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Dust storms and loess accumulation on the Tibetan Plateau: A case study of dust event on 4 March 2003 in Lhasa

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Abstract **Whether the Tibetan Plateau is a significant dust source area is of great importance, because this is related to the understanding of sources, accumulation and environmental effects of dusts on the Tibetan Plateau and in the Far East-Pacific Ocean regions as well as to the evolution of coupling of the Tibetan Plateau and atmosphere-ocean-continent exchange. Synoptic dynamics and remote sensing tracing of a dust storm on 3 to 5 March, 2003 in Lhasa on South Tibet demonstrate that the Tibetan Plateau possesses all factors and conditions of generating dust storms. Accompanied with this dust storm is a strong ascending stream on the Plateau which has raised various sizes of dust particles into different levels. The lifted coarse particles were largely fallen down and accumulated as loess on the eastern Tibetan Plateau, and the fine particles were translated by the westerly jet and subsided in the northern Pacific Ocean. The spatial-temporal distribution of dust-storms between years 1961 and 2000 on the Plateau shows that dust-storms mainly occur in winter and early spring with high frequency, and the path of dust storm moves gradually from south to north, which is closely coupled with the northward moving of the westerly jet from winter to spring over the Tibetan Plateau. Compared with other twelve dust source areas in China, the Tibetan Plateau is one of the key dust source areas for the long-distance transport because its high occurring frequency and elevation cause fine particles easily to be lifted into the zone of the westerly jet.**

Keywords: Tibetan Plateau, dust storm, dust source areas, Tibetan loess.

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Loess is widely distributed on the eastern part of the Tibetan Plateau and Plateau marginal areas surrounding the central and western Tibetan Plateau. Particularly the Plateau loess to the south of the eastern Kunlun Shan-Ngola Shan is mostly deposited above 3500—4500 m altitude. It has been growingly attracted how these loesses form and where they come from (Fig. 1). Current geologic evidence shows that the Tibetan loess is "cold loess" or periglacial loess, has coarser grain size than that of the loess on the Loess Plateau to the northeastern Tibetan Plateau, and most possibly comes from the Tibetan Plateau itself. The middle and high levels of the westerly jet and the Tibetan monsoon are likely to the major generator and carrier of dusts[1—5]. Comparison of ESR signals of quartz grains of Japanese Kosa (means yellow sand or dusts) suggests that much of the Kosa is transported by the westerly jet most likely from the Tibetan Plateau[6]. The study of dust records of deep-sea sediments also reveals that the Asian arid land between 25° and 40°N is the major dust source area and the westerlies is the carrier conveying dusts[7,8]. Current studies demonstrate that loess in the Tibetan Plateau and its marginal areas are mostly formed at about 0.8—1.15 MaBP[2,4,5,9—12], mostly due to a combination of the Tibetan Plateau being raised into a key threshold height of atmospheric kinetics and physiographic landscape where the Plateau rising into the cryosphere and the atmosphere circulation being greatly adjusted with the lower and middle levels of the westerlies being forced to diverged into two jets to flow around the Plateau and the stable occurrence of the Tibetan monsoon[5,11,12]. Furthermore, this event may have caused a strong desertification of Asian inland giving rise to formation of great deserts in NW China and a great expansion of loess southeastwards from the Loess Plateau to East China[5,11,12] as well as have triggered the global cooling at this time (so-called MPR = Mid-Pleistocene Revolution)[13].

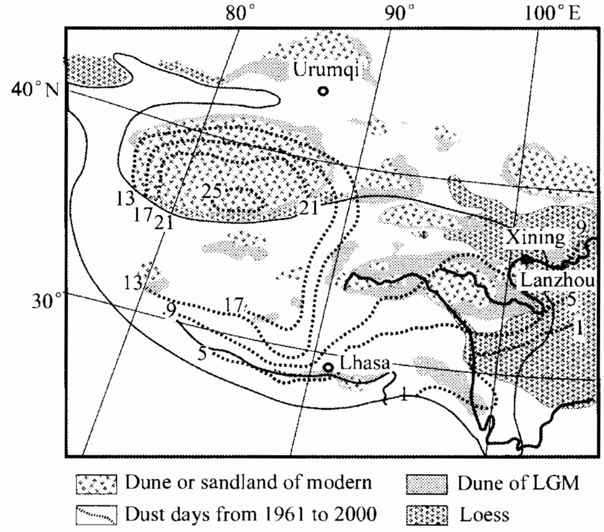

Fig. 1. The distribution map of modern and last glacial sand dunes, desertified sandy land and loess and the spatial mean annual days plot of dust storm from 1961 to 2000 on the Tibetan Plateau. Aeolian sand and loess distribution was drawn according to our field investigation and refs. [1—5], [9—12] and [19—21]. Dust storm data are from the Climate Center of China Meteorological Administration.

Zhang Xiaoye and his co-authors used the chemical element tracer system to analyze the aerosol characteristics and flux of dust storms occurred between September and October 1993 and between April and March 1994 at an altitude of 4800 m at Wudaoliang (35.2°N, 93.1°E) on the central Tibetan Plateau. They concluded that the Tibetan Plateau is not a dust source area[14—16]. However, because the observation data they used are short and only come from one locality, their data are hard to secure a whole pattern of dust fluxes on the Tibetan Plateau both in time and in space. Therefore, whether the Tibetan Plateau is or not a significant dust source area remains still uncertain. The area of the Tibetan Plateau is account for about one fourth of total area of Chain, and is mostly over altitudes of 3500—4500 m, much higher than that of the surrounding desert areas (e.g., about 840—1200 m above the Taklimakan Desert to the north, 1300—1800 m above the Badain Jaran Desert and 400—1600 m above the Tengger Desert to the northeast)[17]. As early as in early 1980s, Duce and others recognized that fine dusts derived from Asia in spring are mostly transported by the westerly jet at 500 hPa (~5500 m) and fallen down in the northern Pacific Ocean[18]. Therefore, fine dust particles on the Tibetan Plateau are much easier lifed into high level of the westerly jet than those in other dust source areas. It deserves being soon clarified if the Tibetan Plateau is a significant dust source area, because it is not only a regional scientific question related to understanding the loess origin and formation on the Tibetan Plateau, but also is significantly related to the uplift of the Tibetan Plateau and its coupling with global ocean-continent-air system.

On 4 to 5 March, 2003, CCTV (China Central Television) successively reported an event of strong blowing-dust from 3 to 5 March in Lhasa. This event forced all the scheduled flights to Lhasa to be cancelled, stopping over 2000 passengers at the Shuangliu airport in Chengdu. This unusual synoptic process of strong blowing-dust on the Tibetan Plateau provides a fair opportunity to study the above-mentioned scientific question. Taking this case, we analyzed the path and vertical ascending movement of the dust-storm. Furtermore, on the basis of statistics of about 40-year data of dust-storms from 91 weather stations on the Tibetan Plateau and integrating dust storm literatures in Japan and Korea, we analyzed the spatial-temporal distribution and long-distance translation of dust storms on the Tibetan Plateau, providing our information on the source of Tibetan dust storm.

1 Geography and source materials of dust storms in the studied region

The studied region includes nearly the whole Tibetan Plateau having topography inclining from the northwest at average altitudes 5000 m to the southeast at about 3500 m. When the westerly jet adjusts, the Tibetan Plateau will appear westerly winds from the Yarlung Zangbo valley and the Qiangtang Plateau as well as northwesterly wind from the Qaidam Basin. These winds meet respectively in the source areas of the Yangtze and Yellow Rivers and in the Lhasa region and form strong convergent upwelling air flows there, providing power for dusts to be lifted. In addition, there are widely distributed flowing sand dunes on the Tibetan Plateau. For example, an area of about 2000 km^2 of desertified surface (with moving sand dunes in winter) occurs in the valleys of Yarlung Zangbo River and its tributaries with an average altitude of about 3600 m (Fig. 1). At the rim of this desertified surface is loess with thicknesses of up to 30 m and ages old back to 0.8 Ma[9,19]. Between the Gangdese and Kunlun Shan are a series of near west-east glaciated mountains and a vast area of planation surface (Plateau Surface) on which there are distributed many varied sizes of lakes and wind-blown geomorphology and moving sand dunes[20]. The wind-blown and desertified surfaces occupy about an area of about 400 km^2, on which the most are moving sand dunes. These sand dunes are greatly activated in winded winter[21]. For example, vast patched moving sand dunes are found in the source areas of the Huang He (the Yellow River) and Chang Jiang (the Yangtze River) (e.g., source area of Tongtian He (River), the vast area to the west of the road from the Kunlun Shan pass to Lhasa, and areas at Xingxing Hai, Rigecuo and Ghoring Lake beach). Moreover, desertified meadow and grass soils occupy area much wider than that of sand dunes and include almost all source areas of the Huang He and Chang Jiang except sand dunes and mountain bedrocks. The parent materials of these soils are relatively homogeneous and consist mostly of silts and fine sands[20]. At present, the desertification land is rapidly increasing. The investigation shows that the area of desertification land only in the Tibetan Autonomous Region reaches about 2047.41×10^4 hm^2, distributed in every county and city, accounting for 17.03% of the total area of the Tibetan Autonomous Region[21]. Moreover, thick connected sand dunes widely appear in those desertification areas. These sand dunes were mostly formed at 14—24 kaBP in the last glacial maximum (LGM)[20], indicating much stronger desertification occurring in the LGM (Fig. 1). These widely distributed sand dunes and desertification land provide plenteous materials for dust storm generation. The average annual days spatial figure of dust storm occurring between 1961 and 2000 shows that the Qiangtang Plateau and Taklimakan Desert to the north are the two high frequency areas of dust storm occurrence. The frequency is over 15 days a year in the Qiangtang Plateau and over 5 days a year in the other parts of the main Tibetan Plateau, with a decreasing trend southeastward from the center of the Qiangtang Plateau (Fig. 1).

2 Synoptic dynamic diagnosis of the strong blowing-dust event in Lhasa

The gale and strong blowing-dust in the Tibetan Plateau on 3—6 March, 2003 was formed in the process of the adjustment of the circulation of mid-low latitudes in Eurasia and the southward moving of the strong westerly jet. Before blowing-dust occurred, the pattern of the circulation on the Eurasia continent presents as two troughs and one ridge in the weather chart of 300 hPa, in which the area from the Tibetan Plateau to West China was controlled by the high pressure ridge, resulting in a 50—60 m/s strong westerly jet locating at 33°N near the Plateau and a weak south branch trough. With the Europe trough being deeper and moving eastwards, the upper air front moved southwards and the south branch trough gradually intensified and developed. Up to 4—5 March, the two low pressure systems in the mid and low latitudes phased together, greatly deepening the south branch trough in the western side of the Plateau and leading the strong westerly jet nearby the Plateau move southwards to 30°N with a wind speed of 60—65 m/s. This combined system led the momentum transfer downwards to low level, providing a basic atmospheric circulation necessary for the dust event in this study. This weather system moved out the main part of the Tibetan Plateau at 08:00 am on 6 March, 2003. Dust storm is a middle scale weather process. Its formation requires three conditions, i.e., sand source, gale and vertical ascending air stream. Because gale and dust storm frequently appear in the heel of negative allobaric center, we use chiefly the movement of 24-hour allobaric center to trace the moving track of the vertical ascending air stream[22,23], thus derterming the trajectory of dust storm. Subsequently, we calculated and plotted the spatial distribution of the vertical speed ω of the dust storm at its biggest on the Tibetan Plateau and the altitude of the vertical ascending air stream in the Lhasa region using methods of dynamics diagnosis.

When the dust storm occurred, the wind speeds had achieved the critical wind speed over 6 m/s in every direct to generate. With the gale and blowing-dust occurring, Fig. 2 shows that there are two negative allobaric centers moving eastwards and southwards, respectively. From 11:00 on March 3, one negative allobaric center moved from the western Plateau to its eastern part and finally out of the Plateau, passing through Shiquanhe (with value of –6 hPa), Gaize (–6 hPa), Dangxun (–6 hPa, Naqv(–8 hPa) and Yushu (–4 hPa) (called south path); the other moved from the northern Plateau to its southeast, passing through Geermu (–8 hPa)and Zaduo (–6 hPa) (called north path) and joining the west path at Yushu at 02:00 on March 5 with its value decreasing to –4 hPa. In the rear of the negative allobaric center along the west path, the blowing-dust appeared successively at Shiquanhe, Gaize, Dingri, Rikaze, Gongga, Lhasa, Dangxun, and Anduo, reaching its maximum at about –8 hPa at 14:00 to 20:00 on 4 March. At the same time, blowing-dust occurred in the rear of the north center successively at Dehaling and Maduo.

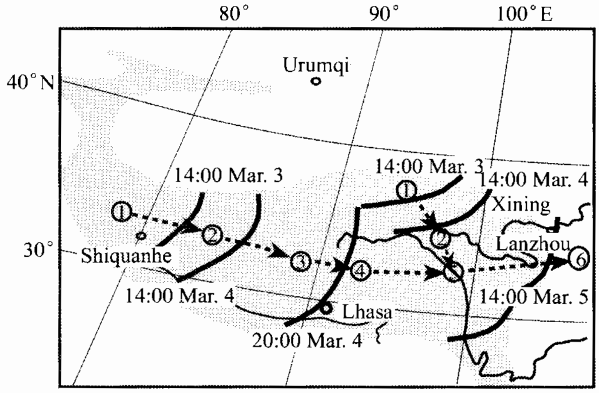

Fig. 2. Sketch map summarizing the weather of the blowing-dust event on 4—6 March, 2003. Black solid line: Boundary and time of the appearance of the blowing-dust event; black circle: Time and location of the appearance of the 24-hour allobaric center; dash arrow: direction of movement of the allobaric center; 1: 11:00 am on March 3; 2, 3 and 4: 02:00 am, 08:00 am and 20:00 pm on March 4, respectively; 5: 20:00 pm on March 5; 6: 08:00 am on March 6.

We used continuous integral equation to calculate vertical speed ω modified by the O'Brien nonlinear equation[23]. Fig. 3 shows the ω at 500 hPa (5.5 km) and from 500—100 hPa along 70°E—100°E at 30°N on the Tibetan Plateau. We can clearly see the ascending movement prevailing on the Tibetan Plateau with three rising centers. The first center is the strongest one with ω at –1.0 hPa/S locating roughly in the source region of the Yellow and Yangtze Rivers; the second has ω at –0.6 hPa/S located in the regions of Lhasa-Namucuo Lake-Dangxun; the last has ω at –0.4 hPa/S located in the southern Kunlun Mountains and northern Quangtang Plateau (Fig. 3(a)). The vertical transection along 86°E—93°E indicates that the vertical ascending movement prevailing the whole levels from 500 (5.5 km) to 100 hPa (16 km) with the largest values at 88°E—89°E (west of Lhasa) (where the ω is as big as to –0.5 hPa/S even at 250 hPa and still at –0.2 hPa/S even at 100 hPa (Fig. 3(b)).

The synoptic dynamics analysis of the dust storm above shows that the Tibetan Plateau possesses all conditions for dust storm generation when the westerly jet adjusts. When dust storm occurs, the vertical ascending movement prevails on the Tibetan Plateau. Our case indicates that the ω at 500 hPa on 4 March, 2003 in Lhasa is much higher than that (–0.53 hPa/S)1) in the Tarim Basin

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1) Lü, L.Q., Fang, X. M., Lu, H. Y. et al., Grain size record of millennial winter monsoon variation on the Tibetan Plateau since last glaciation, Chin. Sci. Bull., 2004, in press.

on 8 April, 2003. This implies that same dust grains can be lifted higher in the Plateau than in the Tarim Basin. Combined with the high altitudes of 4000—5000 m of the Tibetan Plateau, dust grains are much easier to be raised into the westerly jet.

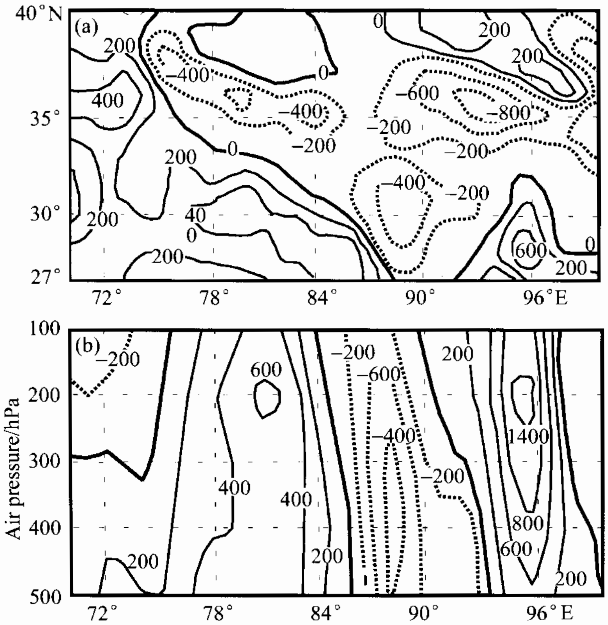

Fig. 3. Distribution of ascending speed ω on the Tibetan Plateau at 20:00 pm on March 4, 2003. (a) ω at 500 hPa; (b) ω from 500—100 hPa along 70°E—100°E at 30°N.

3 Remote sensing monitoring of the blowing-dust event

The complex topography and sparse weather stations on the Tibetan Plateau make it impossible routine monitoring of large-scale regional dust storm. However, this can be supplemented to a certain extent by remote sensing. We used ERDAS Imaging processing software firstly to calibrate the geometry and radiation and to enhance image of MODIS data, then to process the MODIS data on March 1 (sunshine), March 4 (blowing-dust) and March 5 (floating-dust) by monitoring and non-monitoring class methods[24], and finally to map out the distributive area and intensity of the blowing-dust on the Tibetan Plateau, integrated with surface data observed by weather stations and meteorological conditions (Fig. 4). Combined with dust storm images of NOAA-12 at 14:00 on March 2 in the Tarim Basin and at 17:00 on March 3 in the source areas of the Yellow and Yangtze Rivers (Data were issued by the National Meteorological Satellite Center of China Meteorological Administration, and images are not presented here due to limited space), the processed MODIS images on March 4 shows clearly three paths of the blowing-dust, i.e., (1) from the NW Plateau to its eastern part, (2) from the Yarlung Zangbo River valley to the eastern Plateau and (3) from the Qaidam Basin to the southeastern Plateau. Among these dust storms, those occurring in the far-reached Qiangtang Plateau are the most strongest where lots of flowing sand dunes provide plenty dusts for the dust storm generation. Even in the MODIS images on March 5, patched blowing-dusts and floating-dusts still can be seen in the central Tibetan Plateau and the floating-dusts even expanded to the Hengduan Shan of the southeastern Tibetan and the Sichuan Basin (Fig. 4(c)). This observation is quite similar with that analyzed by meteorological dynamics diagnosis, but the scope and intensity of the dust storm are much beyond our imagination. The processed MODIS images of floating-dusts on April 10 in the source areas of the Yellow and Yangtze Rivers also clearly show that the dusts were transported toward the downstream regions. The floating-dusts vestured the valley of the Yellow River and its main tributaries from the Gyaring and Ngoring Lakes to Lanzhou, and a mass of yellow dusts were deposited in the peak area (highest peak at 6282 m) of the Buerhanda Shan and Anyemaqen Shan. Thus, we estimated that these dust grains are lifted at least over 5500 m into the zone of the westerly jet.

4 Spatial-temporal distribution of dust storms on the Tibetan Plateau and the westerly transport of dusts

The spatial-temporal distribution of dust storms between 1961 and 2000 on the Tibetan Plateau and in Xinjiang to the north of the Plateau demonstrates that the occurrence of dust storms on the Tibetan Plateau is principally between December and April and gradually moves northwards from the valley of Yarlung Zangbo River to the southern Qiangtang Plateau, then to the central Qiangtang Plateau and the southern Tarim Basin with the season passing on. This seasonal movement is closely related with the movement of the westerly jet over the Tibetan Plateau. When the westerly jet moves from south to north over the Tibetan Plateau along with the season changing from winter to spring, the southern branch of the westerly jet gradually becomes weaker, whereas the northern branch becomes stronger (the westerly jet over the Tibetan Plateau is diverged into two branches in the winter and spring seasons due to the high topography of the Plateau). Superimposed with the impact of the complicated topography on the Tibetan Plateau, the convergence center of air currents also moves accordantly from south to north in the Plateau, giving rise to a corresponding northward movement of the center of dust storms (Fig. 5).

The content of >63 μm of fine sands in surface sediments of the Tibetan Plateau is over 60%—70%[19—21]. Their short distance transport is mostly proceeded with creeping and bouncing. When gale and dust storm occur, these coarse dust grains can be deposited in downstream slope and adjacent area and finally turn into loess by pedogenesis. For example, the loess in the valley of Yarlung

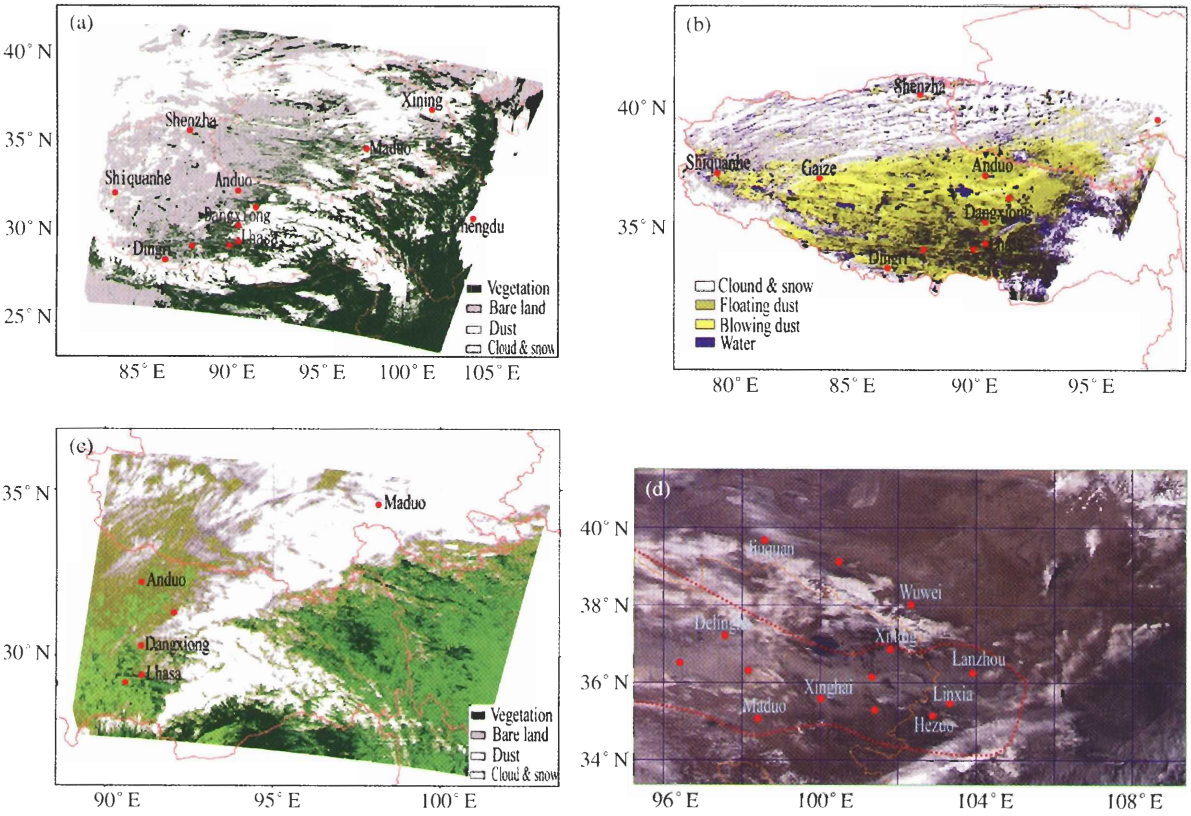

Fig. 4. Remote sensing processed MODIS images of dust storms on the Tibetan Plateau. (a) Sunshine image at 12:00 on March 1, 2003 in Lhasa; (b) strong blowing-dust image at 12:00 on March 4, 2003 in Lhasa; (c) images of blowing-dust and floating-dust at 12:00 on March 4, 2003 in the western Sichuan Basin; (d) floating-dust image at 12:00 on April 10, 2003 in the source areas of the Yellow and Yangtze Rivers.

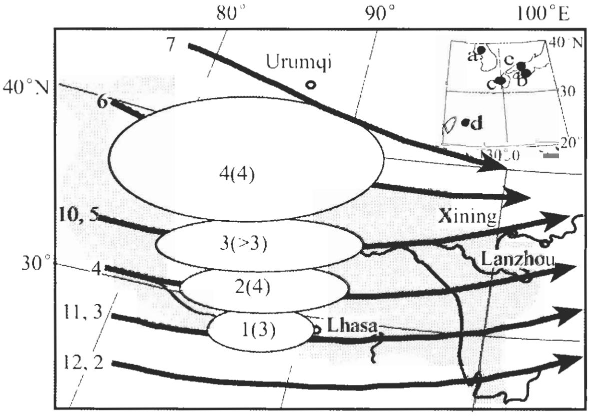

Fig. 5 Monthly spatial-temporal distribution of dust storms and the westerly jet on the Tibetan Plateau. Black solid arrow and number: Westerly jet and month; open circle: Center of dust storm; number and (number) in open circle: Abbreviation for month and number of monthly occurrence of dust storm; black solid circle in the auxiliary figure: Station observing dusts in Japan and Korea; a. Seoul; b. Yashiro; c. Nagasaki; d. Ishigkiis; e. Okayama.

Zangbo River in the Lhasa-Rigaze region is very coarse with >63 μm fine sands over 60%—70%, and becomes coarser when approaching sand dunes[20,25]. In addition, loess is widely distributed on the eastern Tibetan Plateau surrounding the east part of source areas of the Yellow and Yangtze Rivers. The grain size of this loess becomes finer away from the river source areas, but much coarser than the loess in the nearby Loess Plateau[1)]. Consequently, the coarse fractions of the Tibetan loess cannot be transported from sources out of the Plateau but the Plateau itself.

However, the fine fractions of dust grains can be raised by convergent ascending flow onto the westerly jet at 500 hPa (5.5 km) which is the main power for long distance transport of Asian dusts[18,26—28]. Because the altitude of the Tibetan Plateau is higher than that of other source areas in Asia, such as, 840—1200 m, 1300—1800 m and 1400—1600 m higher than those of the Taklimakan, Badain Jaran and Tengger Deserts, respectively[17], only very strong dust storm is able to raise fine dusts in these

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1) See footnote 1) on page 955.

desert source areas onto the westerly jet at 5500 m level. This indicates that the occurrence of dust storm on the Tibetan Plateau over altitudes 3500 to 4500 m approaches or exceeds the main height of biggest dust storms in the Tarim Basin lifting fine dusts, thus fine dusts on the Tibetan Plateau are much easier to be lifted onto the zone of the westerly jet for long distance transport, as shown by the blowing-dust even in Lhasa above.

The dust records in Japan and Korea provide further evidence for the long distance transport of the Tibetan fine dusts. The monthly distribution of dusts at four stations in Japan and Korea (Ishigkiis, Nagasaki , Yashiro and Seoul) shows that high dust records in all four stations appear in December and January to April, and that with latitude higher, the highest frequency firstly appears in the south (24°N) in March and gradually moves to the north in April and May[6]. However, in China, this pattern of higher frequency occurrence of dust storms only appears on the Tibetan Plateau. Therefore, we estimate that a majority of Japanese and Korean dusts in winter may come from the Tibetan Plateau. Further evidence comes from the fact that dusts in Japan often have a two-layer structure in early spring, with the lower layer below 4000 m a.s.l. and the upper one above 4000 m a.s.l. This made Iwasaka and others think that the two-layer dusts may derive from different areas[26,28]. Our study shows that the upper layer of dusts may reflect the long-distance transport of fine dusts mainly from the Tibetan Plateau. For example, there occurred a strong dust storm in the source areas of the Yellow and Yangtze Rivers at 18:00 on April 9, 2003. At 12:00 on April 11, a dust layer appeared at altitudes of 4000 to 7000 m at Okayama (see Fig. 5 for location) in Japan and no dusts appeared below 4000 m, providing direct evidence for the long-distance transport of fine dusts from the Tibetan Plateau to the northern Pacific region[29].

5 Discussion

Apart from the geologic evidence, from the meteorological point of view, whether the Tibetan Plateau is a significant dust source area mostly depends on dust storm frequency and the ability lifting dusts onto the zone of the westerly jet.

Figure 1 shows that the Tibetan Plateau has higher dust storm frequency and the high frequency center is in the Qiangtang Plateau with a trend gradually decreasing southeastwards. We choose five weather stations at Shiquanhe, Lhasa, Shengzai, Wudaoliang and Xinghai to represent the western Plateau, the valley of Yarlung Zangbo River, the southern Qiangtang Plateau, the source areas of the Yellow and Yangtze Rivers and the Qinghai Lake, respectively. These dust stations can reflect principally dust characteristics on the main part of the Tibetan Plateau. Compared with the annual days of dust storm generation in twelve sand desert regions in China[17], the annual days of dust storm generation on the Tibetan Plateau are close to the Hobq Desert, only lower than Taklimakan, Badain Jaran, Tengger and Ulan Buh Deserts, but higher than the Gurbantunggut and Mu Us Deserts and Otindag, Hulun Buir and Horqin sandy lands (Table 1). The Tibetan Plateau is between the high dust regions of northwestern deserts and low dust regions of northern deserts as defined by ref. [30]. Therefore, judging from annual days of dust storm generation, the Tibetan Plateau can be defined as a moderately dust storm occurring region.

Table 1 Annual days of dust storms occurred in all source areas in China (Data except the Tibetan Plateau come from ref. [17])

Dust source area	Altitude/m	Dust storm (blowing-dust)/d
Western Tibet	4279	16.5(58)
Southern Tibet	3650	4—5(16)
Southern Qiangtang Plateau	4674	16(36)
Source area of Yangtze River	4800	12(30)
Southern Qinghai Lake	3324	9(16)
Taklimakan Desert	840—1200	30
Gurbantunggut Desert	200—1000	5
Badain Jaran Desert	1300—1800	20—30
Tengger Desert	1400—1600	20—30
Ulan Buh Desert	1000—1500	20
Hobq Desert	1000—2000	10—20
Mu Us Desert	1000—1500	10
Otindag Sandy Land	1000—1500	5—10
Hulun Buir Sandy Land	500—1000	1
Horqin Sandy Land	0—500	5—10

The westerly jet at 500 hPa is the main power for the long-distance transport of Asian dusts[18,26—28]. The absolute altitude of fine dust grains raised into the westerly jet at 500 hPa can be calculated from all known altitudes of dust source regions in China. The altitudes of twelve dust source regions are at about 1000 to 2000 m. Thus, fine dust grains need to lift about 3500 to 4500 m onto the westerly jet zone at 500 hPa. This means that only strong dust storms have the possibility. For example, the loess on the northern slope of the Kunlun Mountains is the deposition of dust storms from the Taklimakan Desert. The grain size and thickness decrease gradually with the increase of altitude. For instance, the thickest loess is found at an altitude of 2900 m in Ruoqiang, then the loess thins upperwards until about 4500 m[11]. This indicates that the power raising dust grains decreases with rising altitude, thus, only strong dust storms can arrive at mountain peaks. By literature, there totally occurred 32 times of strong dust storms in Hetian in recent 40 years, only 3% of the totality of dust storms at 1036[31]. Even in the case where 2 and others included more dust storms into strong dust storms[32] due to different definition of a strong dust storm[33], they reported the strong and very strong dust storms in the Hexi Corridor also only account for 17% and 3.4% of the total dust storms in recent 45 years, respectively[33]. Therefore the maximum of strong dust storms will be not more than 50% of total dust storms. Taking into account the height lifting fine dusts onto the westerly jet zone above, the number of dust storms rising onto the westerly jet in twelve dust source regions in China will reduce at least 50%. However, dust grains on the Tibetan Plateau only need to raise about 1000 to 2000 m to get into the zone of the westerly jet. The case of Lhasa above indicates that only a weak dust storm, the blowing dust process, can lift fine dusts onto the zone of westerly jet. The sum of annual dust storms and blowing dust process on the Tibetan Plateau is over thirty (Table 1). Even excluding the blowing dust process, the number of dust storms able to rise onto the zone of the westerly jet is still much higher than that in other dust source areas. All these go to a conclusion that the Tibetan Plateau is one of the major source areas for the long-distance transport of dusts.

Zhang and others used the GMW-2310 sampler to collect aerosol samples at Wudaoliang at 4800 m on the central Tibetan Plateau[14—16]. On the postulation that depositional dust flux is equal to released dust flux in an area, their data give out a depositional dust flux of about 100 g/(m^2 • a) for the Tibetan Plateau[15]. Comparing this datum with those from Chinese deserts, Loess Plateau, historic dust-fall regions in northeast and southeast China at 410, 250, 95 and 17 g/(m^2 • a), respectively, they concluded that the Tibetan Plateau is not a dust source region[15].

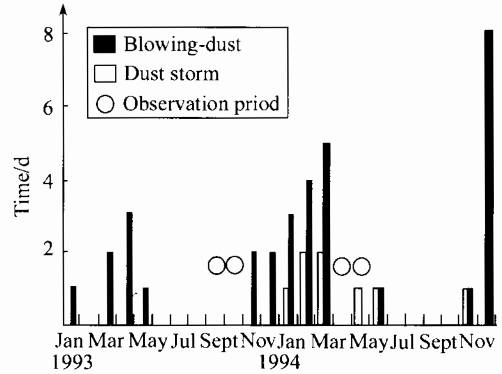

Fig. 6. Monthly days of dust storms at Wudaoliang between 1993 and 1994. Dots mark the period of sampling in ref. [15].

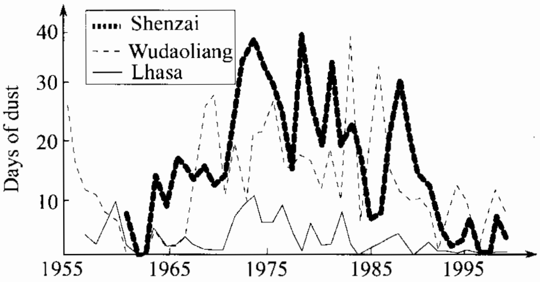

Fig. 7. Annual dust storm days of representative stations on the Tibetan Plateau.

The very large variation of dust concentration in different meteorological processes leads to a great difference in depositional dust fluxes. For example, according to the observed data from four stations like Jilantan, dust concentrations in processes of normal weather, floating dust, blowing dust and weak dust storm are 0.083, 0.356, 1.206 and 3.955 mg/m^3, respectively[17]. And the dust concentration of a very strong dust storm, e.g., that in Jinchang on May 5, 1993, even reaches 1017 mg/m^3[31]. Therefore, whether there occur or not dust storms in the sampling period has great impact on resulting dust flux and thus conclusions have been drawn. Dust storms on the Tibetan Plateau occur mostly in winter and early spring. However, the sampling interval in ref. [15] was just in months of low dust storm occurrence (Fig. 6), so the calculated depositional dust fluxes cannot present the annual dust flux of the Tibetan Plateau. If viewing for a long period, we find that the sampling intervals in ref. [15] lie also in the nearly lowermost period of dust storm generation over the last 40 years on the Tibetan Plateau as indicated by days of dust from Wudaoliang (35.2°N, 93.1°E), Lhasa (29.4°N, 91.08°E) and Shengzai (30.57°N, 88.38°E) (Fig. 7), 2 to 6 times lower than the mean over the last 30 years. Therefore, even for one station at Wudaoliang, observation in ref. [15] represents annual dust flux neither in short term nor in long term, thus their data are far away from the real mean of the Tibetan dust flux. If viewing from geologic time scale, the modern grassland and meadow areas on the Tibetan Plateau were mostly source areas of the past dust storms, because fixed sand dunes are immediately under them, e.g., those in the source areas of the Yellow and Yangtze Rivers. Chronology and deposition of those sand dunes demonstrate that they were mainly formed in the last two glaciations when dunes were very active and provided a tremendous amount of dusts for the Tibetan coarse loess[1,2,19] (Fig. 1). Taking into account spatial distribution, the occurrence of dust storms on the Plateau is a dynamic process changing from south to north (Fig. 5), and is closely related with every synoptic process and distribution of dust source and topography. As a conclusion, because the sampling in ref. [15] was too short and only at one site at Wudaoliang, the data in ref. [15] can neither represent the annual dust flux nor the long-term average dust flux for the whole Tibetan Plateau. The potential as a dust source region for the Tibetan Plateau was greatly underestimated. However, considering the difficulty to collect dust aerosol samples on the Tibetan Plateau, the calculated depositional dust flux by ref. [15] can also reflect the state of fluxes in non- or few dust storm period.

Therefore, both geologic evidence and the characteristics of modern circulation and dust storms on the Tibetan

Plateau demonstrate that the Tibetan Plateau is a significant dust source area.

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