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AN ANALYSIS OF THE STRUCTURE OF THUNDERSTORM IN THE ATMOSPHERIC BOUNDARY LAYER

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ABSTRACT

The structure of thunderstorm in the atmospheric boundary layer in Beijing area is analysed by using three-year data of tower. It is indicated that the outflow current of the thunderstorm in the lower layer is a sort of density current. An area of evident wind direction shear is found at about half an hour to one hour before the arrival of the gust front.The maximum intensity of the shear can reach 0.35sec^{-1}.The inner structure within the density current is also very complicated. At the nocturnal stable boundary layer in summertime, the development of the convective motions is often triggered due to the instability of the Kelvin-Helmholtz wave.

I. INTRODUCTION

The structure of the thunderstorms in the atmospheric boundary layer plays an important role in the development of the cloud and the exchange of the flux of momentum and heat. Recently, a great amount of information on the structure of thundercloud in the boundary layer has been obtained from temporal-spatial continuous data of the meteorological tower or TV tower, acoustic radar and dense ground observation stations[1-3].The experimental result indicates that the outflow current is density current[4].There is a dynamic similarity criterion between the outflow current and density current. It can be expressed by a similarity parameter Froude number. In fact, the structure of the thunderstorms in the boundary layer is rather complicated[5-6]. Therefore, it is very important to find observational facts further . The continuous data of fifteen cases for thunderstorm from 1980 through 1982 were collected by the 325 m tower in Beijing.

II MEASURING INSTRUMENTATION AND DATA

There are 15 levels on the tower, each level of which is equipped with instruments for measuring wind speed,wind direction, temperature difference, etc[7]. The humidity sensors are mounted on elevations of 8,15,47,80,140,240,320 m and the Gill vertical anemometers on 15,47,140,240,320 m.

Most of the thunderstorms with heavy rain took place between mid July and mid August (Table 1) . Each thunderstorm was accompanied with 3—4 showers, with an interval of several to ten-odd minutes. About 80% of the thunderstorms appeared in the afternoon or late at night.

It is evident that the characteristics of the thunderstorms depend on their inner structure The effect of the terrain is very important as well. Next, we will analyse some aspects of the structure of the thunderstorms in the boundary layer.

Table 1. The Thunderstorm Activities in the Rain Season from 1980 through 1982

Year	Month	Day	Hr.	Min.	Day	Hr.	Min.	Rainfall Amount (mm)	Max Wind Speed (m/s)	the Height of the Maximum Wind speed (m)
1980	7	10	16	45	10	13	30	3.0	18.3	240
	7	20	19	00	20	19	30	1.1	23.8	160
	7	21	16	30	21	17	45	/	10.4	120
	8	10	19	00	10	21	16	0.5	8.0	120
	8	15	15	00	15	16	15	30.2	20.0	140
	8	16	17	25	16	17	51	0.9	12.0	320
1981	7	27	14	05	27	15	20	1.2	12.6	140
	8	2	19	50	2	21	40	98.3	15.5	180
	8	12	23	00	12	24	30	17.3	20.0	320
	9	18	18	00	18	20	00	31.8	18.6	180
1982	8	3	15	50	3	20	20	19.7	14.9	320
	8	4	5	05	4	8	20	9.6	7.0	320
	8	4	14	20	4	17	45	/	14.8	180
	8	5	20	56	5	22	00	37.0	12.0	240
	8	16	5	00	16	8	40	8.5	30.2	320

III. THE STRUCTURE OF THE THUNDERSTORM IN THE BOUNDARY LAYER

1. *The Multiple Gust Surges of the Outflow Current in the Thunderstorms*

The outflow current appears when the cold downdraft reaches the ground. It gets much larger horizontal momentum in mid-level environmental air. Finally, a strong vertical wind shear and a gust front are formed in the lower level with a very strong barocline. In addition, the gust surges of the density current are associated with the pulses of the precipitation.

Fig.1(a) shows a case of the thunderstorm in the afternoon on 15 Aug. 1980. It shows the structures of the temperature and gust surges. Four gust surges appear in this outflow current of the lower lever. The first gust surge starts from 15:10, the second from 15:39, the third from 16:08, the fourth from 16:50. The strength of the last two are greatly diminished. There is a

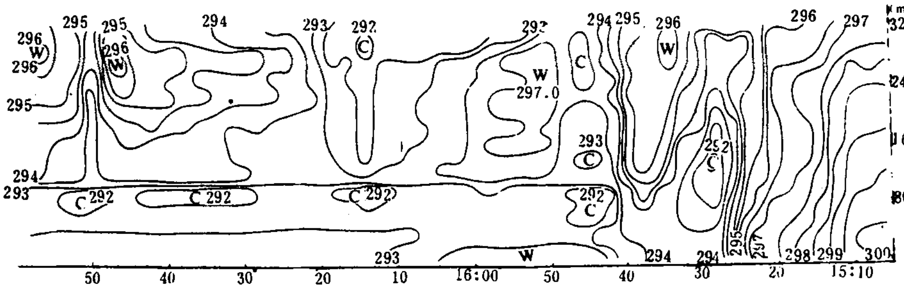

Fig. 1(a). Time-height distribution of the temperature.

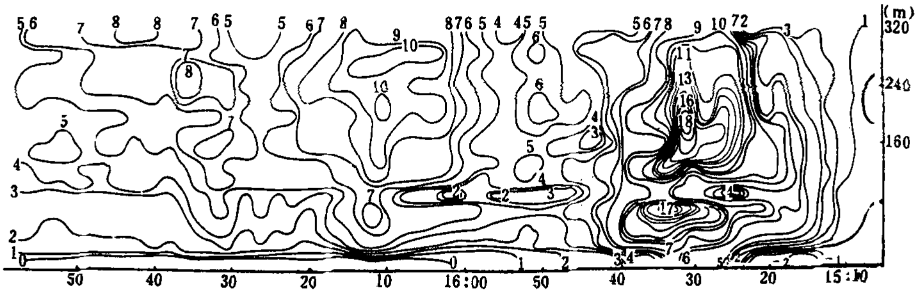

Fig. 1(b). Time-height distribution of the wind speed component *u* on 15 August 1980.

relatively warm district between two surges. The temperature in the warm center is 5°C higher than that in the cold center of the density flow. Such a strong horizontal temperature difference appears and leads to both an intensive convection and an exchange of the vertical and horizontal momenta. Following the gust front, the wind speed rapidly increases within the tower level. The wind speed increases suddenly from 2 m/s to 20 m/s at 140 m in about twenty min. The isotaches are distributed vertically, their ribbon area almost appearing simultaneously with that of the isotherm ribbon. Fig. 1(b) shows the distribution of wind speed component *u* (let *x* be the moving direction of the thunderstorm). We can see that there are four strong centers of wind speed. They occur about 2 min.,later than the appearance of the cold center in the temperature surge.

It should be pointed out that the lower boundary in the strong wind district is the wind direction shear area where the altitude is about 60—80 m. This is the back-flow at the bottom of the density current. The gust surge in the density current causes a complex flow field and a number of changes for the meteorological elements near the surface. It causes a great change for the vertical transfer of the flux of momentum and heat in the lower layer. Calculating results show that the momentum flux in the density current is 2—3 orders of magnitude greater than that in front of the surge. The change of the heat flux in the density current is 1—2 orders of magnitude larger than that before the arrival of the surge. In other words, the transfer of the momentum in the outflow current of the density current is more important.

2. *The Lower Layer Shear in Front of the Gust Front*

It is worth paying great attention to the face that there is a wind direction shear at the mid-lower level of the tower. A north wind appears and forms an area of the evident wind direction shear in conjunction with the south wind ahead of the gust front about 30—50 min. It extends along the moving direction of the thunderstorm. The horizontal distance of the shear area calculated by the time-to-space conversion is about 6—7 km wide. The maximum and minimum widths are 12 km and 3—4km, respectively. The difference of the wind directions at two sides of the shear is in most cases often larger than 90°, sometimes even more than 150°. The maximum intensity of the shear may reach 0.35 $\sec^{-1}$. Fig.2 shows the distribution of the wind direction within the tower before the arrival of the thunderstorm on 4 Aug. 1982. The gust front reaches the local station at about 14:58. From12:50 on, two shears appear at 20 m and 150 m within the tower height. The strong center of the wind speed appears at 15:07.

The maximum strenght of the shear may reach 0.17 $\sec^{-1}$. The wave takes place in the shear while the gust front is coming. The horizontal distance of the shear area is about 11 km wide by the time-to-space conversion. Because the extensional orientation of the shear is in good

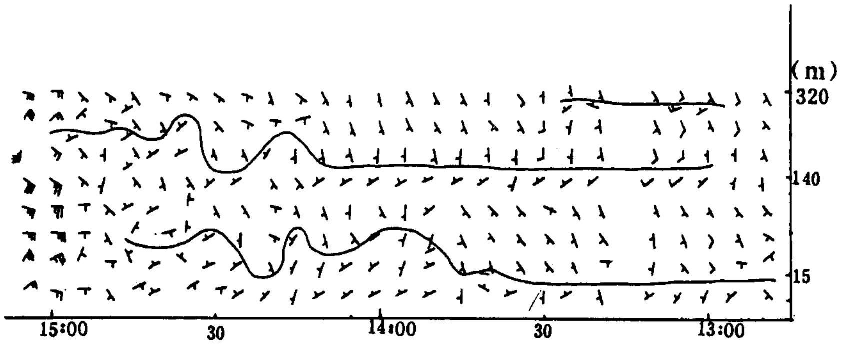

Fig. 2. Time-height distribution of the wind speed during 14:50—15:05 on 4 Aug. 1982.

agreement with the thunderstorm movement , it is possible to provide information for the thunderstorm forecasting about ten minutes to an hour before its arrival.

3. *The Characteristics of the Vertical Speed in the Outflow Current*

Observations show that the distribution of the vertical speed in the outflow current from the thunderstorm is very complicated. By means of the two-dimensional, noncompressive continuity equation, the distribution of the vertical velocity field in the outflow current was calculated by Charba et al. In fact, the result they calculated is rather different from the observations, because only the mean field distribution is reflected. Fig. 3 is the temporal-spatial distribution of the vertical velocity on 15 Aug. 1980.

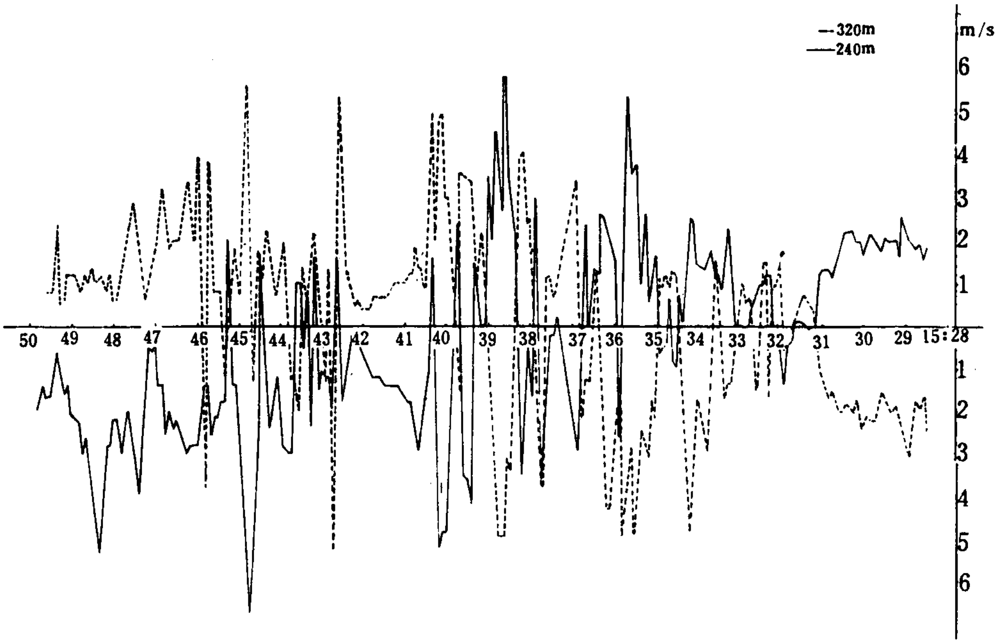

Fig.3. Time-height distribution of the vertical velocity on 15 Aug. 1980.

(1) The distribution of the vertical speed in the strong convection is essentially different from that in the cold front. The vertical speeds appear to be alternately positive and negative. Their amplitudes are very small before the density current arrives, but increase rapidly at its arrival, and to a high value at the middle and rear of the density current,with the maxima varying from $+5.5$ to -5.5 m/s within 15 sec at the 320 m height. Therefore, it is not just as simple as Charba's result, in which updraft appears in the front of the thunderstorm and downdraft in the middle and the rear.

(2) The fluctuation of the vertical speed appears in a certain period, especially at the level of 320 m and 240 m . It has a 2—3 min. period before the arrival of the density current , and the period changes to 4—5 min. after its arrival.

(3) The absolute value of the vertical velocity runs up as the altitude increases[5,8]. Its maximum updraft occurs in the middle of the density current, reaching 5.9 m/s or so. The maximum downdraft occurred in the rear of the density current is about 6.7m/s.

(4) Within the density current, phases of the vertical speeds at various levels often differ from each other. Particularly, the vertical speeds at 320 m and 240 m level appear in opposite phase clearly, thus, convergent and divergent districts are formed in the *x*-*z* plane. This phenomenon is caused by the complexity of the microstructure of the inner flow field in the outflow current.

4. *The Instability of the Kelvin-Helmholtz Wave in the Nocturnal Stable Stratification*

In the fifteen cases of the thunderstorm as mentioned above, some of them occur late at night or at dawn. The temperature stratification within the tower height is almost always stable. Measurements made with the sensors mounted on the tower indicate that the structure of the nocturnal lower atmosphere is very complicated. The formation of inversion is associated with certain atmospheric conditions and/or local topographical features. At night, the drainage winds in the vicinity of mountain ranges flow into the plain. A relatively strong zone of the wind speed appears at 100—200 m. It is the so-called mountain breeze jet, in which the distribution of wind speed has an irregularity

With some centers of about 4—5 m/s. Fig.4 shows a thunderstorm process with precipitation on 4 Aug. 1982. It is shown that a multilayer inversion exists within the tower height, and an east wind at upper levels forms an area of evident wind direction shear in conjunction with the north wind at the lower levels. The wind speeds at the upper and lower

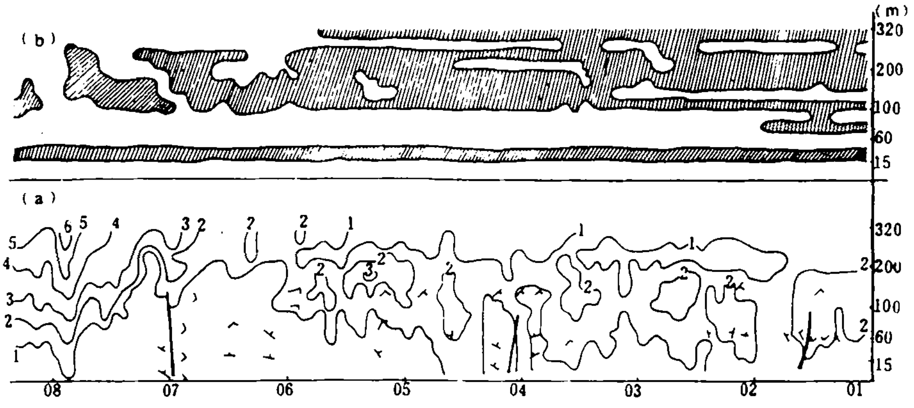

Fig. 4 Time-height distribution of the wind speed (a) and temperature (b) at 23:00—4:08 on 3 August 1980. The shaded areas represent inversion.

levels are only about 1—2 m/s. The jet is at about 140 m. The analysis of the wind direction indicates that there exists a wave with a period about dozens of minutes in the tower levels. After 01:00 on 4 Aug., the Ri number decreases to 0.16 in the middle-lower levels of the tower. At 07:00, the amplitude becomes bigger, followed by a strong convective motion and heavy rain. This phenomenon is known as Kelvin-Helmholtz instability. It is worth pointing out that the disturbance of the wind field in the stable condition in the lower levels plays an important role in the development of the thunderstorm.

5. *The Analysis of the Spectrum for the Thunderstorms*

The energy spectra of the horizontal and vertical wind speed are analysed. The results of the analysis indicate that the peak of the horizontal wind speed has a period of one hour and a half, next one at 8—10 min., the another one at 2—3 min. Among these, the peak with 8—10 min. period is the main energy area. The peak of the spectrum of the vertical velocity is shown with a period of about 8—10 min. and 2—3 min., respectively. Fig.5 shows the analysis of the spectrum for a case of thunderstorms on 16 Aug. 1982. The solid line is the distributional curve of the spectrum as a function of the frequency *N*. Because the curves at different levels are basically similar to each other, the orders of magnitude are mutually close. Therefore, the curve at 180 m is only shown here.

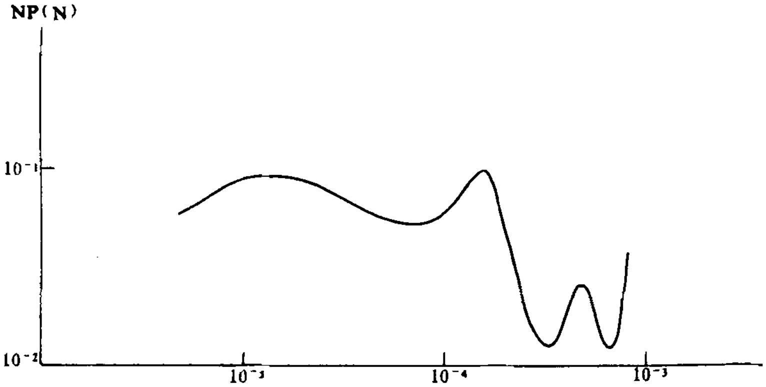

Fig. 5. The analysis of the spectrum for the wind speed.

IV. CONCLUSIONS

The structure of thunderstorm in the atmospheric boundary layer has been analysed by using three-year data of tower. It indicates that the outflow current of the thunderstorm in the lower layer is a sort of density current with multiple gust surges accompanied with precipitation. A north wind appears and forms an area of evident wind direction shear in conjunction with the south wind ahead of the gust front. The maximum intensity of the shear can reach 0.35 $\sec^{-1}$. The gust surge in the density current causes a complex flow field and a number of changes for the meteorological elements near the surface. It causes great changes for the vertical transfer of momentum and heat in the lower layer as well. Calculating results show that the momentum flux in the density current is 2—3 orders of magnitude greater than that in front of the surge. The change of the turbulent heat flux in the density current is 1—2 orders of magnitude larger than that before the arrival of the surge. Therefore, the transfer of the momentum in the outflow current of the density current is much more important. It has been observed that the phases of the vertical speed at various levels of the tower are different. There is convergence within some levels and divergence within some others. Thus, there are several vortexes within the density current, and their horizontal and vertical scales are estimated to be several kilometers and 100 m respectively. The distribution of the vertical speed displays the alternate updraft and downdraft, with a period of 2—3 min. At the nocturnal stable boundary layer in summertime, the development of the convective motion is often triggered due to the instability of the Kelvin-Helmholtz wave. The energy spectrum of the horizontal wind speed indicates that the peak of the energy spectrum is at 8—10 min., next one is at 2—3 min.

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