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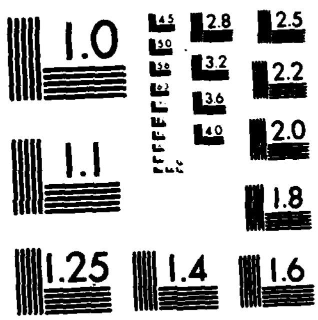
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by

Zhu Chiquan, Ye Zhuojia, et al

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STRUCTURAL ANALYSIS OF AIR OUTFLOW FROM LOW LAYERS OF INTENSE THUNDERCLOUD

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Submitted 30 April 1981

This paper utilizes data obtained from a 325-meter meteorolgoical tower and data from a rain measurement radar as well as conventional meteorological data in analyzing characteristics of low layer density flow of a thundercloud with the passage of a secondary cold front in summer in Beijing. With passage of the thundercloud, several turbulences appeared in the density flow; during turbulence, the momentum and heat transports were greater by two to three magnitudes than during the time without turbulence. One half hour before the violent variation of the meteorological element field and the arrival of the vertical tangential shift of high wind speed of the squall line, within the altitude range (about 100 meters vertically and several kilometers horizontally) of the meteorological tower, there was a vertical trangential shift of northerly and southerly with the maximum tangential shift intensity of the vertical direction at 0.25 second^{-1}. It was discovered upon analysis of the x-z two-dimensional flow field that there are several vrotex zones in the density flow in a range of 100 meters vertically and several kilometers horizontally. The period of the peak energy zone was about eight minutes.

I. Observation Equipment

There were 15 layers of altitude at the meteorological tower (Fig. 1) installed with instruments; in each layer, instruments for wind direction, wind speed, and temperature difference, were installed [1]. Besides, at altitudes of 15, 140, 240 and 320 meters, Gill [2] vertical anemometers were installed; at the altitude of 47 meters, a Gill three-component (u, v, and w) anemometer set was installed. At altitudes of seven layers of 8, 15, 47, 80, 140, 240 and 320 meters, hygrometers (for measuring relative humidity) were installed. At the altitude of 140 meters, a micro-thermometer set was installed. This paper makes a detailed analysis of the micro-structure of the boundary layer for passage of the intense thundercloud on 15 August 1980.

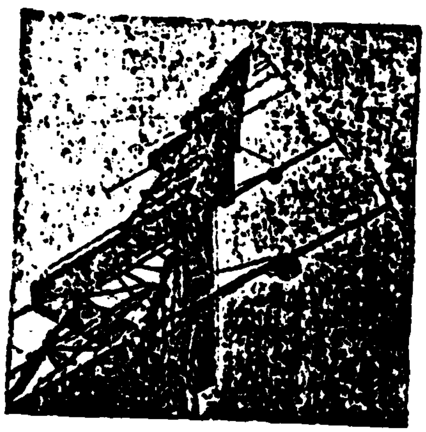


Fig. 1. 325-meter meteorological tower at Beijing.

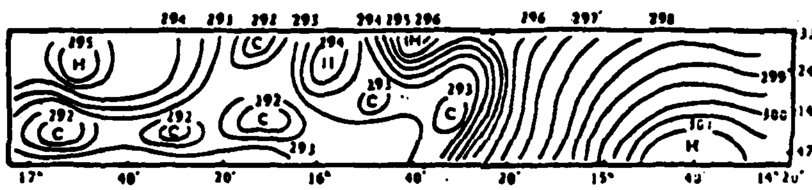
II. Characteristics of Air Outflow From Low Layers of Thundercloud

When the cold descending air flow of the thundercloud reaches low altitude and the ground surface, becoming an air outflow, this air outflow has a greater horizontal momentum than the environmental air in the middle and lower portions of the convection layer. As a result, an intense vertical tangential shift of wind and a squall line form in the low layers with very intense baroclinic characteristics. In the following, discussions are mainly conducted on characteristics of various meteorological elements of the air outflow. Analysis was conducted by utilizing continuous observation data from 14.00 to 17.00 hours on 15 August 1980 at a 325-meter meteorological tower at Beijing.

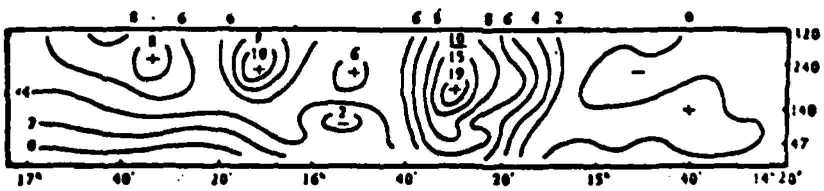
1. Structure of temperature field: Figure 2a shows the temperature data of each altitude for each two-minute interval. In the lower layer of this thunder shower activity, there were two turbulences in air flow from the low layers. The first turbulence began from 15.10 hours, and the second turbulence began from 15.36 hours. The later turbulence was weaker than the first one. There was a zone of relative warmth between these two turbulences; the warm center was 5°C higher than the temperature at the cold center of the density flow, remaining for about five to six minutes. Thus, a considerable difference of horizontal temperatures will cause intense convection activities and exchange between horizontal and vertical momentum. After high precipitation, a clear temperature inversion structure will occur within the tower layers; the highest temperature inversion was 2°C/100 meters.

2. Structure of horizontal wind field: For clarity in analysis, here the observed wind was divided into u and v components, assuming that x is the direction of the system motion, and u and v are components of wind speed at the x and y directions, respectively. As pointed out in the distribution diagram of component u of wind speed, the squall line arrives at this station by 15.10 hours. Before then, beginning from 14.20 hours a norther appeared in the middle and lower layers of the meteorological tower between 15 to 140 meters altitude and above 240 meters. This northerly and the southerly in front of the squall line formed an obvious tangential shift zone of wind direction. The lower layer tangential shift zone was at 15-meter elevation and the upper layer tangential shift line was at elevation between 150 and 240 meters with the maximum tangential shift intensity possibly at 0.25 second^{-1}. The occurrence of this tangential shift zone was about 50 minutes before arrival of the squall line, extending along the extension direction of thunderstorm. In time-space conversion, it had a width of about 6 kilometers for the horizontal distance of the tangential shift zone.

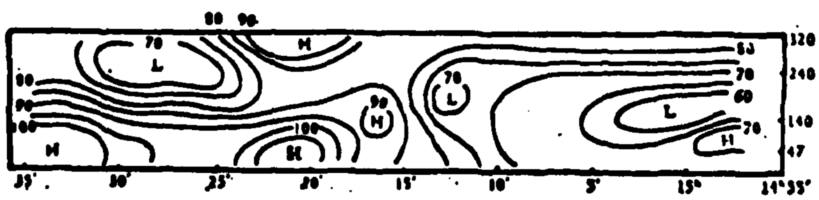
Upon the arrival of the squall line, the wind speed in the tower increases rapidly. For a duration of more than 10 minutes from 15.11 to 15.28 hours, at an altitude of 140 meters the wind speed suddenly increased from 2 meters per second to over 19 meters per second; the wind-speed isopleths were distributed vertically and the concentrated area of isopleths almost simultaneously appeared with the concentrated area of temperature isopleths. Behind the concentrated area there appeared the intense center of the wind speed (19 meters per second), situated at an altitude of 140 meters. Thus, a vertical tangential shift of high wind speed was formed; the intensity of vertical shift is 0.1 second^{-1}, occurring by 15.30 hours, which was followed two minutes later by the occurrence of the cold center of the temperature. Because of friction at the ground surface, near the ground the wind speed isopleths were apparently lagging near the ground; for the middle layer, the isopleths formed a frontal protrusion while a circulating current zone was formed below the "nose."



a. Time-altitude distribution diagram of temperature.



b. Time-altitude distribution diagram of component u of wind speed parallel to the front surface.



c. Time-altitude distribution diagram of relative humidity.

Fig. 2. Time-space distribution diagram of various meteorological element fields in tower layers on 15 August 1980.

A fact worth pointing out is that the lower boundary of the intense wind zone is the wind direction tangential shift zone with altitude in the vicinity of 60 to 80 meters. This is the circulating air flow at the bottom of the density current; the abrupt change of this element field has a special function for low-layer momentum and transport of heat.

3. Several main characteristics of the structure of the vertical speed: (1) the vertical speed appeared in the form of alternate positive and negative values. Before arrival of the density flow, its vibration amplitude is very small. After arrival of the density flow, the vibration amplitude of the vertical speed rapidly increases; at the maximum the speed may change from +5.5 to -5.5 meters per second. (2) The vibration of the vertical speed has a certain periodicity; before the arrival of the density flow, there is the period of two to three minutes. After arrival of the density flow, a period of four to five minutes is relatively clear. (3) The value of the vertical speed increases with altitude; at an altitude of 320 meters, the maximum ascending speed (at 5.9 meters per second) is at the middle portion of the density flow. After the occurrence of the maximum descending velocity, it is 6.7 meters per second at the rear portion. (4) In the density flow, often the phases of vertical velocity at different altitudes are not consistent. This phenomenon is due to the complexity of the microstructure of the internal flow field of the outflowing current.

4. Structure of temperature field: Before arrival of the squall line, there is a layer of piled-up damp air near the altitude of 47 meters. After arrival of the squall line, there is a zone of relative high humidity center at the low layers. Accumulation of warm, damp air in the lower portion of the density flow "nose" causes a submerged dampness. The dynamic forces in the vicinity of instability and the tangential shift zone are not stable; thus, the front fringe of the density flow becomes a zone of unstable altitude. We calculated variations of θ and θ_{sc} with altitude from the high humidity zone at the bottom of the tower layer to the low humidity zone at the middle tower layer in this period; in this zone a considerable amount of submerged dampness exists with unstable energy.

III. Analyses and Discussions

(1) During observations of vertical velocity, it was discovered that at different altitudes of the tower layers, the phases were not consistent. Therefore, this phenomenon caused the appearance of convergence at certain layers, and divergence at certain other layers. We integrated the vertical velocity w and component u of the horizontal wind velocity to obtain the two-dimensional flow field distribution for the moving direction of the thunderstorm in the entire tower layer. It was vividly shown that some vortex activities occurred in the density flow. On estimating with time-space conversion, the horizontal scale of these vortexes was about 5-6 kilometers. However, the vertical scale was relatively oblate, about the magnitude of hundreds of meters. Therefore, the flow field distribution of the density flow was very inhomogeneous, and the form of energy transport was also very complex.

(2) The complex flow field created by the turbulence of the density flow caused considerable variation of meteorological elements in the near-ground layer; this similarly would bring considerable variation of transport of momentum and heat to the low layer. We estimated th momentum and heat fluxes; as revealed by calculation results, the momentum flux during density flow was greater by two to three magnitudes than that before the density flow. In the density flow, the variation of eddy heat flux was greater by one to two magnitudes than that before the arrival of the density flow. In other words, this is to say that the momentum transport is the most important element in the outgoing current of the density flow.

(3) In the front part of the outgoing current of cold air flow, the ascending current was the main one; the descending air flow appeared in the rear portion of the intensive wind center; however, the zone of high wind speed was in the middle portion of the tower layer. Therefore, the frontal portion of the outgoing current of the thunderstorm has a positive direction circulation (counterclockwise); the dynamic regime of this positive direction development of circulation can be simplified into:

$$\frac{d}{dt}\oint_l V\cdot dl = -\oint_l \frac{1}{\rho_c}\nabla P_c\cdot dl = -\oint_l R\frac{\bar{T}}{P_c}dP_c$$
$$= -R\oint_l T\,d\log P - R\oint_l \frac{T}{P}\,df E(T), \qquad (1)$$

In the equation, V is the vector of wind speed; ρ_c is density of damp air; P_c is pressure of damp air; R is gas constant; T and P are air temperature and gas pressure of certain altitude; c is vapor pressure; f is relative humidity; and E(T) is the saturated vapor pressure. It is apparent that the circulation acceleration of the micro-airmass along the circulating route ℓ is determined by the number of force tubes of interaction between isothermal and isobaric lines of dry air enveloped by ℓ, and the number of force tubes of interaction between isothermal and vapor pressure lines. By taking a circulation route, AB is the frontal edge of the squall line ($15^h16'$); DC is the isothermal line ($15^h26'$) of the previous isothermal line of the cold center; BC and AD are, respectively, 8 meters (altitude of the first layer) and 200 meters (altitude of the twelfth layer); and ABCDA closed circulation is shown in Fig. 3. If integration is done for the micro-airmass, then Eq. (1) can be written in the following form:

$$\frac{d}{dt}\oint_{ABCDA} V\cdot dl = R\oint_{ABCDA} T\,d\log P + R\oint_{ABCDA}\frac{T}{P}\,df E(T)$$
$$= R\Delta T\left(\log\frac{P+\Delta P}{P} + \frac{E\Delta f}{\bar{P}}\right), \qquad (2)$$

In the equation, $\bar{P}$ represents the average value of P in air column ABCD along direction E. Since the isothermal lines in the zone of the squall line are close to vertical distribution, between the isothermal and isobaric lines on one hand, and the relative humidity lines on the other, there is almost vertical intersection with intense baroclinic characteristics, and a very high value of circulation acceleration. We know from Eq. (2) that the circulation variation is the result of mutual action of the number of force tubes formed by air, and force tubes formed by water vapor. However, on the diagram the circulation current is positive (counterclockwise) as obtrained from the mutual

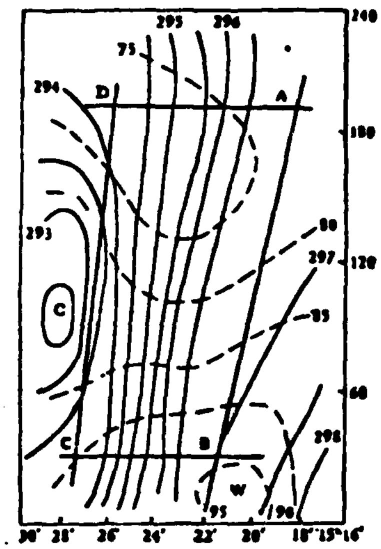


Fig. 3. Closed circulation diagram
in the frontal part of squall line.

positions of the adopted baric gradient, humidity gradient and temperature gradient. Therefore, the function of the force tube is to let the warm air ascend along the frontal edge of the squall line and let the cold air descend. In this procedure, potential energy is released and converted into kinetic energy, while water vapor in the low layer contributes to and speeds up this activity. If in this process, cold air is supplied constantly, then the baroclinic characteristics will be continuously maintained and the circulation flow is accelerated. Otherwise, the baroclinic characteristics will be weakened. Therefore, the consistent and constant supply of cold air is the main reason for maintaining and intensifying the squall line. Sufficient water vapor in the low layer is advantageous to intensifying this process.

(4) As pointed out from analysis of the velocity frequency spectrum, the period of the peak value zone of main energy is in the vicinity of eight minutes; the period of the secondary energy peak zone is two minutes.

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