TRAJECTORY ANALYSES OF THE DUSTSTORMS OVER EAST ASIA*

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ABSTRACT

The transports of dust are calculated using 3-dimensional (3-D) trajectory method for three cases of duststorms in the terrain-following coordinate system, and the synoptic processes are also discussed for each case. The case of 17—20 April 1980, a severe duststorm was associated with the rapid development of a cyclone over the Mongolia Plateau. The dust moved from west to east across several deserts, formed a typical dust path in spring. The other two were weaker and the dust was triggered by the strong wind behind the cold front from northwest or north. Because the vertical velocity is considered in 3-D trajectory analysis, trajectories calculated should better reveal the transport rule of the dust particles and the results seem to be more consistent with the synoptic processes. The trajectory analysis on the 2-D isobaric surfaces is simpler but can be used only in the conditions with weak vertical wind shear and weak vertical velocity. The difference of trajectories at lower levels between two methods may be caused by the different treatment of orography.

Key words: trajectory analysis, duststorm, 3-D trajectory method

I. INTRODUCTION

During April and May, the frequency of duststorms in Northwest and North China is rather high. The airborne dust can be transported to the areas far from the origin and widespread over northern China as well as Korean Peninsula and Japan, even reach the islands in mid-Pacific Ocean. The impacts of duststorms on the environment and human society can not be ignored. To study the mechanism, the chemical composition and the long-range transport of blowing dust has become a concerned subject in atmospheric environmental research. Some scientists analyzed the paths of duststorms using synoptic charts, satellite images and deduced the origins of duststorms with the particle size distribution and the chemical composition. Synoptic and climatological study using historical and meteorological data (Zhang 1984) shows that the duststorms are originated over the desert areas as Gansu, Inner Mongolia, Ningxia and Taklimakan Desert. The origins of dust were also studied by using 2-D trajectory method but in some cases the vertical velocity may be important.

In this paper, two kinds of 3-D trajectory methods are used to study the origins and the pathways of duststorms, i.e., the trajectory in the terrain-following coordinate system (ρ-coordinate, ρTA) and 3-D kinetic trajectory analysis (KTA). Three duststorm cases, which broke during 17—20 April 1980, 25—26 April 1990 and on 30 April 1991, are analyzed. Results are compared with trajectory obtained from the isobaric surface analysis (PTA) where the

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vertical velocity is ignored.

II. THE METHODS OF CALCULATION

The particle size distribution of airborne dust is broad. The large particles deposite on the surface quite soon, which means those particles would fall nearby the original area and only the smaller particles can be transported to distant places. You et al. (1991) analyzed the observational data of a duststorm occurring in the Alxa Desert and the neighboring area during April 1988. The results show that the maximum dust content was between 2.5 and 3.0 km above the sea level (1.4—1.9 km over the surface); the peak concentration of airborne dust was found in the range of 2—30 μm (particle size), about 65% of the total mass concentration; about 30% particles were less than 10 μm. Due to the gravity sorting, about 25% of dust deposited within the downwind area from the origin to 250 km and 50% to 1000 km. About 20% of airborne dust can be transported to the area more than 1000 km. The coarse airborne dust deposited in downwind area could be the source of the large soil particles of the Loess Plateau. The particle size distribution of eolian dust collected in Beijing area on 25 April 1990 shows that the geometric mean diameter of the eolian dust was about 10 μm (Qin et al. 1990). Obviously, many coarse particles in samples were blown up locally, but his result indicates that at least 50% of particle was less than 10 μm, larger than that in the origin (You et al. 1991). From the Stokes' formula, the terminate fall velocity of a particle with 10 μm diameter and 1 g / cm^3 density is 10^{-1} cm / s, which means that the movement of particles related to the air can be ignored. Besides, the dust is a kind of inert particle in the chemistry, so the trajectory of the air particle can be considered as the path of the smaller particle of the dust.

There are several methods of air particle trajectory analysis, e.g. trajectory on isobaric (PTA), on isentropic surface (STA) and in 3–D multi–levels atmosphere. PTA is 2–D, thus the error would be great if the vertical velocity, associated with front and orography forcing is predominant. The physical meaning of STA is clear and it can exactly simulate the path of air mass over no–rainfall area in the free atmosphere, where the diabatic heating is negligible. Merrill (1989) and Iwasaka et al. (1983) used STA to study the transport of Asian dust storms to the Pacific Ocean. But this method would cause great errors as the diabatic processes are important. For these reasons, the 3–D trajectory analysis in the ρ–coordinate system is chosen in this paper. Besides, the KTA and PTA are also given for comparison.

The definition of the vertical ordinate in the ρ–system is

$$\rho(x, y) = \frac{Z(x, y) - h(x, y)}{Z_T - h(x, y)}, \tag{1}$$

where $h(x, y)$ is the elevation of the surface above the sea level, i.e. the bottom boundary. Z_T the altitude of 100 hPa, the top boundary. Values of $\rho(x, y)$ can vary from 0 to 1. The wind fields are analyzed by using Cressman' s method (1959) and the interpolation is used to obtain that on the ρ–surface.

If $\Delta H = Z_T - h(x, y)$, from the continuity equation we have

$$\frac{\partial(\Delta H \cdot u)}{\partial x} + \frac{\partial(\Delta H \cdot v)}{\partial y} + \frac{\partial W}{\partial \rho} = 0, \tag{2}$$

the equivalent vertical velocity $W(= \mathrm{d}\rho / \mathrm{d}t)$ can be calculated, the following formula is used to transform W into w (vertical velocity)

$$W = w - \left[\frac{\partial h}{\partial x} + \rho\frac{\partial(\Delta H)}{\partial x}\right]u - \left[\frac{\partial h}{\partial y} + \rho\frac{\partial(\Delta H)}{\partial y}\right]v. \quad (3)$$

The error of W at high level may be large due to the error of the wind field, so vertical correction of divergence is necessary under the assumption $W=0$ at the top boundary. The computational domain covers 3000×2000 km^2 with the center at (110°E, 40°N), horizontal resolution is 100 km and there are 10 levels in vertical.

For the KTA calculation, the domain is same as that in Eq.(1), but the vertical resolution is 10 levels from the surface, 1000 hPa to 100 hPa with a interval of 100 hPa.

Using the constant acceleration method (Sheng et al. 1992), the trajectories of the air mass can be calculated based on the 3−D wind field with several iterations. The error of the trajectory is dependent on the spatial and temporal resolution of the data. The mean horizontal distance of the sounding in our research domain is about 300 km. For improving computational precision and ensuring the continuity and smoothing of the trajectories, the time step is taken as 2 hours and a linear interpolation in spatial and temporal is applied to obtain the results.

III. THE PATH ANALYSIS OF DUSTSTORM

For these three cases, there are significant differences among their origins and moving paths, as well the intensities and durations (Fig.1).

1. *Case 1* (17—20 April 1980)

Case 1 was a very severe duststorm lasted up to 4 days with broad coverage. The storm arrived in Beijing area in the afternoon on 18 April 1980. Its dust area on the surface is shown in Fig.2a.

Based on the GMS pictures and the elemental composition of eolian dust, Qu et al. (1984) found out that this duststorm was originated from the arid area in the northwestern China

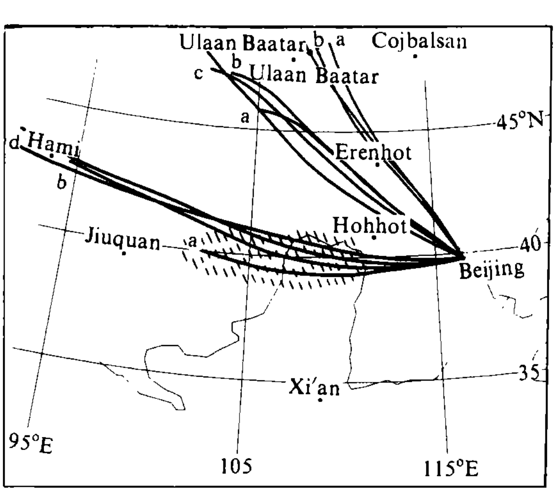

Fig. 1. The backward trajectories of three duststorms with a 36−h duration in the ρ−coordinate system. a—d are trajectories with starting points at 0.5, 1, 1.5 and 3 km over the surface in Beijing area. The shadow area is the origin area of severe duststorms occurred during 1982—1988 that is obtained from the GMS cloud images analysis (Murayama 1988).

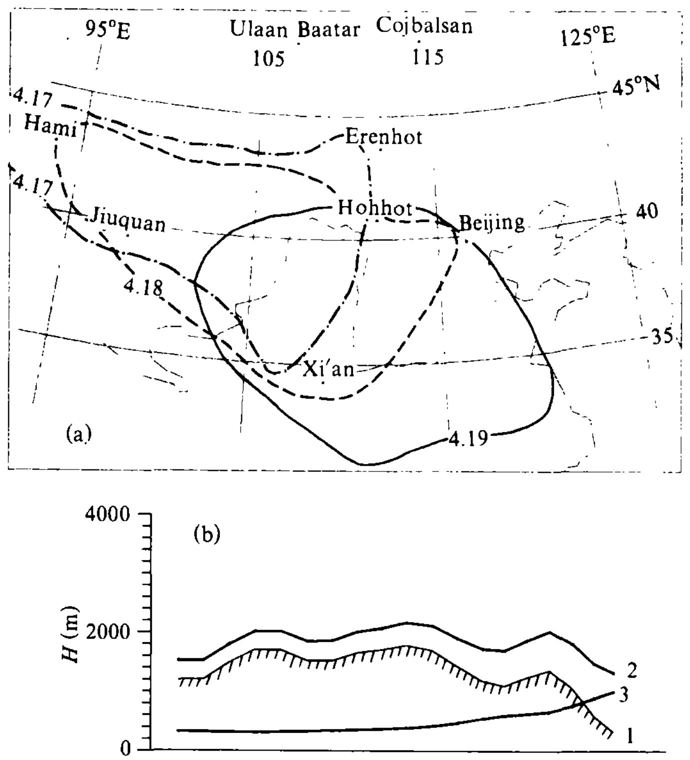

Fig. 2. The duststorm arose during 17—19 April 1980. (a) The actual range of the duststorm at 1400 BT (Qu et al. 1984); (b) The vertical section of backward trajectory in a 36-h duration of Case 1, with starting point at 0.5 km over the surface in Beijing area. 1: The elevation of the surface above the sea level; 2: That of trajectory; 3: The altitude of trajectory over the surface.

covering Inner Mongolia, the west part of Hetao, the east part of Taklimakan Desert, Shanshan and Hami area (Fig.2a). The trajectories calculated are shown in Fig.1 and Fig.2, they pass over several large deserts (100—120°E). Zhang (1984) also showed that the source of eolian dust was located in the desert of middle and west parts of Inner Mongolia and Hexi Corridor (Gansu) which was coincident with our results. His conclusion was based on synoptic analysis and our results were based on trajectory analysis which was more objective. It should be noted that the calculated horizontal tracks by KTA method were also consistent with the results prescribed but there existed deviation in lower levels.

2. *Case 2* (25—26 April 1990)

Case 2 was a strong duststorm associated with a strong cold front from the northwest. On the surface, a cold front was oriented NE–SW in Ulaan Baatar area at 0800 BT (Beijing time) 24 April. It moved southward and arrived in Harbin, Beijing and Yinchuan areas by 0800 BT 25 April. The peak of the duststorm passed Beijing area during 1600—1800 BT 25 April, i.e. 8 hours after the cold front passed. On 26 April, the storm moved out of the continent. The period of this process was two days. The strong wind behind the front could be the trigger factor of the blowing dust. The backward trajectory of the duststorm arrived in Beijing area at 2000 BT on 25

April is shown in Fig.1 and Fig.3. Obviously, all of backward trajectories starting at different altitudes were from NNW and passed through the mid–Inner Mongolia and the Loess Plateau, that was coincident with the surface dust observation (Fig.3a) and the dust areas shown in the satellite images (Fig.3b). There was a widespread upward motion area (Fig.3d) corresponding with the locations of trajectories. It is worth noting that there are several strong ascending areas located along the track, one over Erenhot and the other over the northwestern Beijing, which are helpful to entrain the dust into upper air. As shown in Fig.3c, the track at low level was elevated from 0.15 to 1.0 km altitude along a 800 km route. Zhang et al. (1992), using the multi–stage cascade samples, collected aerosol samples during and after three storms arose in the northern and northwestern China in April 1990 and analyzed trace compositions of particles. They showed that dust samples collected in the first two processes were similar to the Malan loess of Xinjiang and the sample collected on 25 April was like the soil of Inner Mongolia. Qin et al. (1990) showed results of physical and chemical analyses of the airborne and eolian dust samples that the particle size distribution of this case was like that of the soil sample collected in the Loess Plateau. It seems that the chemical composition of dust particles arrived in Beijing area have the characteristics of the soil along the track of the duststorm, i.e. the

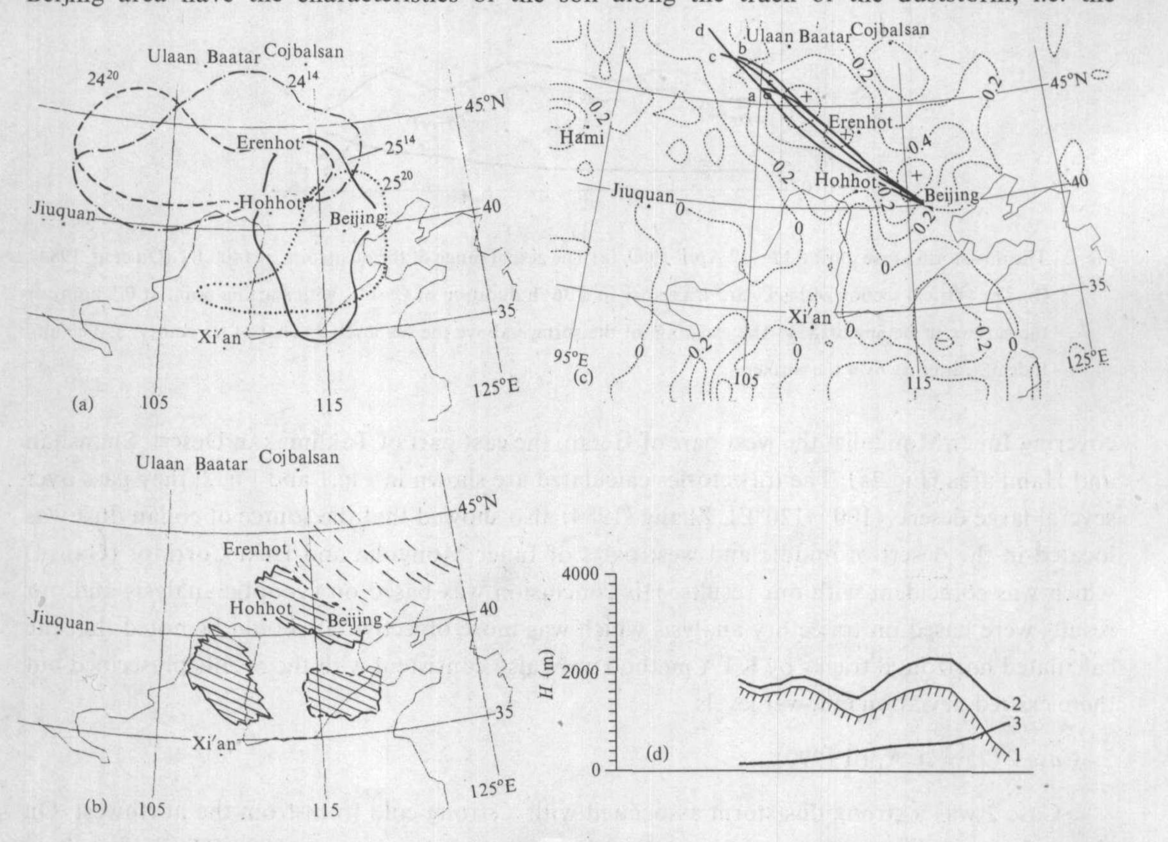

Fig. 3. The duststorm arose during 24—25 April 1990. (a) The actual range of duststorm; (b) The dust area and cloudy area (shadow) in satellite images on 25 April 1990 (You 1992, personal communication); (c) The vertical section of the 36–h backward trajectory with starting point at 1.0 km above Beijing; (d) The vertical flow distribution on the p = 0.25 surface at 2000 BT 24 April (0.5 km above the ground), positive value is upward motion (cm / s).

entraintment of the dust in the long-distance transport can not be ignored.

3. *Case 3* (30 April 1991)

Case 3 was a weaker storm lasted for half a day. As the surface observation in Beijing shows, it had been calm until 1100 BT on 30 April, and only the northern part of the sky appeared dark yellow. Then yellow dust was dispersed over whole sky. It could be believed that the dust came from remote area. The blowing dust stopped gradually at night. The data collected was not so many for the shorter duration. The trajectory analysis shows that the duststorm started near Ulaan Baatar 36 hours before passed Beijing through Erenhot (Fig.1); there are some grasslands and swamps along the track. There are strong ascending air between Erenhot and Beijing. The Hunshandake sandy land (center: 43°N, 115°E) located to the southeast of Erenhot was just in the upward current area, so the desert to the northwest of Beijing might affect this storm.

There are some similarities in circulations of these three storms. The circulation situation on the 500 hPa surface shows that there was a pressure ridge with larger meridional amplitude and a upper trough, so the atmosphere was more baroclinic. The northern flow ahead of the ridge was enhanced and made the polar cold air transport southward. There was a downward motion area between the ridge and trough with the speed up to 40 m / s. The vertical transfer of momentum led to the increasing of low level wind speed. This may be the main mechanism of the blowing dust.

All these three cases are associated with a strong cold front moving from northwest to southeast. The land warmed rapidly in spring and the strong frontolysis weaken to the south of Yellow (Huanghe) River; therefore the severe duststorm was limited in Northwest, North and Northeast China only.

The differences of circulation patterns and paths of three storms are:

(1) In Case 1, the meridional span of the pressure ridge was about 30 degrees of latitude (Fig.4a), larger than other two processes, which was helpful to the flow transfer southward. Correspondingly, a cyclone was initiated over Mongolia Plateau and intensified in northeastern China. The surface cold air entered China from Xinjiang (Fig.4b), which was consistent with the computational results.

(2) The 500 hPa ridges located over Nova Siberia in Cases 2 and 3 were weaker than Case 1 with the meridional span of the 20—25 degrees of latitute. The positions of the Northeast depressions were to the north on the surface charts, and also weaker. The duststorms were triggered by the cold fronts. In Cases 2 and 3, storms entering China from the middle and east parts of Mongolia were eastward of that in Case 1 (Fig.5b), and they were consistent with trajectory analysis too.

As mentioned above, the severe duststorm of Case 1 evoluted with the deepening of Mongolian cyclone, so it was strong, lasted longer and the track was far to the west. For Cases 2 and 3, the dust was weaker and triggered by the cold fronts. Their tracks were to the north. Results of the synoptic and the trajectory analysis were consistent. With the visible and infrared GMS images, Murayama (1988) analyzed the paths of severe duststorms that hit Japan during 1982—1988, and found that most of the duststorms originated in a narrow band around 40°N, 100—110°E (the shadow area in Fig.1). The duststorm in Case 1 passed through this band, i.e., the track went through several deserts which would promote the intensification of the storm.

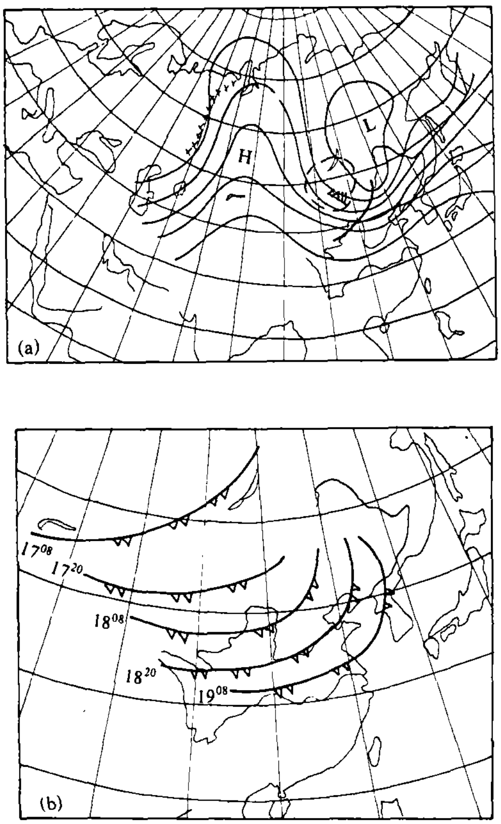

Fig. 4. The weather condition of Case 1 (18—19 April 1980). (a) 500 hPa isobaric chart at 0800 BT 18 April; (b) The moving path of the surface cold front during 0800 BT 17—0800 BT 19 April.

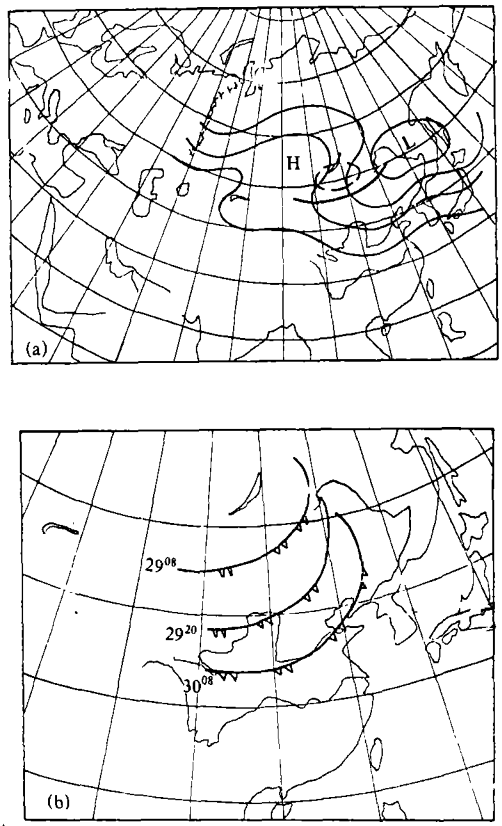

Fig. 5. As in Fig.4 but for Case 3 (29—30 April 1991). (a) 500 hPa isobaric chart at 0800 BT 29 April; (b) The moving path of the surface cold front during 0800 BT 29—0800 BT 30 April.

It seems that the path calculated in Case 1 is typical for a severe duststorm.

IV. DISCUSSION ON THE TRAJECTORY ANALYSIS

Trajectory analysis is a simple and effective method. It is widely used to study the mass-transportation, as well as the long-range transport, but its precision and reliability are dependent on various factors. Generally speaking, the relationship between the source and the receptor can not be determined with a single trajectory calculation. In this paper, the trajectory method is used to determine the origin area of the duststorm.

Three different trajectory analyses are compared and checked with surface observation and the satellite images. It seems that the results of trajectory analysis are acceptable.

(1) The trajectories of three cases are consistent with the dust area displayed in satellite images and synoptic analysis.

(2) The KTA is also used, in which the objective analysis is same as that of ρTA, but the computational method of vertical velocity are different. In ρTA, the orography can affect the coordinate system immediately and $W=0$ in the lowest level. By comparison, the vertical

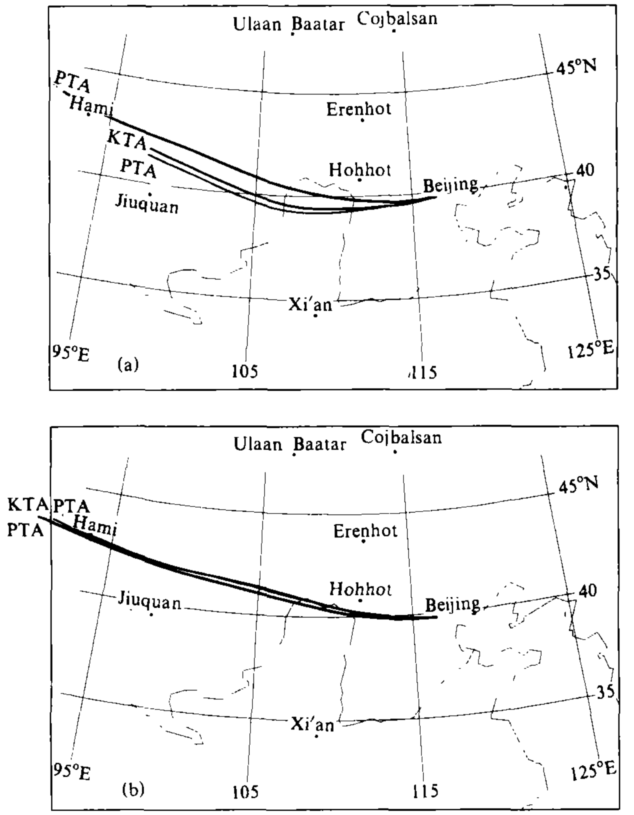

Fig. 6. The comparison of three kinds of backward trajectories. (a) The starting point at 1.5 km (850 hPa) high in Beijing area; (b) The starting point at 3 km (700 hPa) high in Beijing area (ρTA, KTA and PTA see the text).

velocity in the lowest level is influenced by the orography in KTA. $W \neq 0$ and a negative value will be taken for the upward. The trajectories labelled with ρTA, KTA and PTA obtained from three methods are shown in Fig.6. The main trends of trajectory on the horizontal projection surface are consistent. There are some deviations among trajectories with starting points at 1.5 km high (850 hPa), but for those with starting points at 3 km (700 hPa), such deviation is negligible. The larger departure in lower levels may be due to the orographic effect. In general, the elevation of the western China is over 1 km. Thus some wind data at the isobaric surface below 850 hPa are not from observation. This may be one of the reasons for larger departure in the lower level.

(3) The PTA trajectory analyses at 850, 700 and 500 hPa surfaces were still applied. This method is compared with ρTA and KTA. The horizontal trajectories are similar but differ in the last stage. This may be due to the effect of the vertical velocity which is not considered in PTA. If the wind shear in whole air column is smaller and the vertical flow is weaker. The trajectory obtained from PTA can still be a good representative of the horizontal transport of dust.

V. CONCLUSIONS

In this paper, three cases of duststorm transport in the northern China are analyzed and some conclusions are obtained as follows:

(1) The intensities and transport paths in these duststorm cases are different due to different synoptical processes, although the large-scale environment of atmospheric circulation is similar. Usually, the path of a duststorm associated with the deepening of Mongolia cyclone is to the north and will be stronger and last longer. The severe duststorm, Case 1, is an example, which has a typical transport path across several deserts from west to east. If the duststorm is triggered by the cold front (Cases 2 and 3), its path location will be to the north and the intensity is weaker. For example, the path in Case 3 is to the north and it is weaker than those of the other two cases. This is related to the synoptic and orographic conditions.

(2) The trajectories obtained from both ρTA and KTA can be used to study the transport processes. PTA is a simple and usable method, if the vertical wind shear and vertical velocity are weaker. The departure of trajectories calculated by KTA and PTA in the lower atmosphere is larger due to the orographic effect.

(3) The origins and transport directions of duststorms can be obtained by the trajectory method, but this method can not determine the flux of dust and deposition. To develop a numerical model is necessary for the further study of the mechanism of blowing dust and the transport properties of particles with different sizes.

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