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Characteristics of Atmospheric Dust Deposition in Snow on Glacier No. 72, Mount Tuomuer, China

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Abstract

Wind-blown mineral dust derived from the crustal surface is an important atmospheric component affecting the Earth's radiation budget. Deposition of dust particles was measured in snow on Glacier No. 72, Mount Tuomuer, in the western Tian Shan, China. The mean concentration of dust particles (measured as the number of particles) with $0.57 < d < 26$ μm in the snow pack is 706×10^3 mL^{-1}, with a mean mass concentration of 3806 μg kg^{-1}. Dust number size distribution showed the dominant particles with $d < 2$ μm, while volume size distribution showed single-modal structures having volume median diameters from 3 to 25? μm. Results were compared with data from other sites in the Tian Shan and various Northern Hemisphere sites. A backward trajectory model was also employed to examine the transport process of dust particles in this region. Most of the air mass originated from southern China, e.g., the Taklimakan Deserts in springtime, during the Asian dust period. Transport of dust from southern Chinese deserts to adjacent mountains is in agreement with a growing body of evidence on the importance of dust inputs to alpine regions.

Introduction

Wind-blown mineral dust derived from the Earth's surface is an important atmospheric component (Osada et al., 2004) affecting the planetary radiation budget (e.g., Nakajima et al., 1989; Andreae, 1995; Tegen and Lacis, 1996; Gao et al., 1992; Hinkley, 1994; John and Mitsuo, 1989). Mineral aerosol dust is an important indicator of changes in the atmosphere associated with changes in temperature, precipitation, and atmospheric circulation. Ice core records show that high dust concentrations correspond to cold and dry climate conditions of glacial periods, while low dust concentration corresponds to warm and wet conditions of interglacial periods (Thompson and Wayne, 1975; Thompson and Thompson, 1980, 1981; Thompson et al., 1989, 1998; Wake et al., 1994; Aizen et al., 1996; Kahl et al., 1997; Zdanowicz et al., 1998; Liu, C., et al., 1999; Ruth et al., 2003). Aerosol dust information can be recorded in the snow and ice of high mountains and in polar regions. Much research has been carried out concerning dust records in ice cores to understand climate change in ancient times (e.g., Thompson and Wayne, 1975; Thompson and Thompson, 1980, 1981; Thompson et al., 1989, 1998). Other research has measured dust deposition in recent snow to understand recent climate and environmental conditions (Wake et al., 1994; Zdanowicz et al., 1998; Osada et al., 2004). Atmospheric transport and transformation processes (Merrill et al., 1989; Uno et al., 2001) of the dust particles have also been studied to characterize the geochemical role of eolian dust events in Asia. These dust events have been observed frequently in spring over Asia and the western Pacific Ocean (Koizumi, 1932; Arao et al., 2003) because of the strengthened wind speed in springtime.

The Tian Shan, western China, is a large mountain range located in an arid and semi-arid region of central Asia, the source region of Asian dust (Fig. 1). Dust storms are an important phenomenon in this region (e.g., Wake et al., 1994; Aizen et al., 1996, 2004; Kreutz et al., 2001; Dong et al., 2010). Aerosol dust particles deposited in the snow of high mountain glaciers contain information on the atmospheric environment at high elevation, and may be an important indicator of global climate change, as dust concentration and size distribution are different under various climatic conditions. It is thus important to study the characteristics of dust deposition in the Tian Shan (Wake et al., 1994). Chemical analyses and meteorological correlation suggest that the dusty layers found in the snow cover of the Tian Shan form by deposition of Asian dust-storm particles (Dong et al., 2009a, 2009b). However, the processes of formation of the dust layers and characteristics of the dust particles in the snow cover on the glaciers of Tuomuer region in the western Tian Shan remain unclear. Furthermore, the amount of dust deposited close to the snow-forming cloud altitude may provide a useful insight into the free-tropospheric fraction of dust deposition over the central Asian region. Glacier No. 72 is located on Mount Tuomuer in the western Tian Shan, China, and is representative of many other glaciers on Mount Tuomuer. Moreover, few other glaciers have the ease of access that Glacier No. 72 has. Finally, little research has been carried out on snow chemistry and dust deposition on the snow and glaciers in this region. We analyzed the concentration, flux, size distribution, and ionic constituents of aerosol dust in the snow pack on Glacier No. 72, Mount Tuomuer. Backward trajectory analysis was also employed to examine the transport process of dust particles in this region. In addition, previous research at other sites of the eastern Tian Shan, e.g., Glacier No. 51 in Kuitun Haxilegen, Glacier No. 1 at the headwaters of Urumqi River, and Miaoergou Glacier in Hami (Dong et al., 2009a), were also compared in this work to show regional difference of atmospheric dust deposition in the Tian Shan.

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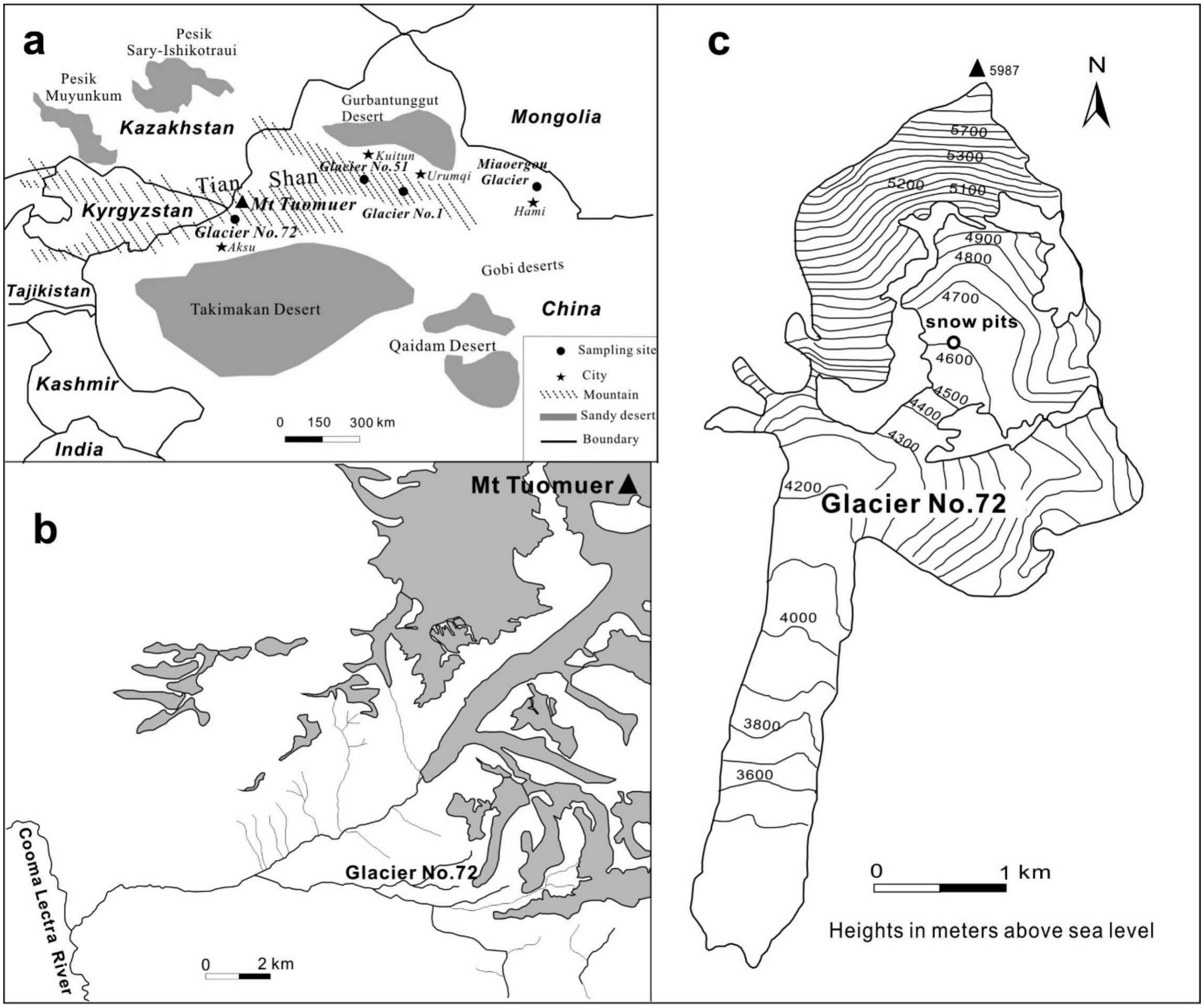

FIGURE 1. (a) Location map of the Glacier No.72 (41°45′~46′N, 79°52′~53′E) in the Tian Shan, central Asia; (b) glaciers of the south part of the Mount Tuomuer; (c) location of snow pits at Glacier No. 72, August 2008.

Material and Methods

Figure 1 shows a location map of the Tian Shan and the sampling sites, Glacier No. 72 (41°45′~46′N, 79°52′~53′E), Mount Tuomuer, western Tian Shan, in the Aksu area of Xinjiang Province, China. The shaded areas in Figure 1 represent the sandy deserts and Gobi (rocky) deserts in central Asia. In August 2008, 2 snowpits with depths of 4.25 m were excavated at the accumulation zone at an altitude of 4600 m a.s.l. on Glacier No. 72 (Fig. 2). The snow deposition environment around the sampling site is suitable for continuous snow accumulation because there is a nearly flat area of about 100 × 100 m^2, leading to uniform snow deposition. We sampled snow by depth after recording snow stratigraphy, and clean, fresh vertical sections were exposed for dust and snow chemical sampling. We collected snow samples, typically 100 g, in 10 cm increments using a pre-cleaned stainless steel shovel and polyethylene gloves; altogether, 85 samples were collected. The sampling instruments were cleaned between intervals. Samples were stored in Whirl-Pak bags and kept frozen until further analysis. Snow density, snow temperature, and snow grain size were measured in the same horizontal layers. 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 analysis.

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 orifice (Zhu et al., 2006; Dong et al., 2009a; Li et al., 2006a). Measurements were performed under class 100 conditions 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 to 400 μm (micrometers) equivalent spherical diameter (*d*). Routine analysis of filtered deionized water blanks showed background counts to be on average 10 times lower than in samples, but background counts were subtracted from the sample data. 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.

The mass and volume size distribution 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 (Wake et al., 1994; Zdanowicz et al., 1998). Mass was

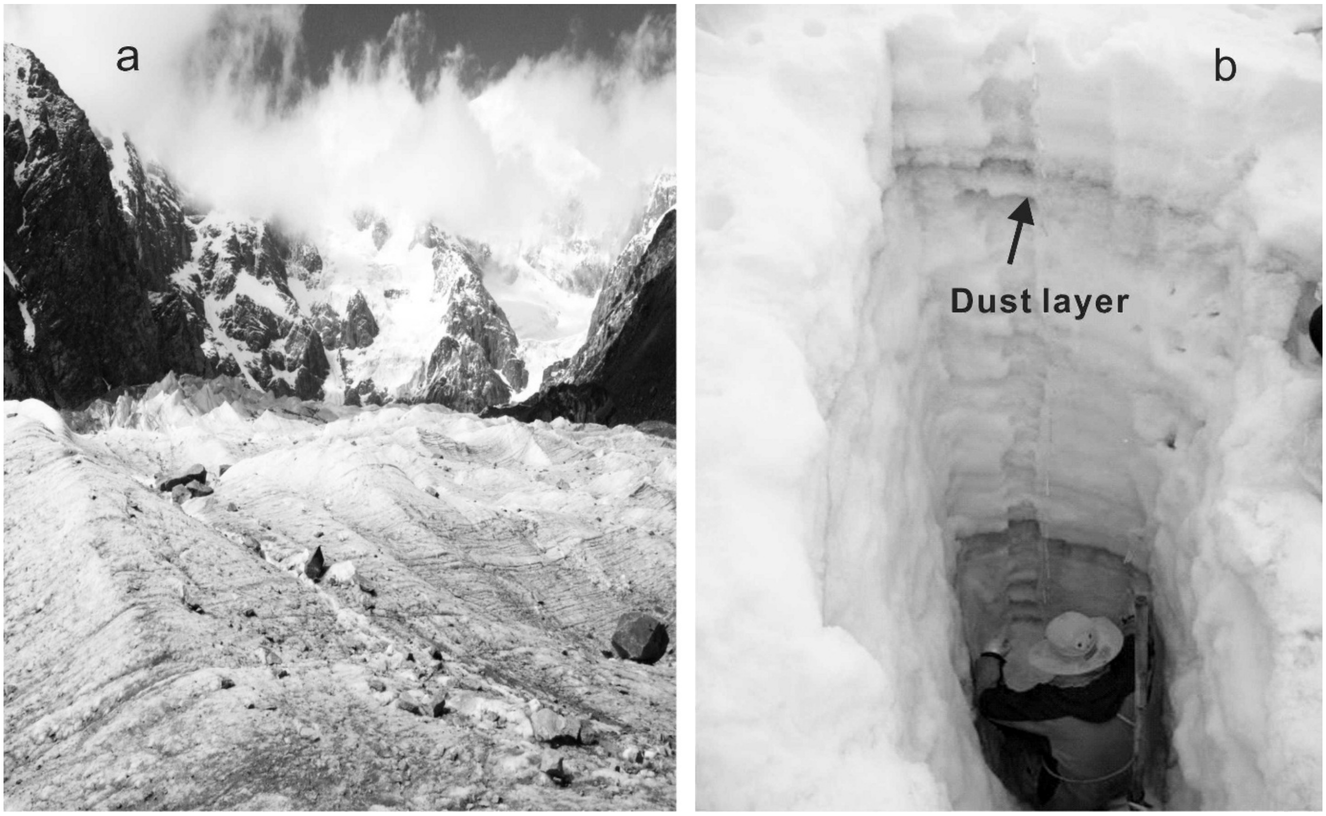

FIGURE 2. The photographs showing (a) the Glacier No. 72 in Mount Tuomuer, and (b) the snow pit for sampling.

derived by integrating the mass size distribution over the measured diameter range and normalizing the result to the sample volume. We also computed the slope, β, of the log-linear Junge distribution,

$$\frac{dV}{d\ln d} = \frac{V}{\sqrt{2\pi}\ln\sigma_g}\exp\left[-\frac{\ln^2(d/dv)}{2\ln^2\sigma_g}\right], \quad (1)$$

fitted to particles with d less than 26 μm (Junge, 1963; Wake et al., 1994; Steffensen, 1997). The number of particles larger than 26 μm is very low, and many of the snow samples contain only a few such particles. These coarser particles make a negligibly small contribution to the total mass deposition.

In addition to micro-particles, the concentrations of major ions (Na^+, Mg^{2+}, Ca^{2+}, Cl^-) were measured at trace levels on a Dionex-600 ion chromatograph using the procedure described by Buck et al. (1992). The blank value for major ions is shown in Table 1(μg kg^{-1}). The mean blank value for the Whirl-Pak bags for dust particles number is 444 mL^{-1} in the laboratory measurements of this work. These blank values were subtracted from the sample data.

Trajectory Analysis

Back-trajectory analysis has been applied widely in the field of atmospheric and glaciological sciences (Kahl et al., 1997; Raben et al., 2000; Theakstone, 2008). The Hybrid Single-Particle Lagrangian Integrated Trajectory model, HYSPLIT4 (Air Resources Laboratory, U.S. National Oceanic and Atmospheric Administration (NOAA), http://www.arl.noaa.gov/ready/hysplit4.html), which has been used to model air-mass trajectories elsewhere (Falkovich et al., 2001; Marenco, 2006), was used to compute back-trajectories to Glacier No. 72 on Mount Tuomuer using NOAA/U.S. National Centers for Environmental Prediction (NCEP) reanalysis meteorological data. Back trajectories up to an altitude of 4600 m for 5 days with a daily resolution were adopted to simulate the routes of air masses arriving at the sampling site at 1200 h Beijing time (0000UTC) during dust storm events in the Tuomuer region.

TABLE 1

The blank value for major ions of the Whirl Pak bags in the lab 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

Results and Discussion

NUMBER AND MASS CONCENTRATION OF MINERAL DUST PARTICLES IN THE SNOW

Previous research shows that if the deposition of snow is continuous, i.e., without redistribution of snow, atmospheric signals such as mineral dust deposition should be preserved in sequence in the snow layers (Osada et al., 2004). In this study, the environment is favorable for continuous snow deposition, as the terrain is flat at the sampling site and annual wind speed around the sampling site is low. The average wind speed was 5.6 m s^{-1} during August 2008 to August 2009, observed by the automated weather station nearby. The snow depth at the sampling site on Glacier No. 72 is about 425 cm, and this depth is approximately the ice surface of the glacier. Previous observations show that the average snow accumulation rate is about 200 cm a^{-1} (Li et al., 2010). The Tian Shan region is

TABLE 2

Concentration of dust number and mass in the typical snow pit samples of Glacier No.72.

Sample	Depth (cm)	Number (mL^{-1})	Mass ($\mu g\ kg^{-1}$)
08-6401	0~5	76,165	500
08-6402	5~15	78,294	345
08-6403	15~25	45,101	103
08-6404	25~35	57,842	761
08-6405	35~45	91,130	1338
08-6406	45~55	122,171	3495
08-6407	55~65	45,282	500
08-6408	65~75	142,276	498
08-6409	75~85	205,133	545
08-6410	85~95	87,134	226
08-6426	95~105	87,134	337
08-6427	105~115	200,727	337
08-6428	115~125	200,727	3367
08-6429	125~135	22,230	90
08-6430	135~145	54,085	158
08-6431	145~155	35,189	182
08-6432	155~165	35,189	182
08-6433	165~175	46,985	247
08-6434	175~185	50,564	201
08-6435	185~195	400,418	7626
08-6441	195~205	47,456	651
08-6442	205~215	325,754	3236
08-6443	215~225	439,951	3915
08-6444	225~235	239,422	1545
08-6445	235~245	522,243	11237
08-6451	245~255	235,031	1516
08-6452	255~265	144,734	1394
08-6453	265~275	212,761	2316
08-6454	275~285	413,769	9669
08-6455	285~295	3,083,174	31588
08-6456	295~305	893,298	6740
08-6457	305~315	530,316	2066
08-6458	315~325	454,312	1390
08-6459	325~335	2,303,048	6419
08-6460	335~345	492,113	1611
08-6461	345~355	3,544,324	10353
08-6462	355~365	757,181	1608
08-6463	365~375	1,279,681	5092
08-6464	375~385	385,175	1699
08-6465	385~395	3,890,447	11101
08-6466	395~405	904,406	4854
08-6467	405~415	6,999,254	21904
08-6468	415~425	175,526	713
Mean	**0~425**	**705,980**	**3806**

mainly affected by westerly winds in spring and summer, bringing plentiful precipitation from the Atlantic Ocean and also moisture from lakes and seas in central Asia and other regions to the west of the study area, such as the Mediterranean and Caspian Seas (Aizen et al., 1996, 2004). Precipitation decreases gradually from the west to the east on the glaciers of the Tian Shan. For example, precipitation on the glacier accumulation zone is 600 mm, 500 mm, and 250 mm, respectively, from the Kuitun region to the Urumqi river source and the eastern Hami glaciers (Dong et al., 2009a). Based on the dust layers and seasonal variation of chemical constituents, the snow pit on Glacier No. 72 reflects the deposition of snow in 2007–2008. Table 2 shows the number and mass concentration of dust particles in the snow pack. The maximum dust concentration (measured as number of particles per milliliter or mL) is 6999×10^3 mL^{-1}, while the minimum is 22×10^3 mL^{-1}, with an average of 706×10^3 mL^{-1}. For dust mass concentration, the maximum is 31,588 $\mu g\ kg^{-1}$, while the minimum is 90 $\mu g\ kg^{-1}$, with an average of 3806 $\mu g\ kg^{-1}$. Based on the net annual snow accumulation rate of 2000 mm, we derived an average value for the modern eolian dust flux to Glacier No. 72 of 761.2 $\mu g\ cm^{-2}\ a^{-1}$ for particles with $0.57 < d < 26$ µm.

To determine how representative the dust deposition on Glacier No. 72 in Mount Tuomuer is of regional to hemispheric atmospheric fallout, we compared the mean dust concentration and flux with similar measurements from remote polar and non-polar sites (Table 3). The mean concentration of micro-particles with $0.57 < d < 26$ µm in snow cover on the Glacier No. 72 is 706×10^3 mL^{-1} with an average mass concentration of 3806 $\mu g\ kg^{-1}$, comparable to that measured on Urumqi Glacier No. 1, Haxilegen Glacier No. 51, and Hami Miaoergou Glacier in the Tian Shan, and the Mustagh Ata and Chongce ice caps, China (Table 3). Nevertheless, dust on Tuomuer Glacier No. 72, Mustagh Ata, and the Chongce ice cap shows greater mass concentrations and flux than at other sites in Asia. These glaciers with higher dust concentrations are situated near the Taklimakan desert of central Asia and have dust deposition rates in excess of 200 $\mu g\ cm^{-2}\ a^{-1}$ (Wake et al., 1994). These sites also have a coarser mode of dust measured in snow. However, Table 3 shows the depositional flux of dust differs from that observed at various remote sites throughout the northern hemisphere. Because of long-range transport, the flux of atmospheric particle deposition is very low at some remote sites (e.g., the Canadian Arctic, where the dust concentration in snow is about 135~243 $\mu g\ kg^{-1}$ and flux is about 4.2~4.8 $\mu g\ cm^{-2}\ a^{-1}$ (Fisher and Koerner, 1981; Zdanowicz et al., 1998). Glacier No. 72 on Mount Tuomuer is close to the dust sources in central Asia, so both the concentration and flux of atmospheric dust deposition are high. This suggests that the dust deposition on the snowpack in Mount Tuomuer is representative of the background crustal aerosol close to a source region.

CHARACTERISTICS OF DUST IN SNOW: IONIC CONSTITUENTS AND SIZE DISTRIBUTION

Figure 3 shows the relationship between ionic concentrations, electrical conductivity (EC) and dust concentration obtained in summer 2008 at the snow pit on Glacier No. 72. The dusty layers correspond very well to high concentrations of Ca^{2+}, Na^{+}, and pH and EC in the profiles. There are good correlations between ions and dust in the snow cover of Glacier No. 72, and similar to results obtained at Urumqi Glacier No. 1, Miaoergou Glacier, and Glacier No. 51 (Dong et al., 2009a) (Table 4). In Table 4, the value of dust is represented by the mass concentration of microparticles. We have found that generally mean particle diameter and dust concentration are positively correlated, and dust concentrations and concentrations of major ions in solution are also positively correlated (Table 4). Previous research at Urumqi Glacier No. 1 has shown that the peak dust concentration corresponds very well to peak concentrations of Cl^{-}, Mg^{2+}, Ca^{2+}, and Na^{+} during the sample period (Li et al., 2006b), indicating that these ions may have the same source as the dust particles. Vertical profiles of dust concentrations are similar to variations in Ca^{2+} concentration. Depth intervals with high dust concentrations found in snow of Mount Tuomuer are inferred to have originated mainly in arid regions of central Asia, because high Ca^{2+} is a tracer of mineral dusts from desert and loess areas in Asia (Ichikuni,

TABLE 3

Atmospheric dust concentration and flux in snow and ice in various northern hemisphere sites.

Study sites	Elevation (m)	Years	Concentration and flux				Ref.
			Size range	Number	Mass	Flux (μg cm^{-2} a^{-1})	
Tuomuer Glacier No.72 (Tian Shan, China)	4600	2007–2008	0.57~26	706	3806	761	This work
			1~26	384	1678		
Urumqi Glacier No.1 (Tian Shan, China)	4130	2002~2005	0.57~26	242	1442	72.1	Dong et al. (2009a)
			1~26	100	666		
Haxilegen Glacier No.51 (Tian Shan, China)	3900	2002~2005	0.57~26	166	969	58.2	Dong et al. (2009a)
			1~26	74	436		
Hami Miaoergou Glacier (Tian Shan, China)	4510	2002~2005	0.57~26	222	3690	73.8	Dong et al. (2009a)
			1~26	94	1016		
Chongce Ice Cap (China)	6327	1980–1987	1~22	616	8220	607	Wake et al. (1994)
Mustagh Ata (China)	5910	1990–1992	1~22	276.4	6780	247	Wake et al. (1994)
Ngazompa glacier (Nepal)	5700	1989–90	1~13	18.17	379	27	Wake et al. (1994)
Tateyama (Japan)	2450	1997~2002	0.1~600			770	Osada et al. (2004)
Penny Ice Cap (Canadian Arctic)	1980	1988–1994	0.65~12	31.6	143	4.8	Zdanowicz et al. (1998)
			1~12	13.7	129	4.4	
Devon Ice Cap (Canadian Arctic)	1800	Last 7000 yr	>1	8.3	235	4.2	Fisher and Koerner (1981)

1978; Suzuki and Tsunogai, 1988). Most Na^+ in the snow originates from a source of salt-rich minerals, most likely the salt lakes in central Asia (Xinjiang), based on the significant correlation with Cl^- and Mg^{2+} concentrations (Li et al., 2006b). The Cl^-/Na^+ ratios in the snow samples of our research sites range from 0.91 to 2.76, with a mean value of 1.56, much larger than 1.165 of sea salt. The increase may be caused by the salt-rich minerals of Asian dust and salt lakes, as the Cl^-/Na^+ ratio in the salt lakes is high, with a mean value of 1.86 in the Qaidam basin (Liu, W., et al., 1999). There are many such salt sources in the Xinjiang region, and some of the Cl^- may come from KCl, the mineral sylvite, which may have originated from dust in the source basins. Research on Tateyama Mountain, in central Japan, indicates that Na^+ concentrations in the snow did not correlate well with dust, because the Na^+ originates from the Sea of Japan (Osada et al., 2004). Our results, taken together with measurements of ion deposition in the snow of Mount Tuomuer, suggest that the dust particles are from the central Asian desert dust sources around this region such as the Taklimakan and Gobi Deserts.

Figures 4 and 5 show the size distributions of dust particles in the snowpack. Figure 4 is the size distribution of dust particles in the snow of Glacier No. 72 (mean of 85 snow samples) (Fig. 4, a), and a comparison with other research sites in the Tian Shan (Fig. 4, b). Fewer fine micro-particles were found in Glacier No. 72, which may imply more coarse particles found in the glaciers of the Tuomuer region, as the total concentration in the snow of Glacier No. 72 is higher than that of other sites. Figure 5 is a volume-size distribution of dust particles of Glacier No. 72 (Fig. 5, a) and a comparison with other research sites in Tian Shan

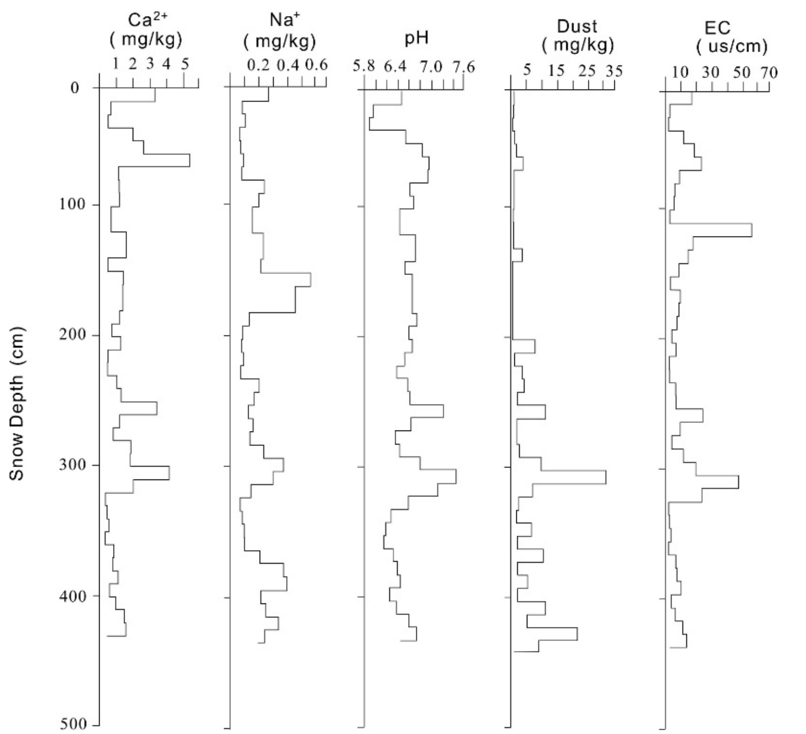

FIGURE 3. Vertical profiles of ionic concentrations, dust concentration, and conductivity on Glacier No. 72.

TABLE 4

Correlation coefficient of ions and dust in the snow in various sites of the Tian Shan.

Dust mass	Ca^{2+}	Na^{+}	Mg^{2+}	Cl^{-}	Reference
Glacier No.72 snow pits	0.78	0.62	0.85	0.69	This work
Glacier No.1 surface snow	0.85	0.63	0.74	0.62	Li et al. (2006)
Glacier No.1 snow pits	0.69	0.65	0.82	0.58	Dong et al. (2009a)
Glacier No.51 snow pits	0.60	0.62	0.53	0.53	Dong et al. (2009a)
Glacier Miaoergou snow pits	0.51	0.49	0.57	0.46	Dong et al. (2009a)

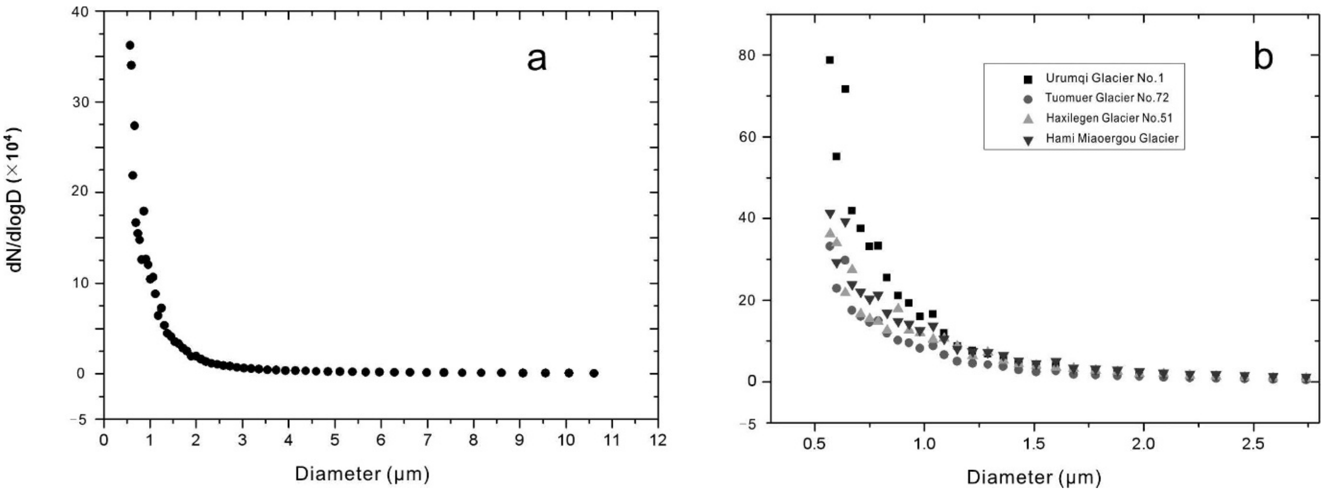

FIGURE 4. (a) Number-size disribution of dust particles in the snow of Glacier No. 72; (b) comparison of number-size disribution of dust particles in the snow of Glacier No. 72 with other sites in the Tian Shan.

(Fig. 5, b), in which the peak value of the curve is the modal size (μm) of the dust particles. Table 5 shows the parameters of volume size distribution of dust particles in various sites shown in Figure 5, part b. The volume median diameters of the dust particles in Glacier No. 72 of Tuomuer mountain range from 3 to 25 μm, but the distribution of volume size shows a single mode. The modal size of the volume size distribution at Miaoergou Glacier is 13 μm, that at Glacier No. 72 is 12 μm, that at Glacier No. 1 is 11.5 μm, and that at Glacier No. 51 is 11.0 μm (Table 5). The atmospheric environment around the four sites in eastern Tian Shan shows regional differences because of the long distance between them (e.g., Miaoergou in Hami and Tuomuer Glacier No. 72 are located in a more arid region than the other two sites). Thus, the dust sources of central Asia (e.g., the Taklimakan and Gobi Deserts) have different influences on the four sampling sites. We infer that Glacier No. 72 and Miaoergou Glacier are influenced more significantly by dust transport than Glacier No. 1 and Glacier No. 51.

Much research concerning dust size distribution has been done at different locations around the world (Dong et al., 2009a). On Tateyama Mountain in Japan, the volume median diameters of the dust particles are 6~21 μm (Osada et al., 2004). In the Spanish Mediterranean area, the mean size fraction of dust particles in "red dust rain" ranges from 4 to 30 μm, characterized by a bimodal structure with peaks of about 4 to 7 and 18 to 22 μm (Sala et al., 1996). Mean dust diameters of 4 to 16 μm have also been reported for Crete (Nihlén et al., 1995). Osada et al. (2004) also reported variations in mean volume diameter from 2.5 to 10 μm

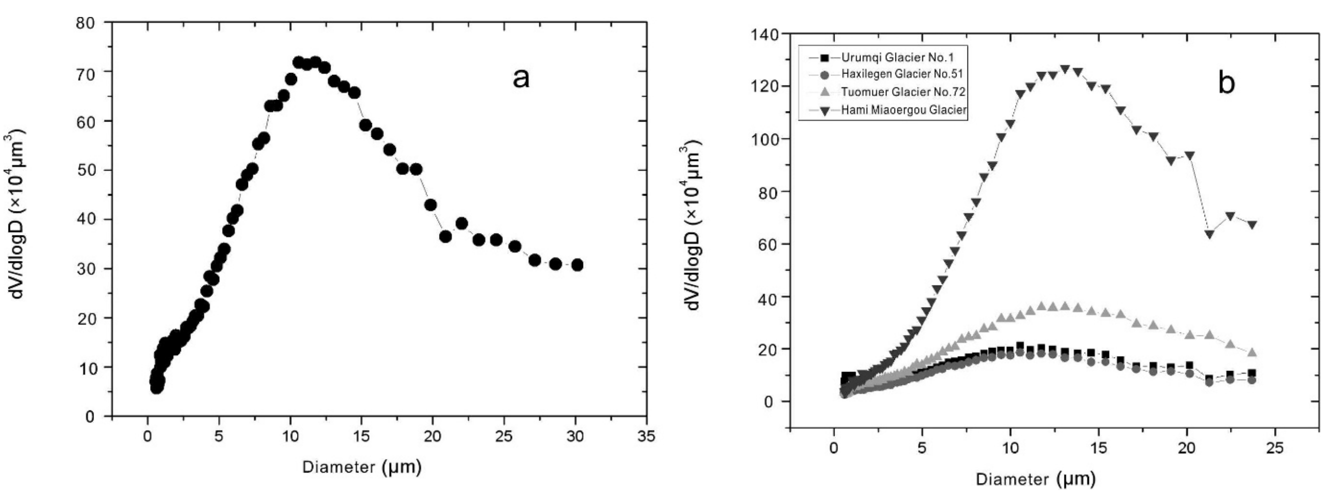

FIGURE 5. (a) Volume-size disribution of dust particles in the snow of Glacier No. 72; (b) comparison of volume-size disribution of dust particles in the snow of Glacier No. 72 with other sites in the Tian Shan.

TABLE 5

Parameters of volume-size distribution of dust in various sites of the Tian Shan in Figure 5, part b.

Sites	*n*	M (μg/kg)	dv(μm)	σg(μm)
Tuomuer Glacier No.72	85	3806	12	10.8
Hamilegen Glacier No.51	32	1442	10	8.6
Urumqi Glacier No.1	54	969	11.5	9.6
Hami Miaoergou Glacier	16	3690	13	11.9

* The mode (dv) and standard deviation(σg) of the size distribution were calculated by a log-normal curve fitting procedure as described in he text. *n* is the number of samples per sample category.

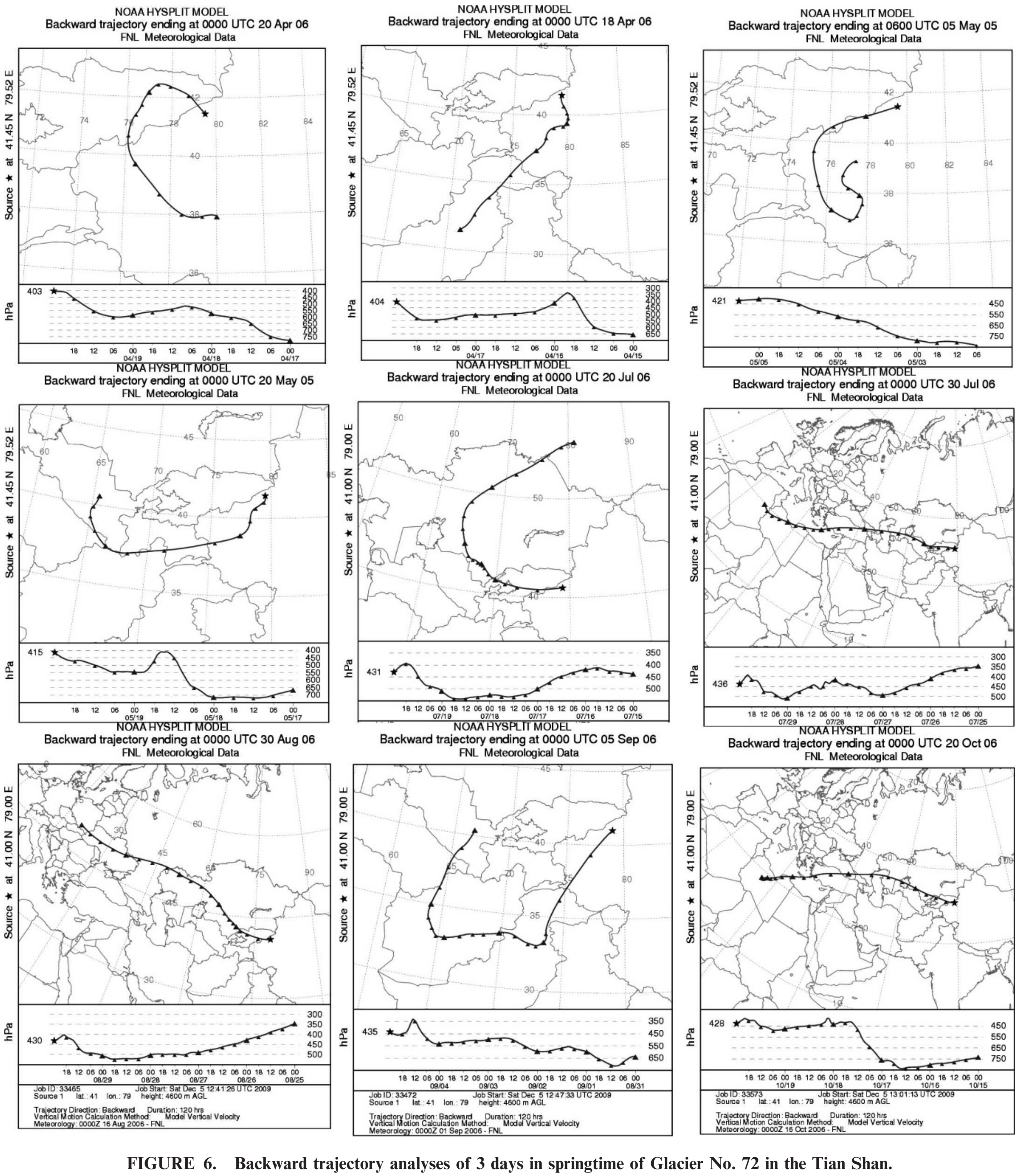

FIGURE 6. Backward trajectory analyses of 3 days in springtime of Glacier No. 72 in the Tian Shan.

for visible Saharan dust layers. The volume-size distribution of dust in glaciers in central Asia exhibits similar size ranges (Wake et al., 1994). Median diameters of dust in snow and ice cores from Greenland, the Canadian Arctic (Penny Ice Cap), and Antarctica are about 1 to 2 μm (e.g., Steffensen, 1997; Zdanowicz et al., 1998; Delmonte et al., 2004; Ruth et al., 2003).

Our results show median diameters that are much larger than those in polar snows, but similar to those in visible dust layers in the snow at Tateyama and at Monte Rosa, European Alps, and the ''red dust rain'' of Mediterranean Spain. The larger volume median diameter appears at sites closest to source regions. Backward trajectory modeling is employed to analyze the sources of air masses and dust particles in the Tuomuer region during central Asian dust storm events (Fig. 6). We infer that the dust in snow on Glacier No. 72 is mainly from regions to the west and south of our sampling sites, and the air mass originates mainly from the south (e.g., the Taklimakan Desert) in springtime. Spring is the most important central Asian dust period, which typically sees transport of abundant aerosol-size dust particles from arid regions (Sun et al., 2001; Wang et al., 2004). Such an air mass transport may significantly affect the transport and deposition processes of dust particles in the snow on the glacier in Mount Tuomuer. According to data derived from backward air trajectories from the Tian Shan, the typical transit time from possible major source regions (the Taklimakan Desert in western China, the Gobi Desert in Mongolia, and the Badain Jaran Desert in northern China; Sun et al., 2001) to the Tian Shan (about 1000 km distant) is 0.5 to 1 days in spring and summer. A recent study (Maring et al., 2003) of the change in size distribution during transatlantic dust transport suggested that a major shift of size distribution may occur within 1 to 2 days of transport. The volume median diameter of dust in Asia is larger than that found in polar areas and is highly variable. We suspect this is due to little change during transport, because in contrast to polar dust, our study area in the Tian Shan is located near the source regions of dust. Furthermore, observed single-modal distributions imply dust particles from identical source locations or wind conditions. Although our preliminary analysis of backward air trajectories showed no conclusive differences for source regions between mono- and bimodal dust events, further systematic representative measurements of very large aerosols and modeling studies may provide insight into variations in size distribution. The use of Sr and Nd isotopes would be a fruitful method to apply in future studies to test the interpretations made in the present study, as these methods have been used to identify source regions of dust particles in the Dunde ice core of the Tibetan Plateau (Wu et al., 2010), and the EPICA-Dome C and Vostok ice cores of East Antarctica (Delmonte et al., 2004). Moreover, the process of aerosol dust deposition in the snow on the glaciers of Mount Tuomuer in the western Tian Shan is still unclear and further research is needed.

Conclusions

Wind-blown mineral dust derived from the crustal surface is an important atmospheric component affecting the Earth's radiation budget. Dust storms are an important phenomenon in the arid and semi-arid regions of central Asia. Deposition of dust was measured in snow on Glacier No. 72, Mount Tuomuer, in the western Tian Shan. The mean number concentration of dust particles with $0.57 < d < 26$ μm in the snowpack is 706×10^3 mL^{-1}, with a mass concentration of 3806 μg kg^{-1}. The concentration and flux of dust particles in this work is very high compared to data from remote sites such as the Penny Ice Cap of Canada, whereas it is comparable to the results of other sites in the Tian Shan, e.g., Urumqi Glacier No. 1, Haxilegen Glacier No. 51, and Hami Miaoergou Glacier, and also sites such as Mustagh Ata and Chongce in the central Asian region and Tateyama Mountain in Japan. Dust layers in the snow cover contain Ca and Na, also found in Asian dust particles. Volume size distributions of dust particles in the snow showed single-modal structures having volume median diameters from 3 to 25 μm. The modal size of the volume size distribution in Glacier No. 72 (12 μm) is larger than that of Urumqi Glacier No. 1 and Haxilegen Glacier No. 51, but smaller than that of Hami Miaoergou Glacier, which also shows the large influence of dust sources, e.g., the Taklimakan and Gobi Deserts. Backward trajectory analysis is also employed to demonstrate the transport process of air masses during Asian dust storm events in the Tuomuer region. The air mass mainly originated from the southern region in springtime during the central Asian dust period, which typically brings abundant dust particles from sandy deserts. The use of Sr and Nd isotopes would be a fruitful method to apply in future studies to test the interpretations made in this study, as these methods have been used to identify source regions of dust particles in ice cores of the Tibetan Plateau and the East Antarctica. Moreover, the process of aerosol dust deposition in the snow on the glaciers of the Mount Tuomuer is still unclear and further research is needed.

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