beijing. This means Tianjin is downstream of Beijing, and the balloon from Beijing would therefore adequately represent the situation at Tianjin in the middle and upper troposphere. Note that, in this case, we need to use the sounding profile in the morning to represent the atmospheric thermal dynamic field in the afternoon, due to the slow movement of the large-scale systems.

2.3 Tower observations

The observation tower is right on the ground of Tianjin station. The station is located at $39^\circ 04' 29.26''\text{N}$, $117^\circ 12' 20.51''\text{E}$, with its surrounding buildings lower than 10 m. The tower itself is 250-m high, with 15 observation levels for the sensors at 5, 10, 20, 30, 40, 60, 80, 100, 120, 140, 160, 180, 200, 220, and 250 m. The sensors record temperature, wind speed, wind direction, and relative humidity, with a frequency of 0.05 Hz (20 s per observation). The local AWS provides pressure data every minute.

2.4 Calculation of vertical velocity

As vertical velocity data are not directly observable, we need to calculate w from the horizontal velocity (Charba, 1974; Zhao et al., 1982). According to

the Galilean equation,

$$\frac{\partial \mathbf{V}}{\partial t} = -C \cdot \nabla \mathbf{V}, \quad (1)$$

where C is the average speed of the gust front propagation, calculated as the average of the propagation distance measured from the radar reflectivity chart divided by the time. We have

$$-\frac{1}{C_x} \frac{\partial u}{\partial t} - \frac{1}{C_y} \frac{\partial v}{\partial t} + \frac{\partial w}{\partial z} = 0, \quad (2)$$

where C_x and C_y are the average speed of a gust front in the x and y directions, respectively. Here, we define x as the radial direction and y as the tangential direction. $C_x = C \cos \theta$, $C_y = C \sin \theta$, and θ is the angle between east and x . Subsequently, we have

$$\frac{\partial w}{\partial z} = \frac{1}{C} \left(\frac{\partial u}{\partial t} \cos^{-1} \theta + \frac{\partial v}{\partial t} \sin^{-1} \theta \right). \quad (3)$$

Performing the integration obtains

$$\int \frac{\partial w}{\partial z} dz = \frac{1}{C} \int \left(\frac{\partial u}{\partial t} \cos^{-1} \theta + \frac{\partial v}{\partial t} \sin^{-1} \theta \right) dz. \quad (4)$$

By computational discretization in the vertical direction, the equation becomes

$$w_i = w_{i-1} + \frac{(z_i - z_{i-1})}{2C\Delta t} \left(\frac{u_{j+1,i} + u_{j-1,i} - 2u_{j,i}}{\cos \theta} + \frac{v_{j+1,i} + v_{j-1,i} - 2v_{j,i}}{\sin \theta} \right), \quad (5)$$

where i is the number of levels of the tower observation and j is the time series, $\Delta t = 20$ is the average time interval.

3. Case description

3.1 Synoptic and mesoscale background

As shown in Fig. 1, at 0000 UTC 13 June 2005, upper-level troughs at both 500 and 700 hPa were present, with the troughs tilting backward with increasing height, indicating that the system was developing (Wang et al., 2010). The shear line of NW-SE winds at 850 hPa lay between Beijing and Tianjin (Fig. 1a), where the east winds provided a moisture channel. Tianjin was inside a surface warm zone. The whole background was conducive to the development

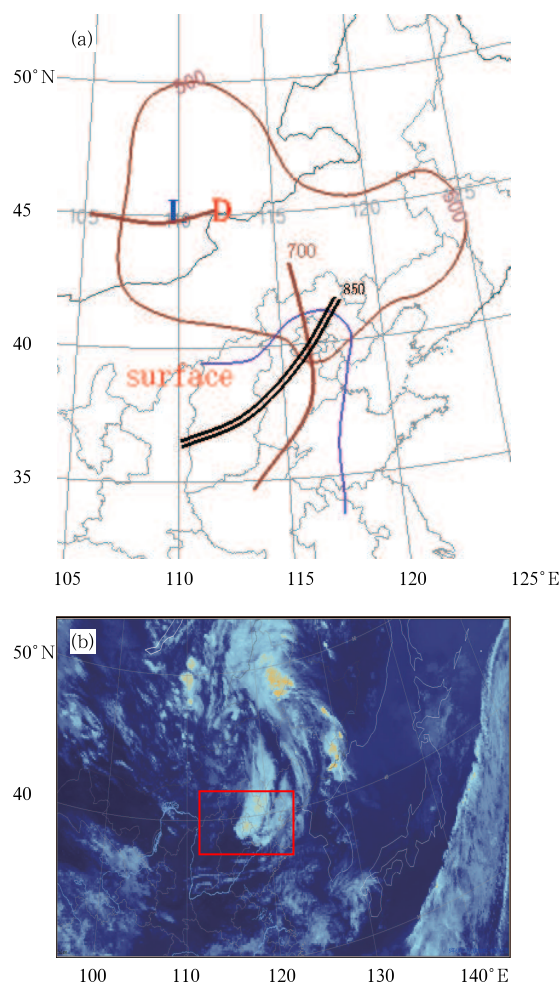


Fig. 1. (a) Large-scale environment at 0000 UTC 13 June 2005 and (b) satellite IR chart at the same time, with the red square showing the Beijing-Tianjin area.

of mesoscale convective systems. As seen from the cloud chart at the same time (Fig. 1b), the tail of a linear convective system was developing right past Beijing and toward Tianjin, from northwest to southeast. This linear convective system was the squall line from where the gust front generated.

The sounding data of Tianjin at 0600 UTC provide a thermal profile as shown in Fig. 2. Vertical wind shear existed at 925 and 850 hPa. From the surface to 850 hPa, the wind shifted anticlockwise, indicating the existence of cold advection. From 850 to 500 hPa, the wind shifted clockwise, demonstrating the presence of warm advection. With the lower layers being cold and the upper layers being relatively warm, it was easy for convection to be initiated at the boundary of

the cold flow. However, the CAPE of only 479.2 J kg^{-1} meant that the local buoyancy was weak. Weak instability with wind shift implied that vertical wind shear was the main contributor to the developing convection. The maximum vertical wind shear was $4.79 \times 10^{-3} \text{ s}^{-1}$, with the wind difference from 0 to 6 km of 26.79 m s^{-1} , compared to 6.80 m s^{-1} from 0 to 2 km. This indicates a strong wind shear in the middle layers, but a rather weak wind shear at the PBL. It was observed that main convection happened in the middle layers, with a maximum vertical velocity of 31 m s^{-1} . The θ_e line shows a thin dry layer between 850 and 700 hPa, and a thick dry layer between 600 and 400 hPa.

Furthermore, the surface mesoscale analysis (Fig. 3) at 0900 UTC shows a local cyclone with Tianjin at its northeastern edge. To its northwest was a meso-high with convective weather and a cold center. Between the cyclone and the meso-high was the baroclinic zone (Sanders, 1999), with a temperature change reaching 10 K within 30 km. The meso-high stayed between two meso-lows, and to their north, a high pressure center existed on a larger scale. All these meso-systems formed a deformation field, and a wind shift line lay between the converging north wind and southeast wind. The high pressure center and its convective systems moved southwestward and split into two cells. The gust front emerged at 0948 UTC (Fig. 4), and it propagated southeastward.

3.2 Radar observation

The radar reflectivity data show that after the convective system moved into the baroclinic zone, as in Fig. 5, the outflow from the newly split cell emerged at 0948 UTC (Fig. 6), 10.4 km from Tianjin, and moving toward the southeast with its intensity increasing. The outflow passed Tianjin at 1000 UTC (Fig. 5), and then continued to move southeastward, joining another outflow and passing Tanggu at 1030 UTC (figure omitted). The outflow's direction of movement was about 30° to the left of the direction of the temperature gradient of the baroclinic zone.

Figures 5e and 5f show that at the elevation of 0.5° (approximately 350 m above ground level), the gust front was clearly seen as a thin line with a radi-

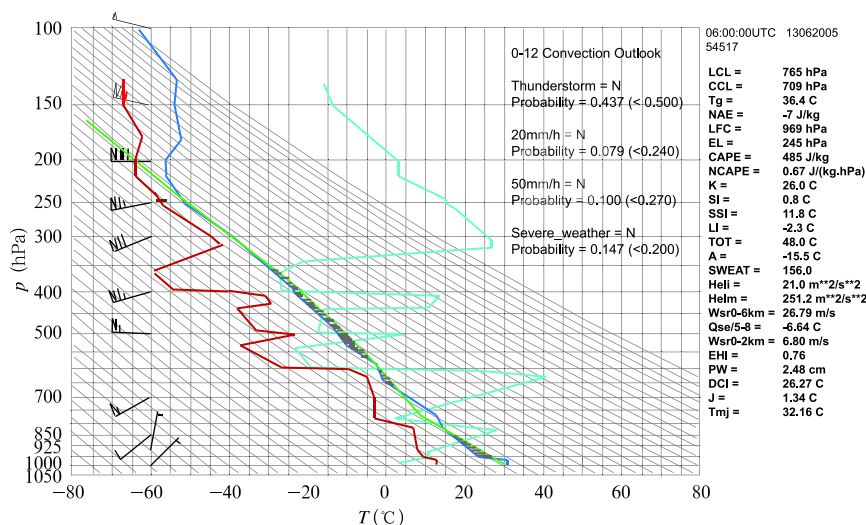


Fig. 2. The T -lgp chart for Tianjin at 0600 UTC 13 June 2005. The red line to the far left denotes dew point. The blue line denotes temperature. The cyan line in the middle denotes θ_e .

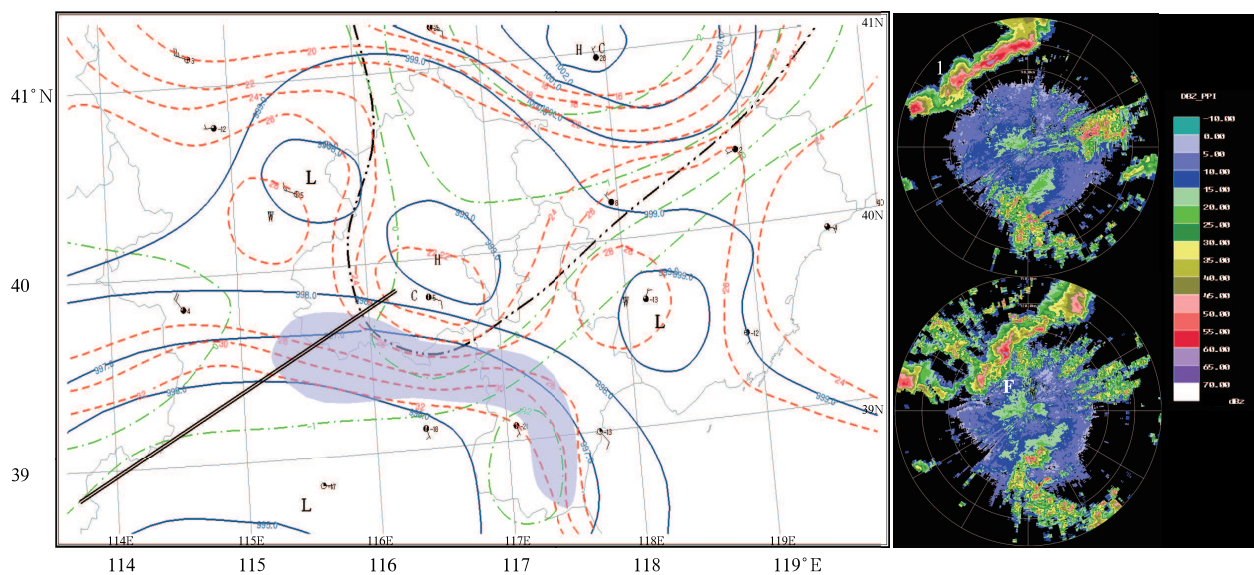


Fig. 3. Mesoscale features of the surface pressure and temperature fields in the Beijing-Tianjin area at 0900 UTC 13 June 2005. Blue solid lines are the isobaric lines. Red dashed lines are the isothermal lines. Green dash-dotted lines are the 3-h pressure change lines. The black dash-dotted line indicates the squall line region. Convective weather associated with the meso-high is shown in the radar image as the strong reflectivity zone. The double black line is the wind shift line. Forty-eight minutes later, the gust front in the radar image is labeled as F.

al velocity couplet. No reflectivity line could be seen at the elevation of 2.4° (approximately 1800 m), while the negative radial velocity meant that the system was tilting toward the radar station, and all parts of the gust front were within the PBL. At the elevation of 2.4° (Figs. 5a and 5b), there was neither a line structure nor large radial velocity, but only a weak single cell

developing, which was not seen before the gust front passed. Such a structure means that this weak cell was triggered by the gust front. In the cross-section of the radial velocity at 0948 and 1000 UTC (Fig. 6), the propagation of the outflow from the squall line structure toward the sea was significant, and tiny circulations above the outflow were around 2 km—one

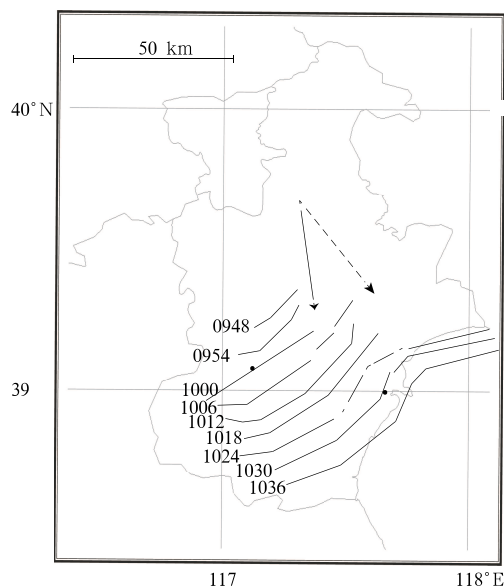


Fig. 4. Propagation of the gust front reflectivity line from radar at the elevation angle of 0.5° . The dot on the left denotes Tianjin station, and the dot on the right denotes Tangu station where the radar is located. The arrow is the temperature gradient direction of the baroclinic zone at 0900 UTC, and the dashed arrow is the actual propagation direction of the gust front.

single circulation above the head of the outflow and two above the rear part. It should also be pointed out that a structure with a height of less than 1 km existed ahead of the outflow but with an opposite propagation direction. This was probably a sea-breeze front.

Furthermore, a couplet of radial velocity (Wilson and Schveiberm, 1986) within a thin velocity zero line (Fig. 7), whose spatial scale was less than 4 km, was apparent, which would have evolved into a meso-vortex. Some similar meso-vortexes were recently observed and analyzed during severe convective cases (Wakimoto et al., 2006a, b; Atkins and Laurent, 2009a, b). They had fine-scale characteristics than traditional meso-cyclones.

From the wind profile right across Tangu radar station, we can obtain the vertical kinetic structure of the gust front (Fig. 8). The height of the gust front was approximately 600 m, and right above the head of the gust front there existed a weak wind zone, from 1200 m to around 3000 m. This suggests the existence of a vertical circulation above the head of the gust front that may be associated with sub-generated

convective cells.

3.3 Tower observation

We use the tower observation data from 0955 to 1030 UTC because during this period, the entire structure of the gust front, as well as the possible secondary systems, passed over the tower. In order to examine the different scales of structure within the gust front and the associated wind speed and secondary systems, we ran a pair of moving averages on different time scales on the observation data: one was a 5-min moving average (Fig. 9), and the other was a 1-min moving average (Fig. 10). To obtain the chosen pair of moving averages, we first ran four sets of moving averages (1, 2, 5, and 10 min) on the original observational data. The original data contained too much turbulence, especially for the fine scale. The mesoscale structures were preserved well in the 5-min moving averaging, while the 10-min average only retained a basic front-like feature. The 1- and 2-min averaged data contained fine-scale structures that were not shown in the classical gust front conceptual model, and the 1-min results were more clear.

Figure 9 shows that the 5-min average provided a whole head range of the gust front. The strong wind zone split into two: one near the potential temperature gradient zone and the other mostly at the end of the head. The difference between the kinetic front and the thermal front also became distinguishable. The surface pressure increased through the whole potential temperature gradient zone, reaching a maximum right after the front, but with no significant pressure jump. The wind direction shifted with the kinetic front. The vertical velocity was arranged in the form of a series of couplets, with the first and strongest updraft between the kinetic and thermal fronts, while the most intense downdraft at the rear of the head region. The radial velocity within the head region was stratified, with the upper layer toward the front and the lower layer away from the front, indicating the existence of backflow, and the height of the backflow layer increased toward the back of the head, and then stayed the same after the head. The tangential velocity also showed stratification, but was only significant within the head region. This suggests that the direction of the backflow was

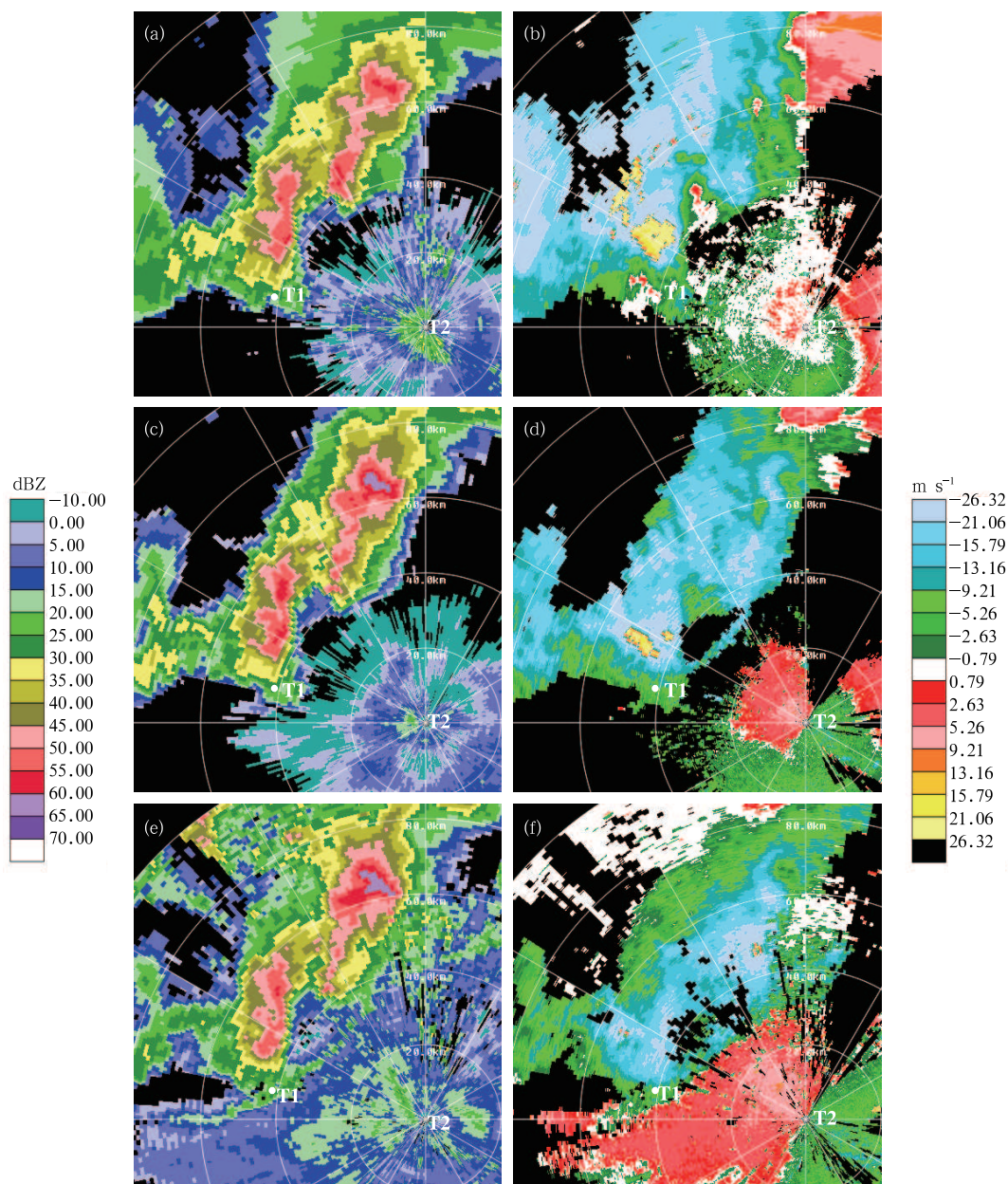


Fig. 5. Radar reflectivity and radial velocity at the elevation angles of (a, b) 2.4°, (c, d) 1.5°, and (e, f) 0.5° at 1000 UTC 13 June 2005. T1 and T2 represent Tianjin and Tanggu stations.

not just parallel to the propagation route of the gust front, but lay at various angles. Although the back-flow region in both the radial velocity and tangential velocity fields overlapped perfectly, there was no wind speed jump at the boundary of the backflow and the main flow, albeit the strong wind zones were mainly related to the maximum radial velocity zones. Both radial and tangential horizontal vorticity fields reached their maximum around the velocity boundary, and the

maximum regions were shaped as a single continuous belt.

Figure 10 shows that the 1-min average was the only way to truly observe the pressure jump, which was in the thermal gradient zone. The horizontal vorticity was clearly a series of small circulations from the back of the head to the front, and the vertical velocity at the back of the head was much greater than that at the front. The maximum wind speed was also contri-

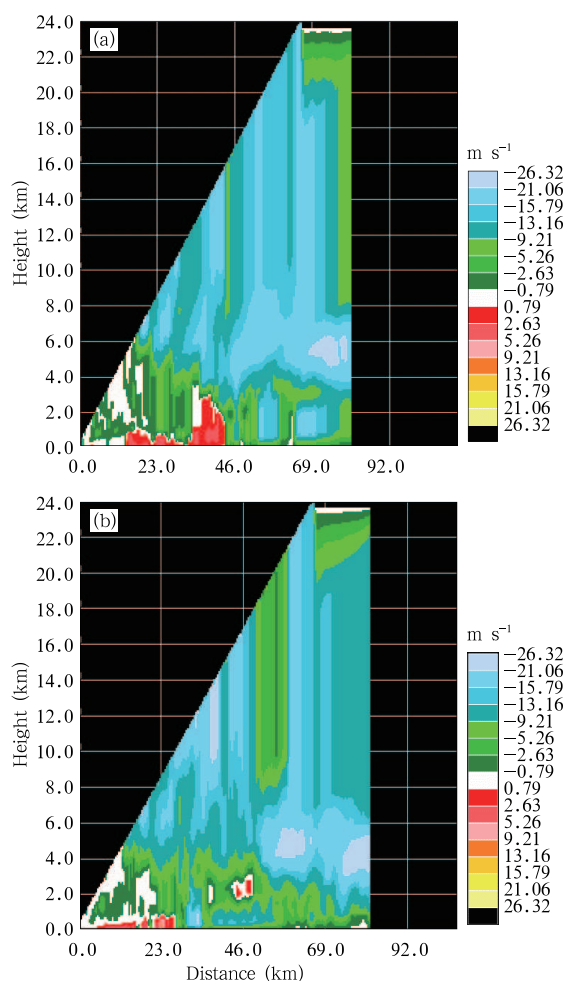


Fig. 6. Cross-section of radar radial velocity at (a) 0948 UTC and (b) 1000 UTC. Tianjin station is at a distance of 43 km.

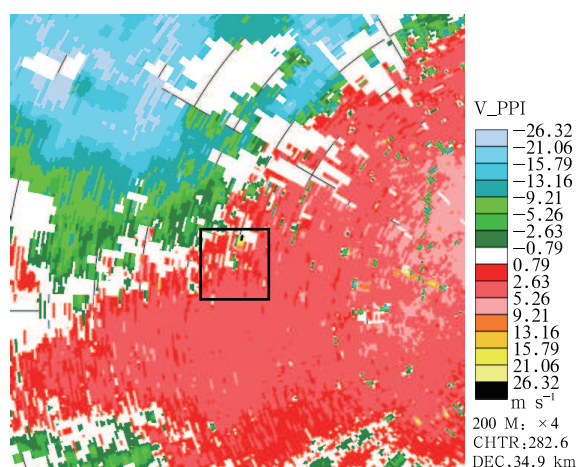


Fig. 7. Radar radial velocity at the elevation angle of 0.5° at 0954 UTC 13 June 2005. The black square shows the location of the meso-vortex.

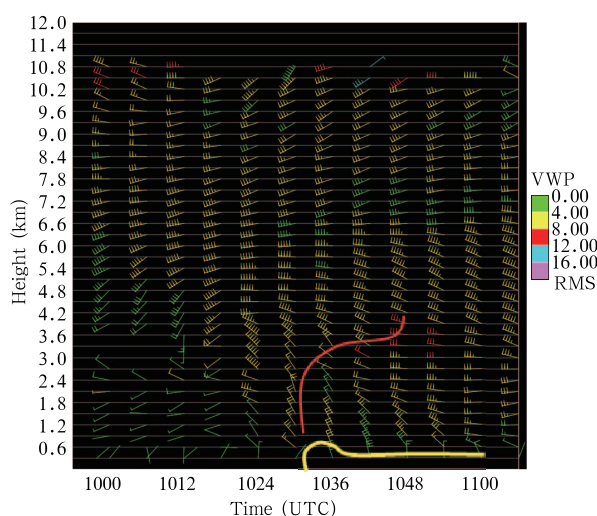


Fig. 8. The vertical profile of wind at Tanggu radar station. The yellow line denotes the gust front and the red line is the relative low-speed line.

butted by the downdraft at the end of the gust front head, with vertical velocity couplets being more significant. This was more like the near-surface structure in a moving downburst, in that the fine-scale circulations in the bottom layer of the outflow tended toward the propagation direction of the downburst, while they were depressed in the opposite direction (Fujita, 1981). It is also important to note that the surge part in the classical model of a gust front's structure was barely apparent, even at the finest scale systems observed from the gust front. Therefore, we can say that, in this case, the surge was not sufficiently significant, and the strong wind zone was trapped in a single head of the gust front. The intensity of the gust front downdraft was relatively larger compared to the calculated velocity from the thermal gradient. In the classical model of a gust front, the intensity of the downdraft at the rear of the head section is due to that of the updraft at the front, resulting from the frontal thermal gradient. Thus, other factors would affect the downdraft intensity. In this case, the downburst-like structure should be considered.

4. Observation analysis

4.1 *K-H wave and its propagation*

Almost all gust fronts will trigger K-H wave from

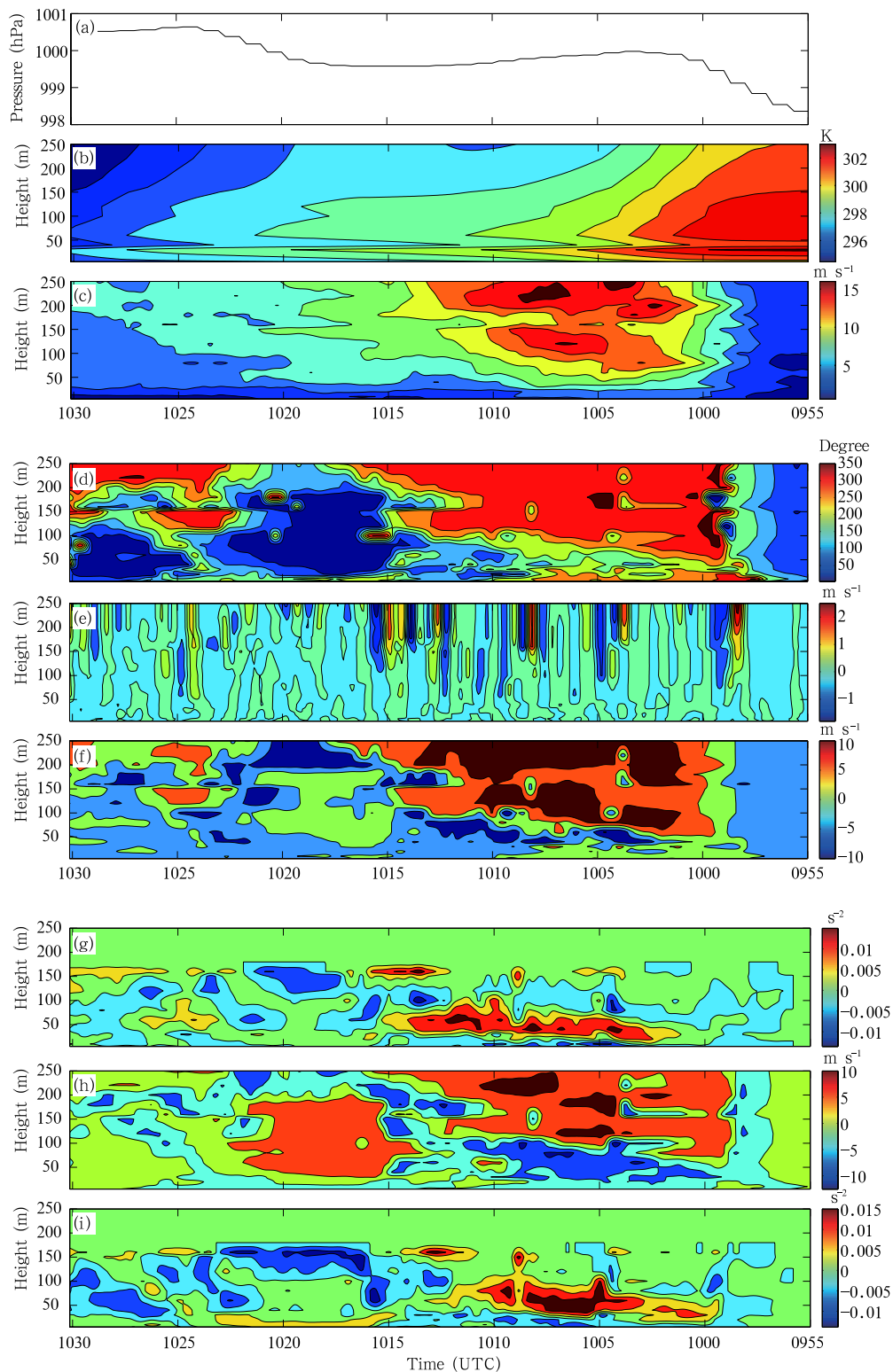


Fig. 9. The 5-min moving average of tower observations of (a) pressure, (b) potential temperature, (c) horizontal wind speed, (d) wind direction, (e) vertical velocity, (f) radial velocity, (g) radial horizontal vorticity, (h) tangential velocity, and (i) tangential horizontal vorticity.

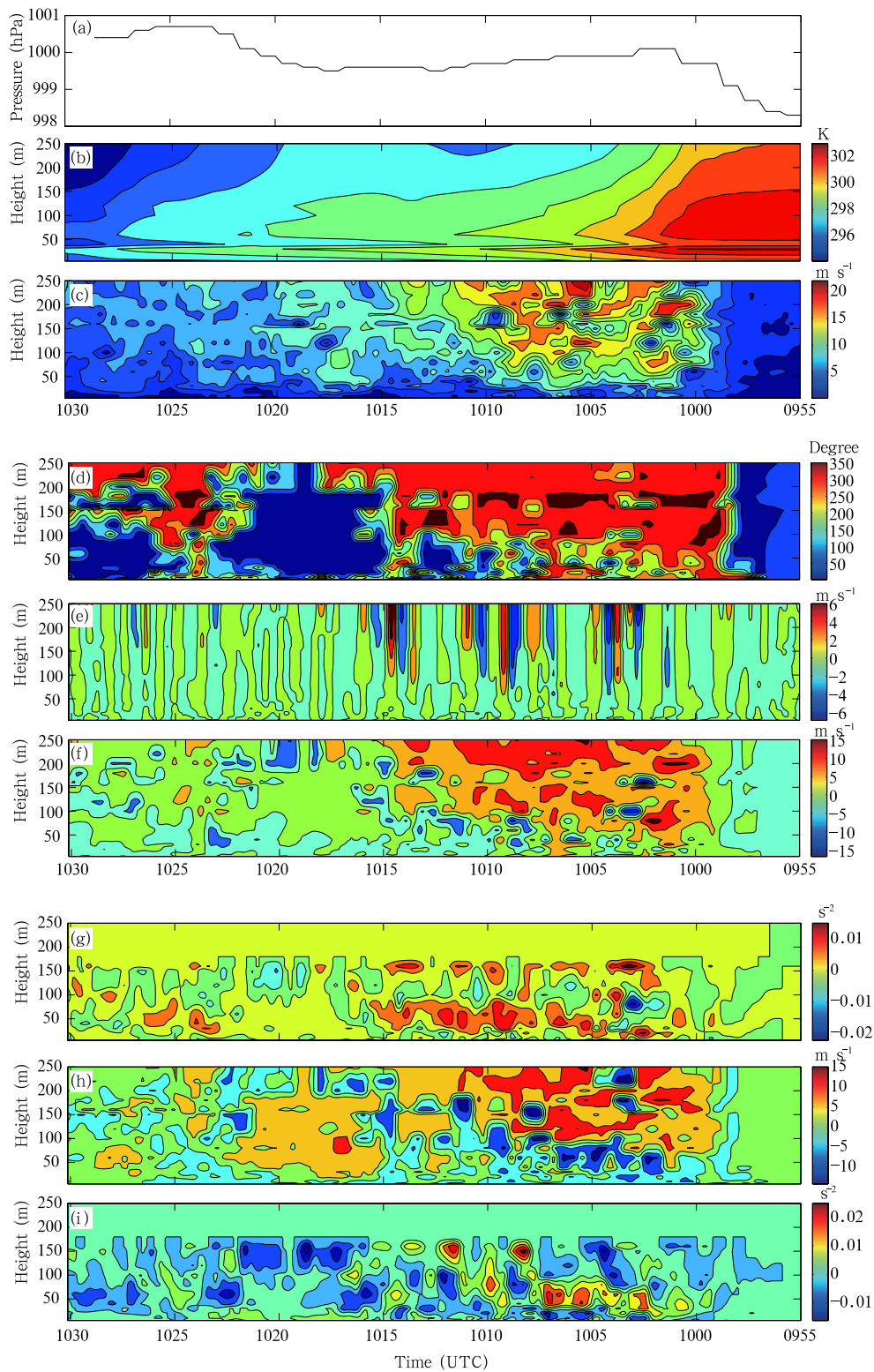


Fig. 10. As in Fig. 10, but for the 1-min moving average of tower observations.

the head. Assuming that the gust front is two-dimensional, we can obtain the wavelength of the K-H wave by

$$\lambda = \frac{2\pi\rho_0\Delta\bar{u}^2}{g\Delta\rho} \left[1 + \frac{\bar{u}_1 + \bar{u}_2}{\sqrt{2(\bar{u}_1^2 + \bar{u}_2^2)}} \right]^{-1}, \quad (6)$$

and the velocity by

$$c = \frac{\rho_2\bar{u}_2 - \rho_1\bar{u}_1}{\rho_2 + \rho_1} \pm \left[\frac{g\lambda}{2\pi} \frac{\rho_2 - \rho_1}{\rho_2 + \rho_1} - \rho_1\rho_2 \left(\frac{\bar{u}_2 - \bar{u}_1}{\rho_2 - \rho_1} \right)^2 \right]^{-1/2}, \quad (7)$$

the results of which are presented in Table. 1. As the head of a gust front is roughly 3/4 of the K-H wavelength, the length of the head was calculated as 1763 m, and the period as approximately 10 min.

4.2 Environmental parameters

We know from the observations that the K-H wave in this case was restrained. As the head section of a gust front is formed by the K-H wave, the propagation of the K-H wave being opposite to the gust front's direction of movement is the cause of the surge of the gust front. In the current particular case, the surge section was hard to recognize, but the head section was obvious. Using the observed propagation speed and the propagation time of the head section, the calculated length of the head section was 2499 m, which was longer than the head length based on the K-H wave calculation. As K-H instability is sure to occur in every gust front case (Mueller and Carbone, 1987), the reason for this long head without a surge was the lack of a proper K-H wave propagation; the main reason for this was the environment, because K-H instability can only develop when the environmental Richardson

number (Ri) is less than 0.25. Ri is the partition of the environmental buoyancy to vertical wind shear. In this case, from Fig. 3, we know that although the buoyancy was rather weak and the total vertical wind shear was strong enough that convection developed, the low-level vertical wind shear was much weaker. Note that the entire gust front was within the PBL. Based on the sounding data from surface to 850 hPa (approximately 1500 m), Ri was calculated. The Ri was 0.32, suggesting that no further K-H wave propagated backward to form the surge.

4.3 Gust front intensity

The intensity of the gust front is shown by the data presented in Table 2. We can see that the intensity of the gust front was not very high, with a shallower thermal gradient and a lower propagation speed than in most cases (Moncriff and Liu, 1999). Nevertheless, this gust front still caused severe wind damage, suggesting that the mesoscale features were not the critical part. The horizontal wind speed caused by a classical mesoscale gust front should be proportional to the intensity of the gust front itself, as the momentum transfer is caused by the frontal pressure gradient. A weak gust front cannot provide enough momentum transfer to cause strong damaging winds solely from its head circulation. Thus, finer-scale structures must have been involved.

4.4 Scale analysis

As gust fronts can be cataloged into β or γ -mesoscale systems, we first presume that all factors related to the gust front are mesoscale structures, meaning that they should have a Rossby number of 1. The

Table 1. Parameters of the K-H wave

Fr	λ (m)	c (m s ⁻¹)	T (s)	f (Hz)	Length of the head (m)
2.43	2351	4.1974	560.10	0.001785	1763

Table 2. The intensity of the gust front and related parameters

Time of the minimum wind (UTC)	Time of the wind shift (UTC)	Time of the thermal front (UTC)	Average change of potential temperature (K)	Duration of the baroclinic zone (s)	Maximum wind speed (m s ⁻¹)	Average observed propagation speed (m s ⁻¹)	Average calculated propagation speed (m s ⁻¹)
5620	5730	5900	3.6	300	21.2	8.33	14.23

Rossby number (Ro) is calculated as

$$\text{Ro} = \frac{U}{2\Omega \sin \varphi L'}, \quad (8)$$

which represents a comparison between the inertial force and the Coriolis force. If $\text{Ro} \leq 1$, the Coriolis force cannot be ignored, i.e., the rotation of the earth is significant and the system is of large or meso scale. If $\text{Ro} > 1$, the Coriolis force can be ignored and the system is fine scale.

We should also note another non-dimensional number, the Froude number (Fr), which is

$$\text{Fr} = \frac{\frac{1}{2}\rho_0 U^2}{\Delta\rho g H}, \quad (9)$$

and represents the partition of the inertial force and gravity. A mesoscale system always has an Fr number that approximately equals 1. In the case of a gust front, Fr is more or less around 1.

Therefore, if we presume both Ro and Fr are equal to 1, we can calculate the characteristic length of the gust front by

$$L \sim \frac{1}{\sqrt{2}\Omega \sin \varphi} \sqrt{\frac{\Delta\rho}{\rho_0} g H}. \quad (10)$$

Putting L back into Eq. (8), we can obtain the characteristic velocity U of the gust front, which indicates the maximum wind speed that the gust front can lead to. For the present case, the results are listed in Table 3.

The calculated value of U is less than the actual horizontal velocity, meaning that the actual wind, partly due to the gust front itself, was also affected by some fine-scale structures. Based on the definition of Orlanski (1975), with $L = 2$ km as the shortest characteristic length of the mesoscale structure, if $\text{Ro} = 1$, then $U_{2\text{km}}$ should be 5.33 m s^{-1} according to Eq. (8),

comparable to the real horizontal velocity of 7.66 m s^{-1} (obtained by subtracting U from U_r). This result suggests that the affecting finer-scale structure had a characteristic length of 2 km, which was approximately the length of the head section of the gust front.

Next, the wavelet method was used to filter the observation data, in order to separate structural waves of different timescales, similar to a direct scale analysis. The result is presented in Fig. 11. The significant signals and their corresponding timescales can be identified. The base wave represents the 10-min average, and the high-frequency waves represent the different timescales from 5 min to turbulence of less than 1 min. We calculated the magnitude of the filtered signals of vertical velocity and associated errors. The magnitude of the 1-min moving average signal was roughly the same as the error. Thus, the filter longer than the 1-min moving average could be considered valid. Furthermore, we can see the front region with the amplitude of the wave increased, and fewer structures existing and affecting the base wave mostly at the front and the back of the head. The lack-of-surge feature was also apparent in the analysis result.

We then calculated the turbulence flux to see whether all fine-scale structures were turbulence-based. The result is shown in Fig. 12. We can see that most of the turbulence-affected area was around the frontal zone around 1203 UTC, whose intensity was much greater than that around the back of the head around 1210 UTC, although the classical model shows that the back of the head is related to turbulence shattering. Moreover, the turbulence flux had couplets, indicating the existence of a coherent structure. Such structures are related to turbulence vortices that might cause an increasing of the fine-scale vertical velocity by tilting and intensifying the wind speed.

Table 3. Characteristics of the gust front

H (m)	ρ_0 (g m^{-3})	$\Delta\rho$ (g m^{-3})	L (km)	U (m s^{-1})	U_r (m s^{-1})	$U_{r-2\text{km}}$
600	1.1579	0.01815	146	13.54	21.2	7.66

H is the height of the gust front; ρ_0 is the intensity of ambient air; $\Delta\rho$ is the variation of the intensity of the air; L is the characteristic length of the gust front; U is the calculated maximum wind speed when Ro equals 1; and U_r is actual maximum wind speed.

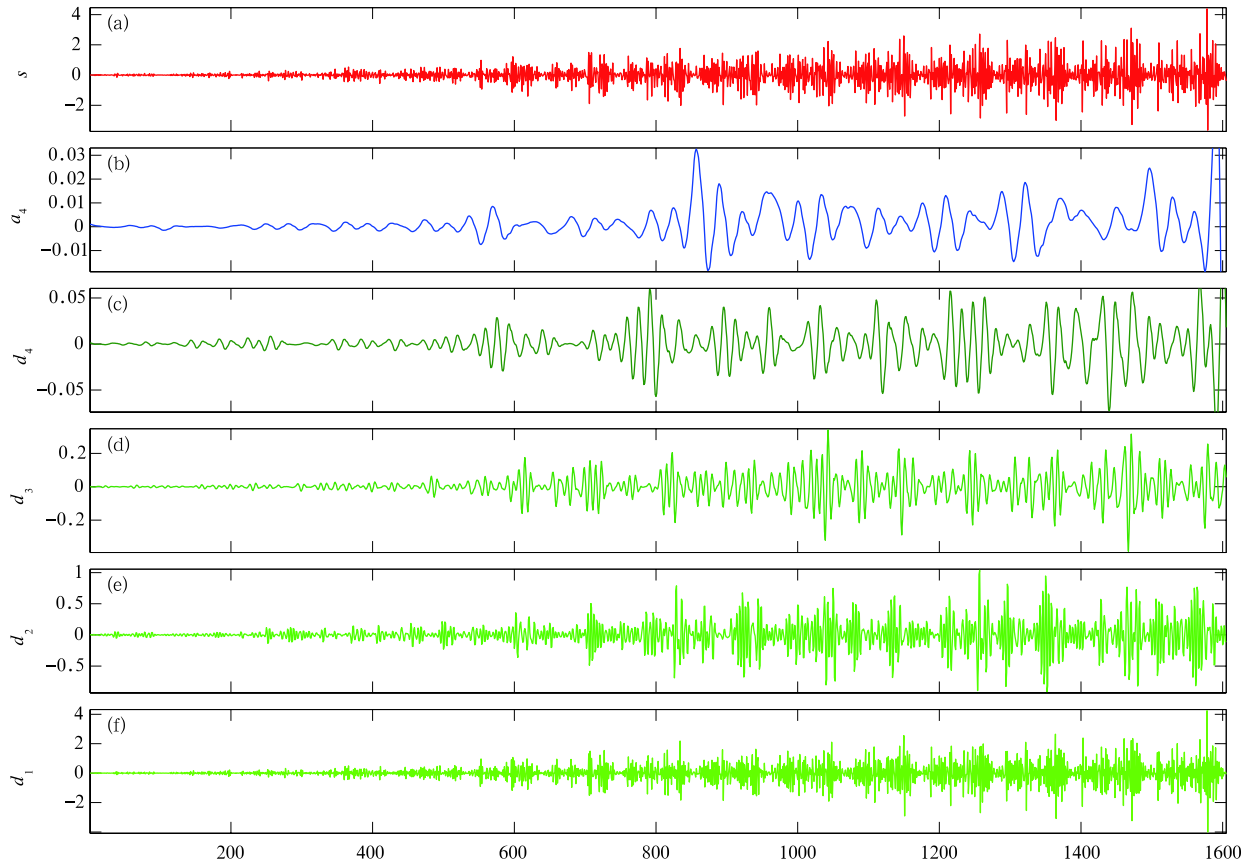


Fig. 11. Wavelet analysis of the case (s). The base wave (a_4) is about the 10-min average, while d_4 , d_3 , d_2 , and d_1 in (c)–(f) are the 5-, 2-, 1-min, and less than 1-min average, respectively.

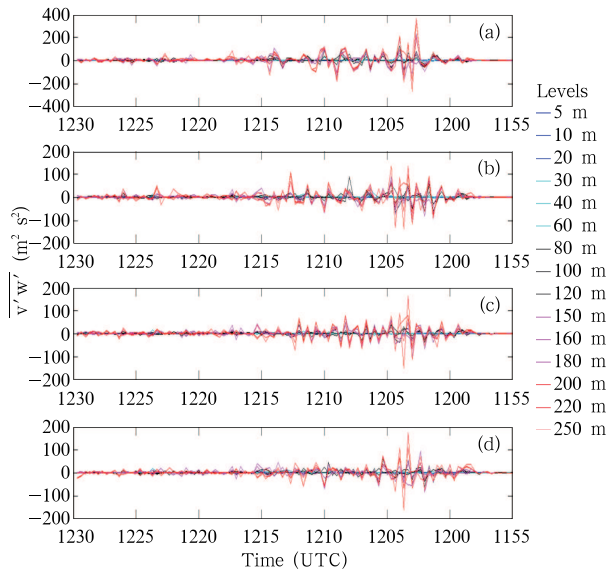


Fig. 12. The turbulence flux ($\overline{v'w'}$) of different time-scales: (a) 1, (b) 2, (c) 5, and (d) 10 min. The numbers on the right indicate the levels at which the tower observations are available.

4.5 The fine-scale instability

The reason why the non-turbulent fine-scale structures distribute more at the frontal zone of the head is due to the fine-scale instability. The fine-scale instability is the instability from the systems on a spatial scale of less than 2 km. The instability was calculated based on moving-average results of the tower observations. As stated in the scale analysis section 4.3, the 5- and 10-min moving averages provided the mesoscale or coarser scale structures, while the 1- and 2-min moving averages provided the structures with horizontal scales of less than 2 km, i.e., fine scale. As the tower is static, the structures of a gust front passing directly over the tower would be free from the gust front propagation effect. Removing the high frequency perturbation components would also remove the acoustic wave.

To calculate the fine-scale instability, the equa-

tions of perturbation are first examined, which are written as

$$\left\{ \begin{array}{l} \left[\frac{\partial}{\partial t} + \bar{u} \frac{\partial}{\partial x} + \bar{v} \frac{\partial}{\partial y} \right] u' = -\frac{1}{\rho} \frac{\partial p'}{\partial x} + f v' \\ \quad - \left[u' \frac{\partial}{\partial x} + v' \frac{\partial}{\partial y} + w' \frac{\partial}{\partial z} \right] \bar{u} \\ \left[\frac{\partial}{\partial t} + \bar{u} \frac{\partial}{\partial x} + \bar{v} \frac{\partial}{\partial y} \right] v' = -\frac{1}{\rho} \frac{\partial p'}{\partial y} - f u' \\ \quad - \left[u' \frac{\partial}{\partial x} + v' \frac{\partial}{\partial y} + w' \frac{\partial}{\partial z} \right] \bar{v} \\ \left[\frac{\partial}{\partial t} + \bar{u} \frac{\partial}{\partial x} + \bar{v} \frac{\partial}{\partial y} \right] w' = -\frac{1}{\rho} \frac{\partial p}{\partial y} + \frac{\partial}{\partial x} g \\ \frac{\partial u'}{\partial x} + \frac{\partial v'}{\partial y} + \frac{\partial w'}{\partial z} = 0 \\ \left[\frac{\partial}{\partial t} + \bar{u} \frac{\partial}{\partial x} + \bar{v} \frac{\partial}{\partial y} \right] \theta' = - \left[u' \frac{\partial}{\partial x} + v' \frac{\partial}{\partial y} + w' \frac{\partial}{\partial z} \right] \bar{\theta} \end{array} \right.$$

where u is tangential to the propagation direction of the gust front, and v is radial. By separating the radial and tangential parts from the equations and calculating the momentum and kinetic perturbation, we can obtain the distribution of perturbation within the head region. As our focus is on the fine-scale instability, we use the 1-min data to perform the calculation and the results are shown in Figs. 13 and 14. Figure 13 shows that the tangential perturbation tends to propagate more in the rear part of the head, stretching backward and out of the head region. Although the

momentum transfix seems to be complex, the kinetic energy transfix only concentrates on a belt from the circulation belt in the head up to a higher backward region. The perturbation tends to propagate to the left of the gust front, with nearly no energy transfix to the right. While the radial perturbation is weaker and mainly within the head, it overlaps with the internal horizontal vorticity maximum regions, which means that the radial perturbation is mainly due to the fine-scale internal circulations, and is the cause of the vertical instability and high-frequency waves within the head region.

5. Discussion

From the observation analysis presented in this paper, we can provide a fine-scale structural model of the studied gust front; in particular, this is a model of the gust front without a surge. Figure 15a is the standard gust front model (based on tower observations at Tianjin on 22 June 2004; Quan, 2013), which shows a similar internal pattern as the case in this paper, with only a more buoyant environment, in which the surge section of the gust front is obvious. The fine-scale circulation at the low levels of the head propagates from the end of the head, both forward to the frontal zone and backward. The forward propagation creates a series of positive radial horizontal vorticities, and the

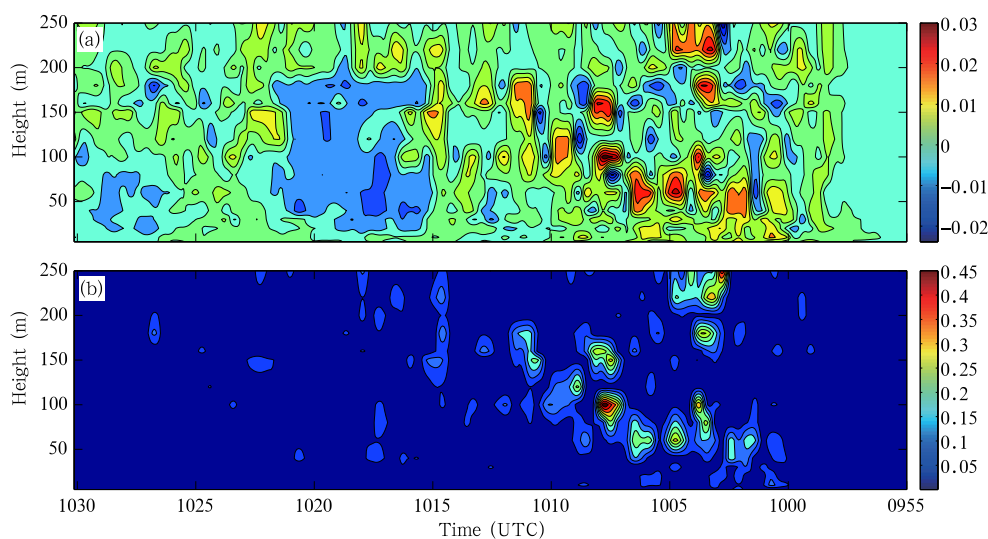


Fig. 13. The tangential perturbation of 1-min average data: (a) momentum and (b) kinetic energy.

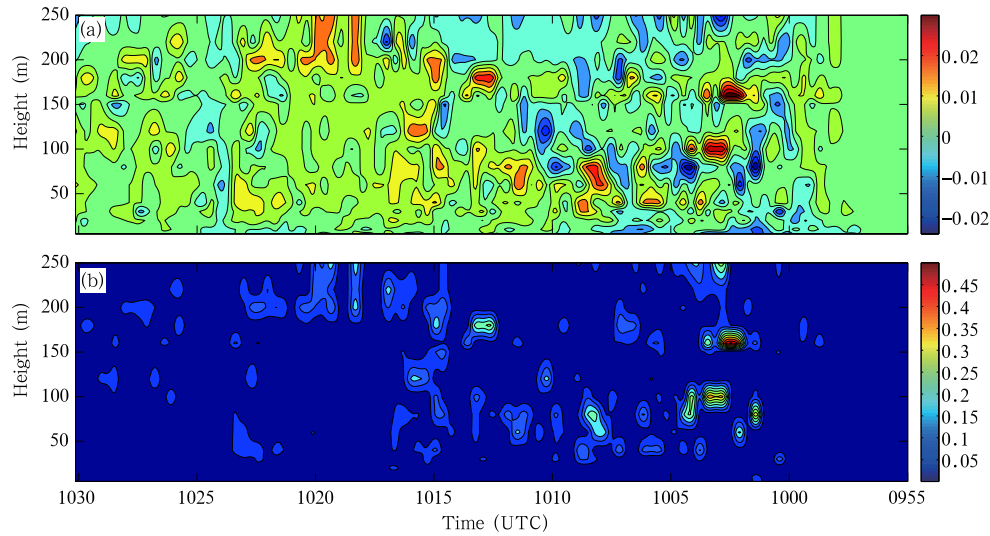


Fig. 14. The radial perturbation of 1-min average data: (a) momentum and (b) kinetic energy.

backward propagation creates a series of negative ones, similar to the circulations generated by the backflow. The frontal zone shows a distinguishable gravity current pattern, while a shallow updraft rising between the kinetic and thermal fronts runs past the thermal front and merges with the main updraft behind the thermal front, and the two updrafts are different in intensity. Because of this, a negative radial horizontal vorticity forms between the two updrafts, where the relative minimum wind speed occurs within the strong wind zone. The surge is caused by the K-H wave's backward propagation and duplicates the pattern of the head, and only the intensity is weaker.

Figure 15b provides the structure when the gust front lacks a surge part, due to environmental low vertical wind shear that prevents the propagation of the K-H wave. As the energy cannot propagate out, it intensifies the downdraft at the rear of the head, which provides a semi-downburst structure (Järvi et al., 2007), thus increasing the wind speed at the rear part and the internal circulation. Furthermore, as the semi-downburst is more affected by the turbulence, the straight-line wind zone is more shattered. On the other hand, as the downdraft intensity increases, the whole circulation at the head is also magnified, meaning that the updraft before the head is also intensified. With the strong mid-level vertical wind shear, a sub-

generated convective cell develops, and the downdraft from the cell also contributes to the downdraft at the rear of the head.

6. Conclusions

In this study, the mesoscale background and meso- and fine-scale internal structures of a gust front were examined. The distribution and intensity of the straight-line wind zones were associated with all of the structures, yet their functions differed. The synoptic-scale and mesoscale surface and sounding observations could barely capture the gust front itself, but succeeded in providing the background that may have determined the possible relevant systems and propagation pattern of the gust front and its mesoscale shape. Environmental parameters, especially Ri , determined the propagation of the K-H wave. As the momentum and energy failed to propagate out, they intensified at the rear of the head section of the gust front and produced stronger horizontal winds than a classical gust front.

By using scale analysis, the fine-scale structures were separated from the mesoscale structures. Some of these structures, as they generated the convective cell, could be identified from radar observations, but more detailed structures were revealed by the tower

observations.

Beside the classical mesoscale structures within a

gust front, which were shown based on the 5-min averaged data, the fine-scale structures were also revealed

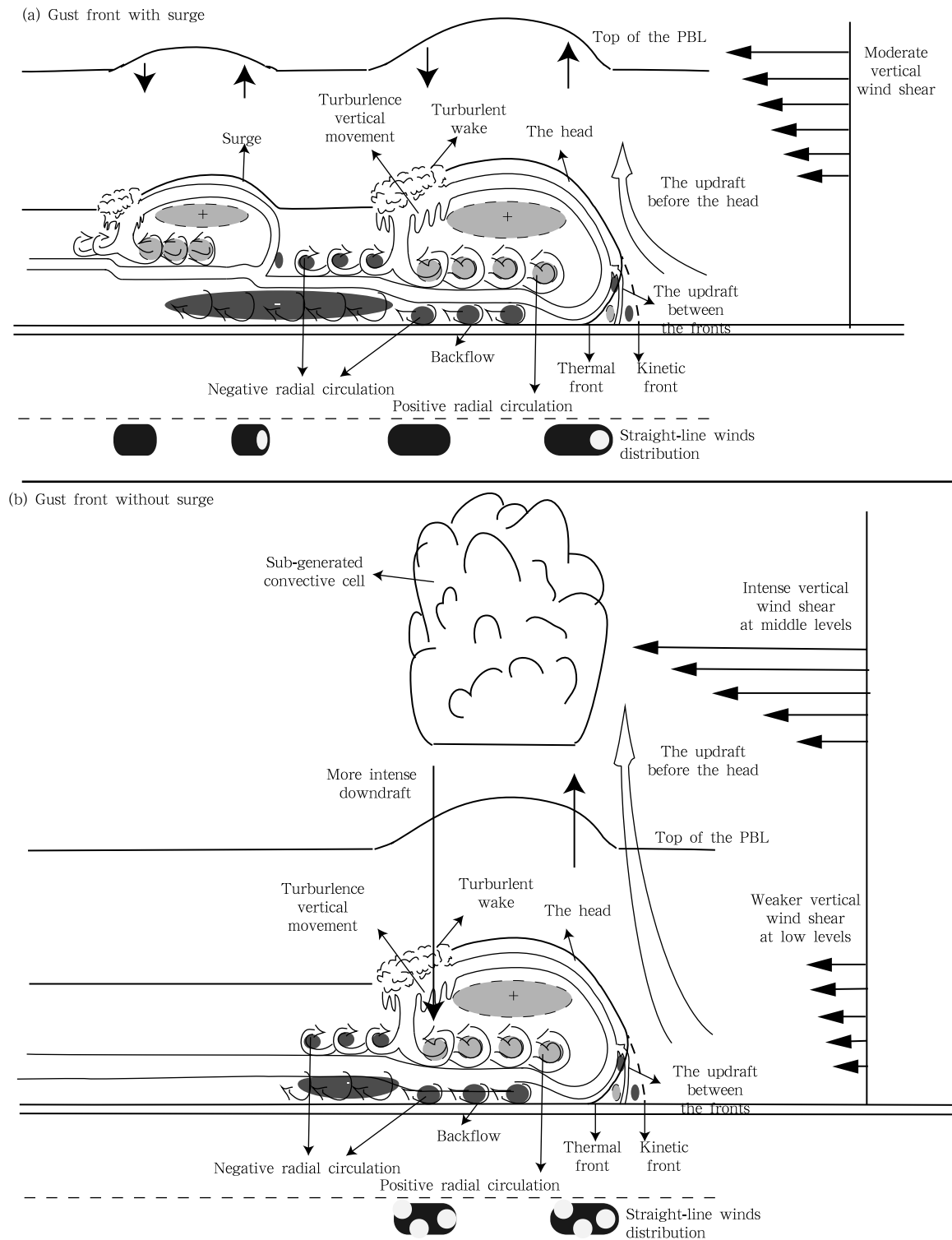


Fig. 15. Fine-scale structural model of a gust front: (a) standard gust front with a surge and (b) gust front without a surge. The straight-line wind zone in (b) is shattered.

from the 1-min averaged observations, and these fine-scale structures were strongly affected by turbulence but were not dominated by random effects. A minor updraft existed between the kinetic and thermal fronts, generating a relatively negative radial circulation with the main updraft after the thermal front due to the low intensity of the minor updraft. The horizontal wind speed reduced at the location of this negative circulation, and thus split the straight-line wind zone into two. As the flow formed, the head downdrafts at the back of the head triggered formed a series of circulations propagating forward and backward. The forward-propagating circulations were positive and the backward circulations were negative; plus, they were similar to the structures generated in a downburst as the flow reached the surface, and some of them were even identified as downbursts. This suggests the general existence of intense horizontal wind shear at the back of the head of the gust front.

With the calculation of fine-scale instability, the tendency of instability propagating tangentially was observed, which was significant with the time scale of 1 min (whose spatial scale, according to the propagation speed, was roughly less than 1 km). The model of Weckwerth and Wakimoto (1992) on the tangential propagation within a gust front concerns the generation of new cells of γ -mesoscale, while the observation of tangential instability in the present study was of a finer scale. Such a phenomenon will be discussed in more detail in a numerical simulation study of the same case in future.

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