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ORIGINAL ARTICLE

Characteristics of aerosol dust in fresh snow in the Asian dust and non-dust periods at Urumqi glacier no. 1 of eastern Tian Shan, China

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Abstract Windblown mineral aerosol dust derived from the crustal surface is an important atmospheric component affecting the earth's radiation budget. Deposition of atmospheric dust was measured in the fresh snow on glacier no. 1 at the headwater of the Urumqi River in eastern Tian Shan, central Asia. An analysis of seasonal variation of concentrations of dust particles in the snow suggests that the number concentration of dust particle is significantly high from April to June, which may be caused by Asian dust storms in the spring. The comparison of mass-size distribution of dust particles from April to August shows an obvious seasonal change trend. The distribution of particles changes from single model (3–21 μm) in the non-dust period before dust events in April, to bi-model (3–21 and 20–80 μm) during the Asian dust period, and to single model (3–21 μm) after July in the non-dust period again. The Ca^{2+} concentration in the fresh snow is also very high from April to June, while NH_4^+ and SO_4^{2-}, as water-soluble constituents, have concentration changes that are different from each other. Backward trajectory was also employed to examine the transport process of air mass in this region.

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Introduction

Windblown aerosol mineral dust derived from the crustal surface is an important atmospheric component (Osada et al. 2004) affecting the earth's radiation budget (Nakajima 1989; Andreae 1995; Tegen and Lacis 1996). Aerosol dust information can be recorded and stored in the snow and ice of high mountains and of the Polar regions. Atmospheric transport processes (Merrill et al. 1989; Gao et al. 1992) and transformation processes of the dust particles have also been studied to characterize the geochemical role of aeolian dust events in the Asian region. These dust events have been observed frequently in spring over the Asia-Pacific region (Niimura et al. 1998; Gao et al. 1992; Seinfeld and Pandis 1998). In some Asian regions, observations and studies of the characteristics of aerosols or the number concentrations of aerosol dust particles during Asian dust events have been performed not only in spring (Chun et al. 2001; Prospero et al. 2002), but also in autumn (Watanabe et al. 2006). However, relatively long-term simultaneous measurements of aerosol dust number concentrations and chemical compositions at the same site including the Asian dust period have rarely been conducted.

The Urumqi glacier no. 1 in eastern Tian Shan is located in an arid and semi-arid region of central Asia, at the source region for Asian dust (Fig. 1). Dust storms are an important phenomenon in this region. Aerosol dust particles deposited in the snow of high mountain glaciers contain information on the atmospheric environment at high elevations (Wake et al. 1994). Chemical analyses and meteorological correlation suggest that the dusty layers

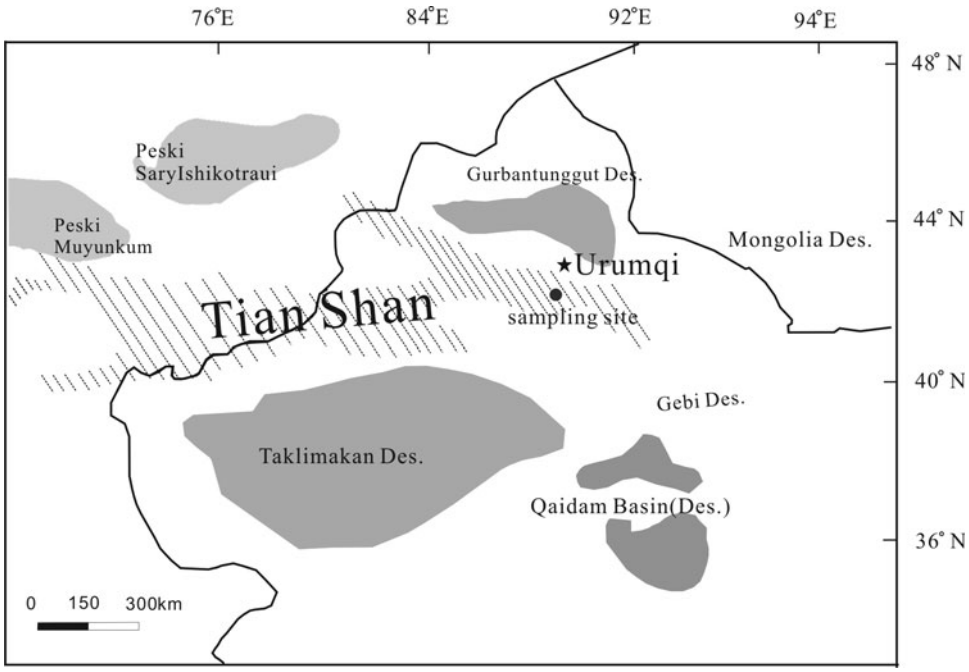

Fig. 1 Location of the sampling site on Urumqi glacier no. 1 in eastern Tian Shan

found in the snow cover of the eastern Tian Shan form by deposition of dust storm particles. However, the processes of formation of the dust layers and seasonal characteristics of the dust particles in the fresh snow of this region remain unclear.

In this paper, the characteristics of aerosol dust number concentrations and chemical compositions of particles on glacier no. 1 at the headwater of Urumqi River in China during the spring and summer seasons are examined, and the properties of dust particles in fresh snow on the glacier during the Asian dust term and non-dust terms are compared to show the effect of dust activities on snow dust deposition in high altitude. Backward trajectory analysis is also employed to examine the transport processes of the air mass at Urumqi glacier no. 1.

Snow sampling, laboratory analysis and dust measurements

Figure 1 shows a location map of Urumqi glacier no. 1 in eastern Tian Shan. In April–August 2005, a total of 22 fresh snow samples were collected for 5 months at 4,130-m altitude on the glacier. Samples were collected on the fresh snow before the snow melted because chemical and dust constituents may redistribute due to water percolation. After recording the snow properties, clean, fresh snow for dust and chemical snow was sampled. The typically 100-g samples were collected using a pre-cleaned stainless steel shovel and polyethylene gloves. All snow samples were shipped frozen from the sampling sites and stored at −18°C until time for analysis. Samples were then melted, and aliquots were collected for micro-particle and chemical analyses. Micro-particle concentrations and size distributions were measured on an Accusizer 780A counter, which uses the single particle optical sensing (SPOS) method, equipped with a 120-tm orifice, by comparing the measured pulse height of dust particles of snow samples to a set of homogeneous standard particles with known diameters to obtain a standard curve to establish the size distribution of dust particles during a time period (Zhu et al. 2006; You et al. 2006). Measurements were performed under class 100 conditions of a super-clean workbench on sample aliquots diluted with a pre-filtered NaCl solution to give a 2% vol electrolyte concentration. The data were acquired for a size range of 0.57–400 μm equivalent spherical diameter (d). Routine analysis of filtered deionized water blanks showed background counts to be on average ten times lower than in samples. All samples were analyzed in random order and in triplicate. Results were then averaged for individual samples, yielding an estimated error of 10% or less on particle concentrations.

Micro-particle concentrations are for 0.57 (mass) as μg kg^{-1} ice or ppb. The mass and volume size distributions of micro-particles were calculated from the raw count data by assuming spherical particles of uniform density $\rho = 2.6$ g cm^{-3}, which is close to that of average crustal material. Mass was derived by integrating the mass size distribution over the measured diameter range and normalizing the result to the sample volume. The slope, β, of the log-linear Junge distribution was also computed,

$$\frac{dV}{d\lg r} = \frac{V_o}{\sqrt{2\pi}\lg\sigma}\exp\left[-\frac{1}{2}\left(\frac{\lg r - \lg \mu}{\lg\sigma}\right)^2\right] \quad (1)$$

fitted to particles with d less than 25 μm. In the equation, V is the volume of dust particles, V_0 is the volume of snow samples, r is half of the diameter of particles, and μ and $\sigma$are the parameters of physical meanings of size distribution of dust particles (Junge 1963; Wake et al. 1994; Steffensen 1997). In addition to the micro-particles, the concentrations of major ions (Na^+, Mg^{2+}, Ca^{2+}, and Cl^-) were measured at trace levels on a Dionex-600 ion chromatograph using the procedure described by Buck et al. (1992). The mean blank value for the whirlpack bags for dust particle number is 444 ml^{-1} in the laboratory measurements of this work, and the blank value for major ions are shown in Table 1. Blank values were subtracted from the sample data.

Backward trajectory analysis is also employed to examine the transport processes of the air mass in Urumqi glacier no. 1. The analysis was based on the HYSPLIT4 (hybird single-particle lagrangian integrated trajectory) model, including the vertical motion mode. Backward trajectories up to an altitude of 4,130 m were calculated for 3 days.

Results and discussion

Dust particle number concentrations

The measured result shows that in fresh snow on glacier no. 1 of the Urumqi river source the number of finer particles ($d < 1$ μm) is much more than that of coarser particles ($d > 1$ μm); the difference is nearly 1.5 times on average. Time series of the number concentrations of dust particles during the periods from April to August in 2005 are shown in Fig. 2. The high number concentration of dust particles (including those smaller than 1 μm, larger than 1 and 0.57–100 μm) was sometimes seen during April and May, for example, 25 April and 30 May (439 × 10^3 ml^{-1}), which is much more than the average value for the measured time period (241 × 10^3 ml^{-1}) (Fig. 2). The increase in the particle number was due to Asian dust events, which usually occur in the spring. The wind speed in the Urumqi river source is also much higher during the Asian dust period (April–June) than in the non-dust period (July–August), especially with very high wind speed in 27–28

Table 1 The blank value for major ions of the whirlpack bags in the laboratory analysis (μg kg^{-1})

	Na^+	Ca^{2+}	Mg^{2+}	Cl^-
Blank value	0.5223	1.6984	0.0968	1.5826
Standard deviation	0.1408	0.4578	0.0261	0.4265

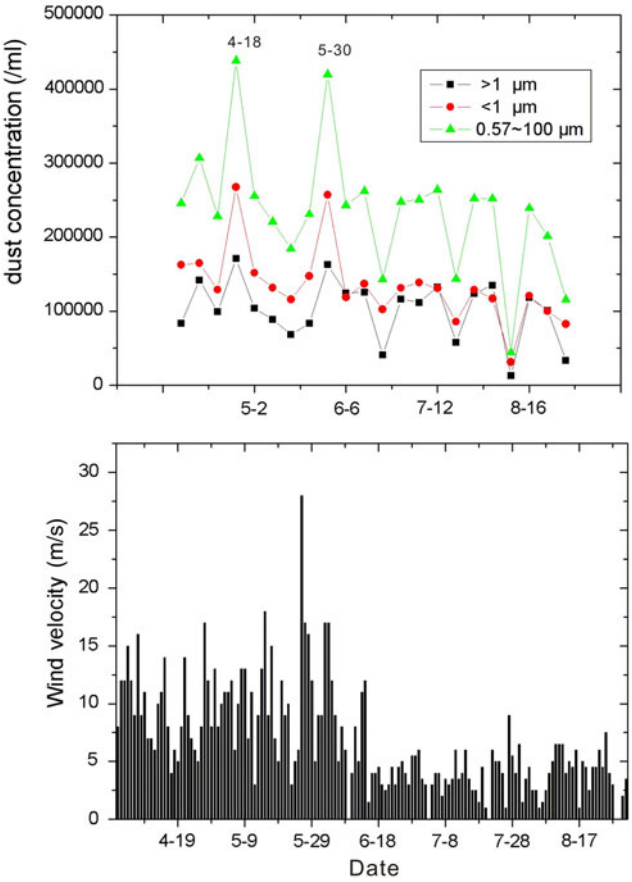

Fig. 2 Variation of dust particle concentrations in surface snow and wind speed in April–August 2005

May, which coincides with a high dust concentration at the same time (Fig. 2). Similar phenomena, high concentrations of aerosol dust during Asian dust events, have been observed in parts of the Eastern Asian and Northwestern Pacific rim (Chun et al. 2001; Uematsu et al. 1983; Watanabe et al. 2006). The concentrations of dust particles, both finer and coarse, were relatively low in summer (Fig. 2). Low finer particle (smaller than 1 um) and low coarse particle (larger than 1 um) events were frequently observed in July and August in the Asian Pacific regions. In 2005, the summer (July–August) was cool with frequent rainfall in the Urumqi River Source region in central Asian. As a result, the atmospheric aerosol dust could have been washed out, and the photo-chemistry might have been suppressed. The concentrations of particles were relatively large and stable in April and May when clear days continued.

Asian dust storm phenomena were observed in the western and northern parts of China on 18 April and 27–28 May in 2005. Examples of a 3-day backward trajectory on 18 April (left panel) and 28 May (right panel) are illustrated in Fig. 3. The backward trajectory analysis shows that the air mass in Urumqi glacier no. 1 originated from

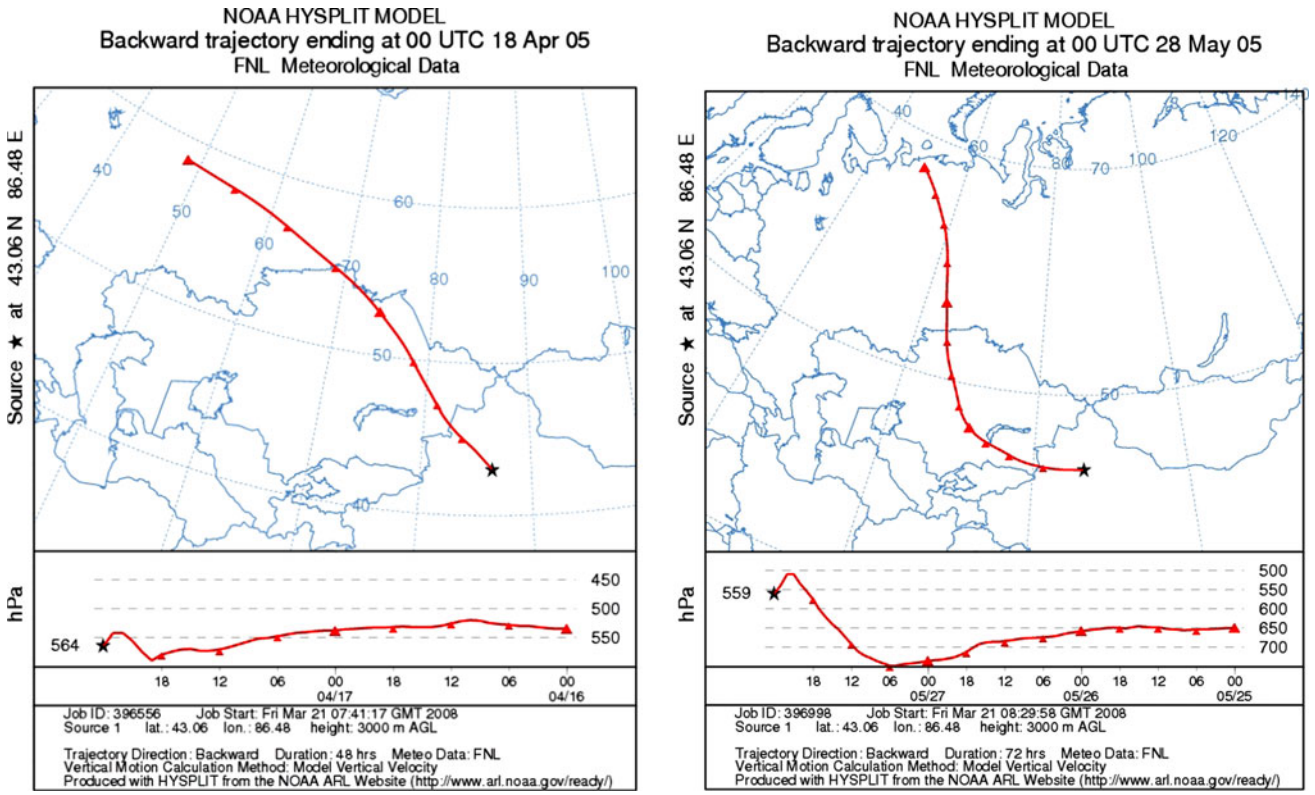

Fig. 3 Typical results of 3-day backward trajectory analysis on 18 April and 28 May in 2005

the arid regions northwest of central Asia, for example, the Sary-Ishikotraui Desert and Muyunkum Desert. The dust concentration of snow samples before 18 April was low (Fig. 2), but in the next sample on 25 April, the number concentration was very high, which indicates that the Asian dust event in central Asian brings particles with high concentrations to be deposited in the fresh snow in Urumqi glacier no. 1 in eastern Tian Shan. Then the concentration gradually reduced, like in the snow sample from 2 May because of rainfall washing out. The next dust events in 27–28 May caused the dust particle concentration to increase significantly again, as shown in Fig. 2, and after some time, the concentration reduced again as the precipitation increased in the summer period (July and August). In this study, the finer particles and the coarse particles have the same change as the seasonal change from April to August, because this region is mainly dominated by the central Asian dust activity rather than human activities. This is different from the research results in Toyama, Japan, in eastern Asia, where the finer particle concentration decreased in the dust period as the wind speed increased. Research in eastern Asia showed that the finer particles contain primary particles from combustion sources and secondary materials such as sulfate, nitrate and ammonium (Seinfeld and Pandis 1998). Similar phenomena during Asian dust events were also observed in Toyama in April 2002 (In and Park 2003). Air quality in the city of Toyama seems to be more polluted than that of the Urumqi river source located in a alpine area. According to the backward trajectory analysis, the air sampled in Toyama had been transported passing through the polluted regions in the Asian continent. Not only mineral dust, but also air pollution might have been transported. However, the Urumqi alpine snow is more sensitive to the Asian dust events than that of the eastern Asian region.

Size distribution of dust particles

Size distribution of dust particles deposited in fresh snow in alpine glaciers can reflect the wind conditions and dust storm activities in the central Asian dust source region. Mass-size distribution of aerosol dust is also affected by the local atmospheric environment. Some previous research on snow and ice has indicated that dust volume-size and mass-size distribution always includes a single model structure and bi-model structure (Osada et al. 2004; Zdanowicz et al. 1998). The single model structure may show the dust origination is simple, while bi-model particle structure indicates a complicated dust origination.

Figure 4 shows the variation process of dust mass-size distribution during the Asian dust period and non-dust

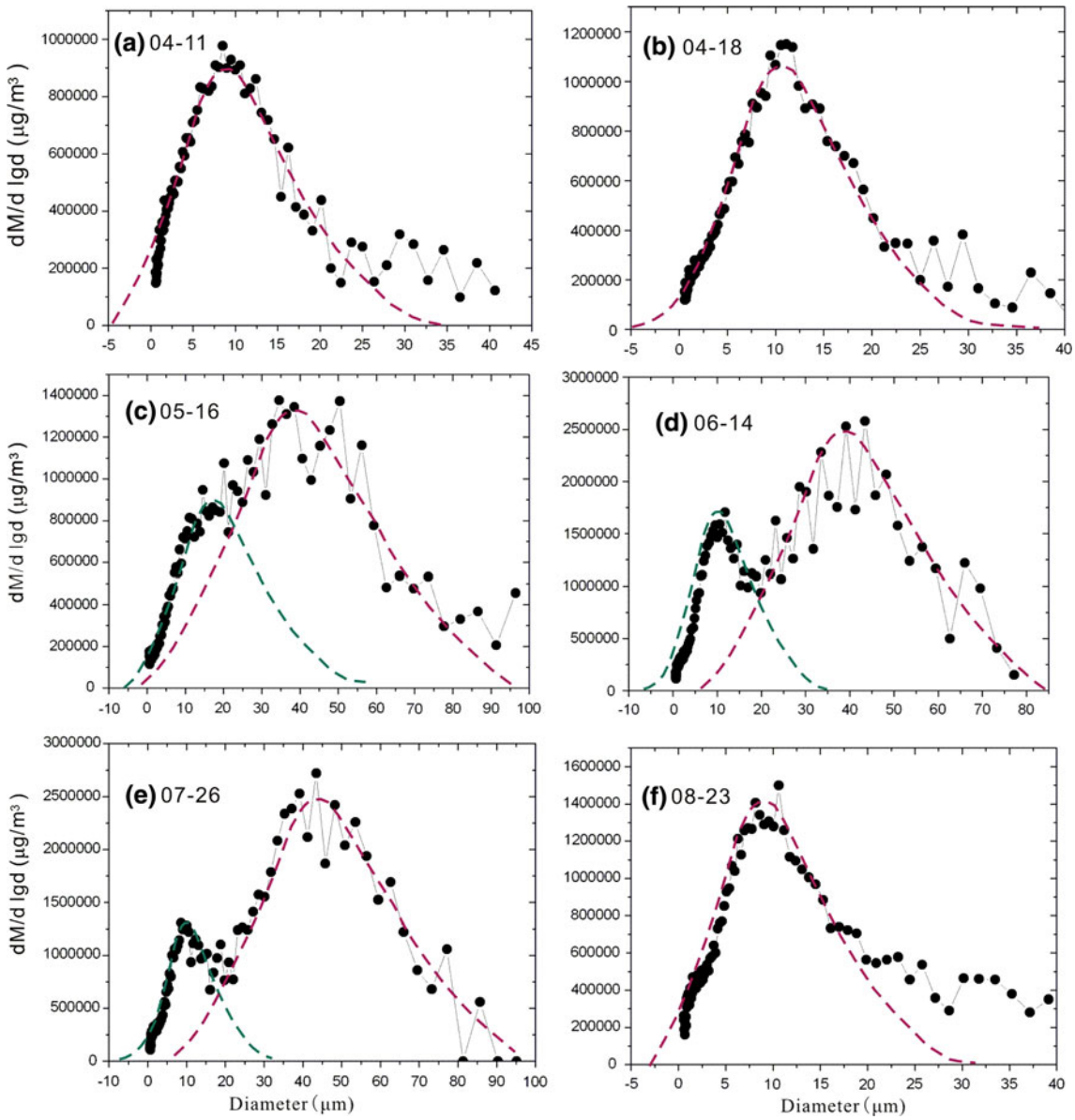

Fig. 4 Seasonal variations of dust particle mass-size distribution in snow

period from April to August in the fresh surface snow on Urumqi glacier no. 1. The size distribution of dust particles was composed by two models in the samples during the measured periods. One part is the particles that are mainly distributed in the diameter range of 3–21 μm with a mass median diameter of 10 μm (the relatively finer part), which is the normal aerosol dust particle size distribution for a dust source region in central Asia. Another part is the particles distributed between 20 and 80 μm with a mass median diameter of 40 μm (relatively coarser part), which is only caused by the strong dust activities in the Asian dust period (Fig. 4). Some season mass-size distribution is a single model composed by one part, and sometimes it is a bi-model composed by both parts.

There is an obvious seasonal change for mass-size distribution as shown in the Fig. 4. In the snow samples of 11 and 18 April (Fig. 4a, b), the particle size is mainly distributed in the diameter range of 3–21 μm, which is from the basic aerosol dust in normal atmospheric conditions. This is the size distribution before dust events, and the distribution is a single model only with finer parts. The sample from 16 May, which is the sample collected after Asian dust events, showed a bi-model having mass median diameters from both 3 to 21 and 20 to 80 μm (Fig. 4c). In the samples of June and July (Fig. 4d, e), the distributions are more obviously composed by the two parts, including the median diameters from 3 to 21 μm (relatively finer part) and 20 to 80 μm (relatively coarse part). Until the

samples in late July and August (Fig. 4f), which are from summer with many rainfalls and with disappeared dust events, the size distribution in the fresh snow is finally back to a single model again having mass median diameters from 3 to 21 μm, without the coarser part (20–80 μm), which is similar to that of 11 April before the dust events happened. Such an obvious seasonal change of dust particle size distribution indicates that the alpine fresh snow and atmospheric environment in central Asian are tightly correlated, and the effect of Asian dust events on the aerosol dust deposited in the snow is significant.

Figure 5 shows the comparison of the finer part (3–21 μm) of dust particle size distribution in Fig. 4 from April to August in 2005. Although the median diameters are all about 10 μm in the compared samples, the mass of median diameter has significantly changed in curves 4a-4d-4e-4f, within which the curve 4d (14 June) has the largest mass, which is caused by the high dust concentration during the dust events. The dust mass decreased in July and August 2005 (curve 4e and 4f) as the rainfall increased in the summer.

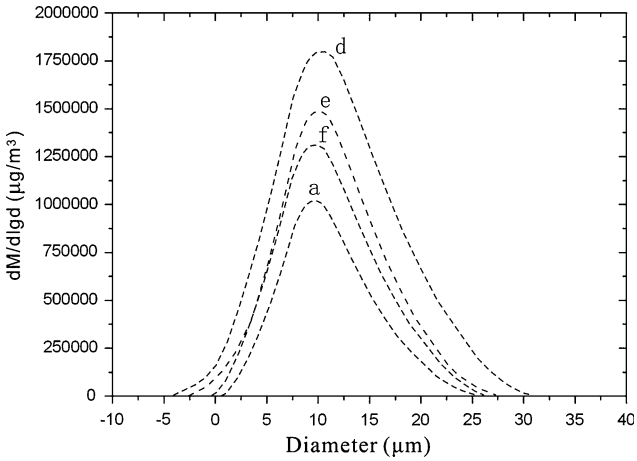

Fig. 5 Comparison of mass-size distribution of dust particles in Fig. 4

Ionic constituents of dust particles

Figure 6 shows the concentration variation of ionic constituents of dust particles in April–August in fresh snow on Urumqi glacier no. 1 in central Asian. The concentration of particulate Ca^{2+}, Na^{+}, Cl^{-} and SO_4^{2-} shows very significant seasonal change between the Asian dust period and non-dust period, which is very coincidental with dust particle concentration change, having a very high ion concentration in the Asian dust term of April–June but a low concentration in the non-dust term of July–August in summer. Particulate Ca^{2+}, which is mostly present in the coarse particles, was significantly high in April–May. The concentration changes of particulate NH_4^{+} and SO_4^{2-}, as water-soluble constituents, are different from each other, as NH_4^{+} and K^{+} concentrations are rarely changed comparing the Asian dust period with the non-dust period (Fig. 6).

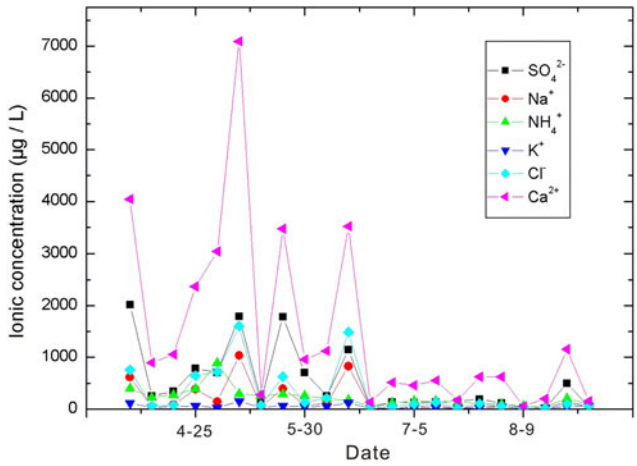

Fig. 6 Ionic concentration variation of dust in surface snow during April–August in 2005

Table 2 shows the correlation coefficients of ions in the surface snow during the dust period. The species have good correlation coefficients (Li et al. 2006). Research has shown that Ca^{2+} is mostly present in coarse particles, with high concentrations in spring in the atmosphere of the Asian region, which is always caused by dust events. Sulfate is generated as H_2SO_4 particles by the homogeneous and heterogeneous (oxidation of SO_2 aqueous phase in cloud processes) processes, followed by the transition to $(NH_4)_2SO_4$ through a reaction with NH_3. These processes produce fine-mode particles (e.g., Seinfeld and Pandis 1998). The equivalent ratio of SO_4^{2-}/NH_4^{+} in the accumulation mode was about 1. The chemical composition of the soluble part of the finer particles might have been close to that of $(NH_4)_2SO_4$. Particulate Na^{+} was similar to Ca^{2+} (most Na^{+} existed in coarse particles), and there was a significant difference between the Na^{+} concentration in April–May and that in the other months.

Figure 7 is the backward trajectory analysis to examine the transport processes of the air mass in Urumqi glacier no. 1, including the vertical motion mode. The start height of the trajectory was set at 4,130 m above sea level. The air mass in Urumqi mainly originates from the northwest region of central Asia in spring in April–May, which may bring plenty of dust particles from the arid regions such as Kazakstan. On the other hand, most of the air mass mainly originated from the southwest region of the Asian continent in summer (June–August), which may bring the precipitation from the Indian Ocean, affecting the chemical compositions and ionic characteristics of dust particles. Such a difference of air mass transport may significantly affect the transport and deposition of dust particles in the snow at the Urumqi river source.

Table 2 Correlation coefficient of ions in the surface snow during dust period

	Ca^{2+}	Na^{+}	SO_4^{2-}	NH_4^{+}
Ca^{2+}	–			
Na^{+}	0.89	–		
SO_4^{2-}	0.65	0.72	–	
NH_4^{+}	0.54	0.65	0.67	–

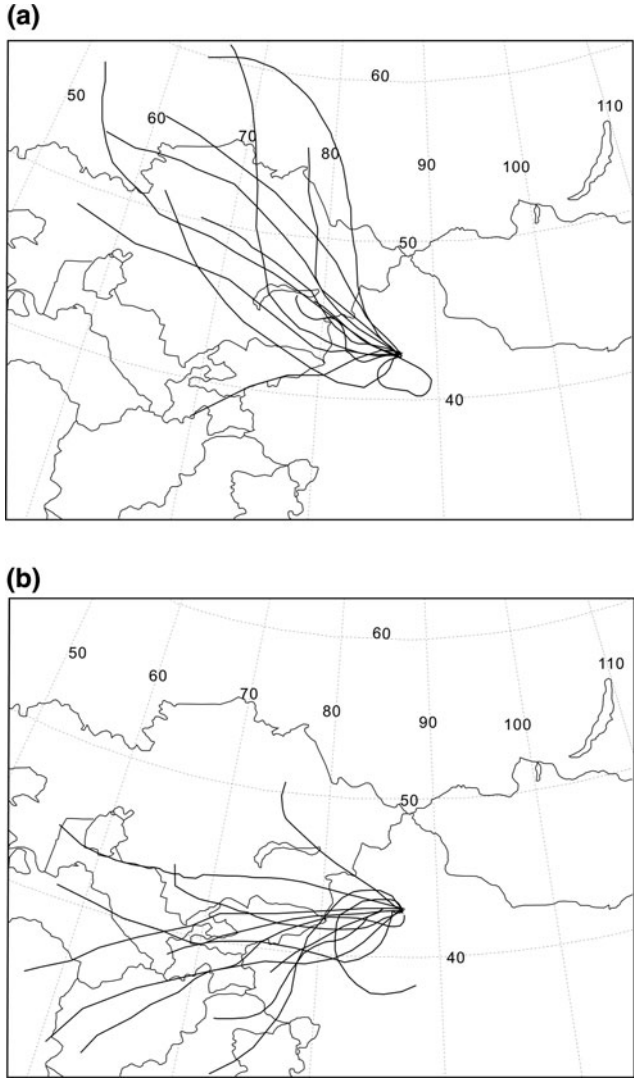

Fig. 7 Composite plots of 3-day backward air trajectories from the observation site in April–May (**a**) and July–August (**b**) in 2005

Summary

Windblown mineral aerosol dust derived from the crustal surface is an important atmospheric component affecting the earth's radiation budget. Deposition of atmospheric dust was measured in the fresh snow on glacier no. 1 at the headwatesr of the Urumqi River in eastern Tian Shan, central Asia. An analysis of seasonal changes in concentrations of dust particles in the snow cover suggests that the number concentration of dust particles is significantly high from April to June (439×10^3 ml^{-1}), which may be caused by Asian dust storms in spring. The comparison of mass-size distribution of dust particles between April and August shows an obvious change trend. The distribution of particles changes from a single model (3–21 μm) in the non-dust period before April, to a bio-model (3–21 and 20–80 μm) during the Asian dust period and to a single model (3–21 μm) after June in the non-dust period again. Ca^{2+} concentration in the fresh snow is also very high from April to June, while the concentration changes of NH_4^{+} and SO_4^{2-}, as water-soluble constituents, are different from each other. Backward trajectory was also employed to examine the transport process of the air mass in this region. The air mass in Urumqi mainly originated from the northwest region of central Asian in April–May in spring. On the other hand, most of the air mass originated from the southwest region of the Asian continent in summer, which may have brought precipitation from the Indian Ocean. Such a difference of air mass transport may significantly affect the transport and deposition of dust particles in the snow at the source of the Urumqi river.

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