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Physico-chemical Characteristics and Environmental Significance of Snow Deposition on Haxilegen Glacier No.51 in Tian Shan, China

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Abstract: Snow chemistry on the glaciers of alpine regions is a good indicator of atmospheric environmental change. We examine snow chemistry in three snowpits at different altitudes on the Haxilegen Glacier No. 51, in the Kuitun River source, Tian Shan, China, during July-September 2004 to 2007. We use correlation analysis, factor analysis and sea-salt tracing methods to examine the characteristics and sources of major ions and mineral dust particles in the snow. Results show that mineral dust particles and major ions in the snow pits vary seasonally. During the Asian dust period in springtime, the concentration of mineral dust particles and major ions deposited in snow is high, while the concentration is relatively low during the non-dust period of summer and autumn. This may be caused by dust storm activity in central Asia. The order of major ionic concentrations in the snow packs was determined to be $Ca^{2+} > SO_4^{2-} > NH_4^+ > NO_3^- > Cl^- > Na^+ > Mg^{2+} > K^+$. Ca^{2+} was the dominant cation; SO_4^{2-} was the dominant anion. We find, with the exception of NO_3^-, that the variabilities of ionic concentrations are highly correlated. Results show that the glacier region was significantly affected by dust activity and anthropogenic source. The major ions, especially Na^+, originate from dust sources of central Asia and from the Ocean, transported by the westerly winds.

Keywords: Snow chemistry; Mineral dust; Environmental significance; Haxilegen glacier No. 51; Tian Shan

Introduction

Snow and ice in alpine glaciers is a packet of kinds of components in the atmosphere, in which there are kinds of climatic information, such as chemical ions, aerosol dust particles, greenhouse gases and black carbon, etc., and all these are important indicators of climatic and environmental change (Wake et al. 1994; Zdanowicz et al. 1998; Thompson et al. 1981, 1998; Ming et al. 2008, 2009; Xu et al. 2009; Wu et al. 2009). Snow chemistry study has become an important approach for global change research. Mineral dust particles and major ions deposited in the ice and snow of alpine glaciers are important indexes reflecting the conditions of atmospheric environment. Therefore, it is important to find out the source and deposition process of the chemical constitutes in the snow on glaciers. There are many alpine glaciers in Tian Shan. Glaciers are also

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important water resource in arid and semi-arid region of central Asia. Thus it has significant meaning to study the characteristics of snow and ice in Tian Shan (Wake et al. 1994; Aizen et al. 2001; Aizen et al. 2004; Okada et al. 2004; Li et al. 2006; Zhao et al. 2008). Much research has been carried out on snow chemistry at Urumqi Glacier No.1, eastern Tian Shan (Williams et al. 1992; Li et al. 2006, 2010; Dong et al. 2009, 2010). However, little research has been done on the snow chemistry and the origin source of major cation and anion in the snow on glaciers of Haxilegen region in Kuitun area. Tian Shan is located in the source region of Asian dust, and atmospheric environment is significantly affected by dust activities in central Asia (Arimoto et al. 2006). Chemical analyses and meteorological correlation suggest that the dusty layers found in the snow cover of the eastern Tian Shan are formed by deposition of dust storm particles. However, the characteristics of mineral dust, chemistry and environmental significances of the snow in Haxilegen Glaciers remain unclear. Based on the snow samples collected on Haxilegen Glacier No. 51 of Tian Shan during 2004 ~ 2007, we analyze the characteristics, seasonal variation and environmental significances of snow chemistry, and also discuss the sources of the major ions in the snow.

1 Sampling and Laboratory Analysis

Figure 1 shows the location map of Haxilegen Glacier No. 51 (43°43'N, 84°24'E) in Kuitun area, Tian Shan, China. In July 2004, Sept. 2005 and Sept. 2007, a total of 3 snowpits (depths 1.85 ~ 2.50 m), was excavated at different altitudes. The snow deposition environment around the sampling sites of Haxilegen Glacier No. 51 is suitable for continuous snow accumulation, as the topography is nearly flat, leading to uniform snow deposition.

We worked on the snow pits after recording snow stratigraphy, and clean, fresh vertical sections were exposed for dust and chemical snow sampling. We collected snow samples, typically 100 g, in 10 cm increments using a pre-cleaned stainless steel shovel and polyethylene gloves. A total of 66 snow samples were collected from the snow pits. The sampling instruments were cleaned between intervals. Samples were stored in Whirl-Pak bags and kept frozen for 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.

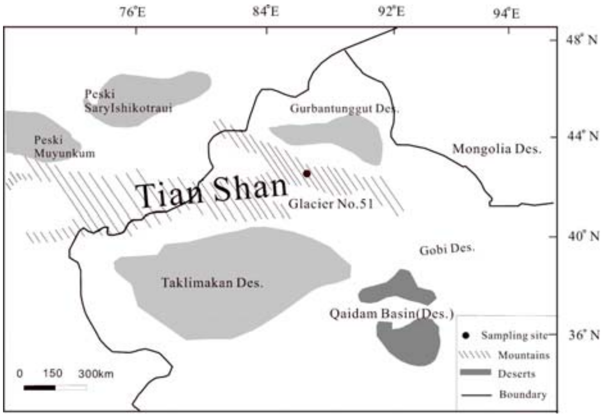

Figure 1 Location map of Haxilegen Glacier No.51 in Tian Shan

Samples were then melted and aliquots were collected for micro-particle and chemical analysis. Mineral dust particles 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. 2009). 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 ~ 400 μm (micro meter) equivalent spherical diameter, *d*. 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 (Steffensen et al. 1997). Cations were analyzed on an Ion Chromatograph (Dionex-600) and anions were analyzed on an Ion Chromatograph (Dionex-300) in State Key Laboratory of Cryospheric Science in China. The analytical precision could reach 10^{-9} g/ml and the standard deviation is less than 5%.

2 Methods

Methods of correlation analysis and trend analysis are always used to determine sources of major ions on glaciers and snowpacks (Li et al. 2008; Barrie 1985; Johnsen et al. 1972; Jouze et al. 1987; Holdsworth et al. 1985; He et al. 1994; Yao et al. 1993; Huang et al. 1998). Moreover, the method of sea-salt ions tracer was also applied in this research (Church et al. 1982; Xiao et al. 1993; Kneene et al. 1986). Although the study area is in the dust source of central Asia, moisture is mainly from the ocean source that brought by the westerly wind and also moisture from lakes in central Asia, precipitation in summer account for over 90% in the total annual precipitation (Li et al. 2006; Zhao et al. 2008; Dong et al. 2009). Ocean moisture is the major source of precipitation to the glacier. The rules of choosing sea-salt tracer ion are as follows: (1) If the quantity ratio of Cl^-/Na^+ and $Mg^{2+}/Na^+ \geqslant$ corresponding value of standard sea-water ($Cl^-/Na^+ = 1.165$, $Mg^{2+}/Na^+ = 0.227$), Na^+ is sea-salt tracer ion; (2) If the quantity ratio of Na^+/Cl^- and $Mg^{2+}/Cl^- \geqslant$ corresponding value of standard sea-water ($Na^+/Cl^- = 0.859$, $Mg^{2+}/Cl^- = 0.195$), Cl^- is sea-salt tracer ion; (3) If the quantity ratio of Na^+/Mg^{2+} and $Cl^-/Mg^{2+} \geqslant$ corresponding value of standard sea-water ($Na^+/Mg^{2+} = 4.403$, $Cl^-/Mg^{2+} = 5.126$), Mg^{2+} is sea-salt tracer ion.

After fixed sea-salt tracer ion, making use of formula: $NNA = A - R*M$, (A for ions concentration, NNA for the non-marine source part of ions, M for tracer ion concentration, and R is the ratio of A/M of standard seawater) the non-marine source part of ions is determined. The sea-salt tracer ion is Na^+ in the study area according to the method mentioned above, namely that marine moisture is the source of Na^+.

Furthermore, backward trajectory analysis is used to examine the transport process of air mass to the Haxilegen Glacier No. 51 at three different altitudes of the sampling sites, which is based on HYSPLTIT 4 (hybrid single-particle lagrangian integrated trajectory) model, including vertical motion of the air mass. The backward trajectory of air mass transport for 5 d of the sampling sites is calculated in this work.

3 Results and Discussion

3.1 Comparison of major ions and mineral dust particles concentration in the snowpits

Table 1 is a comparison of the concentration of major ions, mineral dust particle, pH and EC (electrical conductivity) in the snowpits on Haxilegen glacier No. 51. The cation excess △C (total cation equivalents minus total anion equivalents) for snowpit samples averaged 50.91 μg/L. The large ionic imbalances can be attributed to the carbonate (CO_3^{2-}) and bicarbonate (HCO_3^-) ions in the snow. Previous work revealed a linear regression between the calcium ion (Ca^{2+}) and △C ($R = 0.98$, $N = 45$, $p < 0.01$) in the snow, suggesting that the △C represented primarily the CO_3^{2-}/HCO_3^- (Wake et al. 1992; Williams et al. 1992; Li et al. 2006). The cation excess involves the carbonate component of the dust and the $CO_2 - HCO_3^-$ equilibrium. Since no direct measurements of HCO_3^- were available, the concentration of HCO_3^- was estimated from the theoretical relationship between pH and HCO_3^- (Parashar et al. 1996; Momin et al. 2005; Tiwari et al. 2007). According to this relationship, when the pH of a sample is above 5.6 and the sample is in equilibrium with atmospheric carbon dioxide pressure, the concentration of HCO_3^- is given as $[HCO_3^-] = 10^{-11.2+pH}$, with HCO_3^- concentration in mol/L. Estimated average values of HCO_3^- at Glacier No.51 were 28.7 μg/L, compared with the cation excess △

Table 1 Comparison of dust, major ions and pH and EC in the snowpit of Haxilegen Glacier No.51 in Tian Shan

	Elve. (m)	Ca^{2+} (μg/L)	Na^+ (μg/L)	Mg^{2+} (μg/L)	K^+ (μg/L)	NH_4^+ (μg/L)	SO_4^{2-} (μg/L)	NO_3^- (μg/L)	Cl^- (μg/L)	△C	Dust (10^3/ml)	pH	EC (μs/cm)
Snow pit-1	3900	133.19	16.91	16.51	19.52	105.92	112.69	99.01	49.35	31.0	408	5.7	3.1
Snow pit-2	3800	219.94	26.95	22.42	22.4	114.8	188.86	101.5	62.08	54.07	1094	5.8	3.6
Snow pit-3	4000	69.42	21.07	22.07	15.82	65.37	31.75	54.51	39.8	67.69	327	5.6	2.09
Mean	3900	140.85	21.64	20.33	19.25	95.36	111.1	85.01	50.41	50.91	609	5.7	2.9
Non-Marine source	-	99%	97%	100%	98%	66%	42%	89%	99%		-	-	-

C (total cation equivalents minus total anion equivalents) for Glacier No.51 snow samples averaged 50.91 μg/L. It seems that the snow at Glacier No.51 is heavily influence by both mineral aerosols ($CaCO_3$) and dissolved atmospheric CO_2.

Major ions and mineral dust concentration are quite different between the snowpits at different altitudes. With a raised altitude of the snow pits, the ionic concentration shows a decreasing trend. As the altitude of snowpit-2 is the lowest (Table 1), with an altitude of 3800 m, the concentration of major ions and mineral dust in snow is high value; and, the altitude of snowpit-3 is the highest of 4000 m, while the major ions and mineral dust concentration is in relatively low values (Table 1). Such a spatial distribution of chemical concentration shows an obvious effect of the altitude change. Previous research has indicated that the concentration of dust particles and major ions (Ca^{2+}, Mg^{2+}), originated from the crustal surface carried by the air mass, is gradually decreased with the altitude rise on the glacier region during transport process (Wu et al. 2005; Wake et al. 1994). This may be caused by two reasons. Firstly, with the altitude rise, precipitation variation shows a trend to increase first and then decrease, which may influence the mass input to the snow of the glacier region. Secondly, the ions deposited in the snow are always carried by dust particles, and, the concentration of dust is also affected by the increase of altitude. For example, the concentration of mineral dust particles in the snowpit in Rongbuk Glacier in Everest Mountains (6000 m a.s.l) is much lower than that of eastern Tian Shan (4000 m a.s.l), as dust particle concentration deposited on glaciers of Tian Shan is also much lower than that of Tateyama Mountain (2100 m a.s.l) in central Japan (Osada et al. 2004; Wu et al. 2005; Dong et al. 2009).

From Table 1, we find that the order of major ionic concentrations in the snow pits is $Ca^{2+} > SO_4^{2-} > NH_4^+ > NO^{3-} > Cl^- > Na^+ > Mg^{2+} > K^+$. Ca^{2+} is the main cation; SO_4^{2-} is the main anion. The concentration of Ca^{2+} is much higher than that of other ions. As the high-alkaline Ca^{2+} is a tracer of mineral dust in Asian region, Ca^{2+} concentration has good correlation with dust concentration. According to research at Urumqi Glacier No. 1, Tian Shan, the concentration of Ca^{2+} and SO_4^{2-} in fresh snow varied seasonally (Li et al. 2006; Dong et al. 2009), Ca^{2+} and SO_4^{2-} concentrations were high during the period of dust activity in springtime, which indicated that the chemical composition of snow is significantly influenced by dust storm activity (Dong et al. 2009). In this study, results also show that the concentrations of mineral dust, Ca^{2+} and SO_4^{2-} in the snow pits of Haxilegen Glacier No. 51 are all high (Table 1), which may have originated from the crustal surface with dust storm activities in central Asia. Some research has also shown that, 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 be close to that of $(NH_4)_2SO_4$. Particulate Na^+, similar to Ca^{2+}, with high concentration (Table 1), is always from crustal surface with aerosol dust transported to alpine glaciers in Tian Shan (Li et al. 2006; Dong et al. 2009). The composition of chemical ions and mineral dust particles in snow on the Haxilegen Glacier No. 51 could very well reflect the atmospheric environment conditions close to dust source regions in central Asia.

3.2 Seasonal variation of major ions and mineral dust particles

Haxilegen Glacier No. 51 is located in arid and semi-arid region of central Asia, and surrounded by many large deserts such as the Taklimakan Desert, Gobi Deserts and other desertification regions, where dust storms are the main phenomenon of atmospheric environment. Influenced by Asian dust sources, major ions and mineral dust in the snow on alpine glaciers in this region have obvious seasonal change during the dust period in springtime and non-dust period in summer and autumn. Figure 2 shows seasonal variation of mineral dust obtained from snowpit-2 in 2005, in which we can find good relationship between dust layers in the snow pit and the peak value of mean diameter of dust particles (Figure 2). There are plenty of dust incidents occurring in winter and springtime, while the summer and

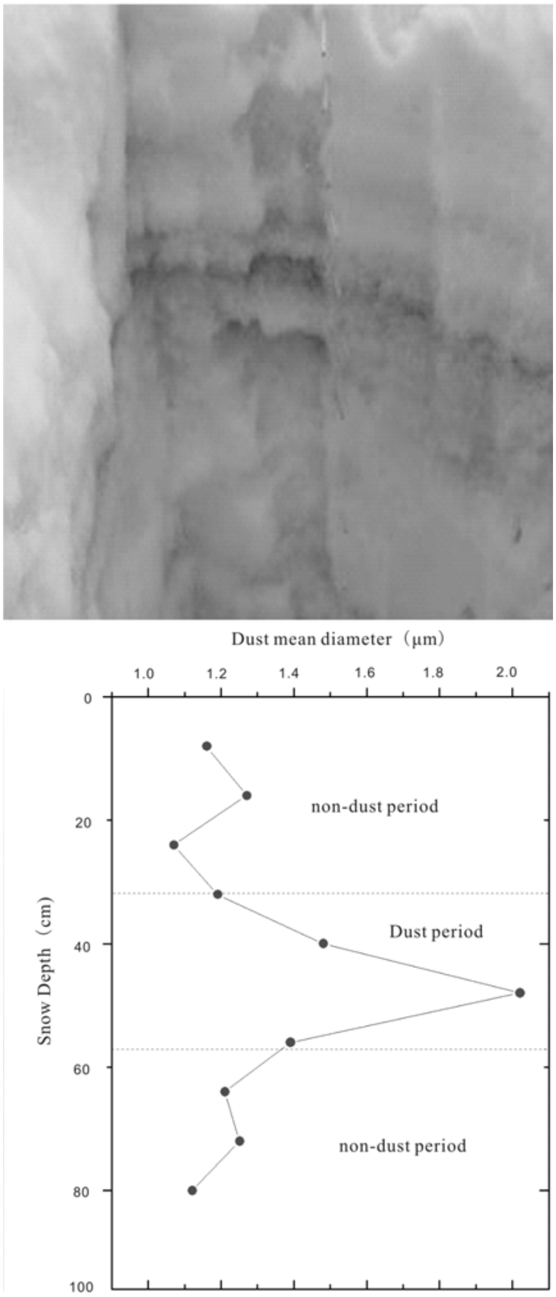

Figure 2 Seasonal variation of dust profiles in the snowpit of 2005

autumn are non-dust periods with plenty of precipitation (Wake et al. 1994; Wei et al. 2004; Dong et al. 2009). According to chemical analyses and meteorological correlation, dusty layers in the snow of glacier No.1 51 are formed by the deposition of dust particles during the dust period in spring. Thus we can find seasonal change of chemical constituents (e.g. $\delta^{18}O$ and dust) in the snowpit. Mean diameter of dust particles in snow can always reflect dust mass concentration (Dong et al. 2009), as the greater of the average mean size diameter, the more coarse particles there are, and the greater of the dust mass concentration. Figure 2 reflects obvious seasonal change of mineral dust particle between dust and non-dust period. Such a seasonal variation also shows that Haxilegen Glacier No. 51 is significantly influenced by dust activity in central Asia.

Moreover, mass-size distribution of dust particles deposited in the snow pits was compared between a dust period and non-dust period. Size distribution of mineral dust particles could reflect the wind conditions and dust storm incidents in Asian dust source region. Research on size distribution of dust particles is significant for atmospheric environment change. Figure 3 shows the changes in size distribution of dust particles in the snow on the Haxilegen Glacier No. 51. The

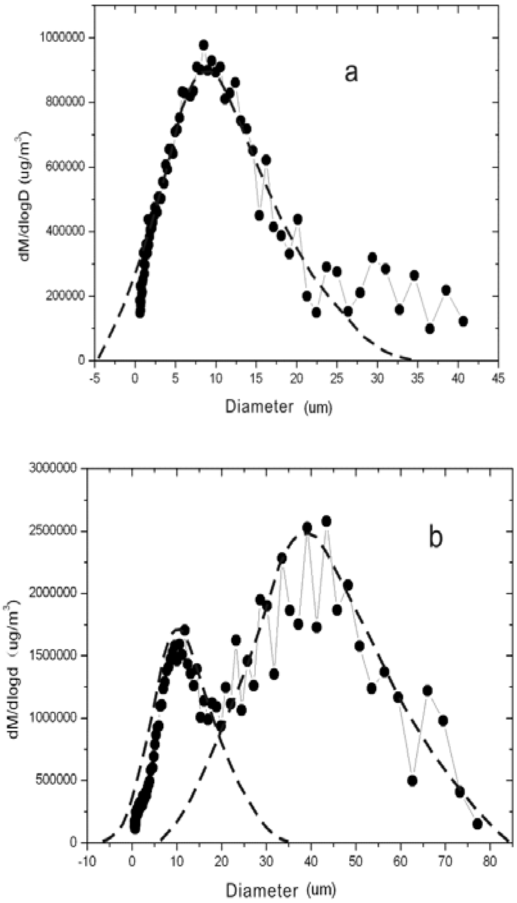

Figure 3 Comparison of dust particle mass-size distribution in snow on Glacier No.51 between (a) non-dust period of summer, and (b) dust period of spring

mode μ of size distribution of mineral dust particles corresponds with the peak value of the curve in Figure 3. Mass-size distribution of mineral dust in the snow could very well reflect the size composition of dust particles. Size distribution also shows the basic conditions of the atmosphere, and is closely related to the change of the atmospheric environment during different time periods. Results show that the modes of dust particle mass-size distribution in the snow on Haxilegen Glacier No. 51 include both single model and bio-model. Single model reflects the simple source of mineral dust, while bio-model shows the complexity of mass input from dust sources. Size distribution of dust particle is not only affected by the wind speed, but also affected by the distance of dust transport process in the atmosphere. As shown in Figure 3, size distribution of dust particles in the snow on Haxilegen Glacier No. 51 was composed by two parts: (1) snow samples during the non-dust period, which could reflect the basic aerosol dust originated from long distance transport of the fine particles. The particle size is concentrated in the range of 2-26 μm; and medium diameter of particle size distribution is around 10 μm (Figure 3a), obtained from the average of 15 samples. (2) Samples taken during the dust period, besides the smaller part of particles range from 2-26 μm. Snow chemistry is also affected by large particles from local dust activities. Strong wind during the dust period in springtime in central Asia could bring a lot of dust particles from dust sources, such as the Taklimakan Desert, Gobi Deserts, etc. Size distribution of dust is concentrated in the range of 20-80 μm, the medium diameter is about 40 μm (Figure 3b), obtained from the average mean value of 8 snow samples. These results show that dust activity has significant impact on snow chemistry in Haxilegen Glacier No. 51, and the size distribution of mineral dust also has obvious change between the dust and non-dust period.

Figure 4 shows the comparison of seasonal variation of mineral dust and Ca^{2+} concentration, the shadow part in the figure shows the Asian dust periods, and the peak value of average mean size of dust particles has a good correlation with dust periods. Table 2 shows a comparison of correlation coefficient between various major ions and dust particle concentration in the snow pits, which is the average of all 66 snow samples. Results show that major ionic concentration in the snow is highly correlated with that in the dust. Ca^{2+}, as a tracer of mineral dust in Asia, concentration is often high during the dust period. Concentration of Na^+ has good consistency with Ca^{2+}. At the same time, the concentration of dust particles also has good correlation with that of other major ions (Table 2), such as Mg^{2+}, Na^+, Cl^-, etc. These results may imply that ionic concentrations are significantly influenced by dust activities in this region, deposited with mineral dust particles to the snow on Haxilegen Glacier No. 51.

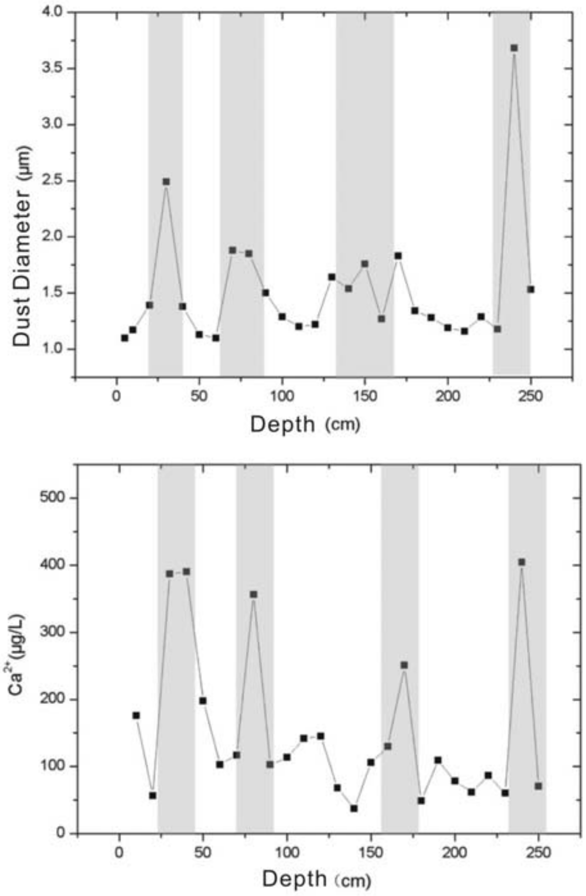

Figure 4 Comparison of dust and Ca^{2+} concentration in the snowpit of 2004

3.3 Source analysis of major anion and cation in snowpits

To connect the chemical elements to their sources, correlations among the elements were further investigated using factor analysis (Table 3). Factor 1 loadings are the highest for Cl^-, Ca^{2+}, Na^+ and K^+, which are significantly correlated with each other. This factor may be interpreted as a local-plus-regional source component, though Na^+ may have more complicated source. Potential sources include local aerosol dust entrained in the atmosphere by the strong winds that prevail during spring along with a more regional Asian dust flux. Previous studies indicate that local bare rocks and glacial sediments are readily available sources for the elements (Williams et al. 1992; Hou and Qin; 2002). Factor 2 loadings are the highest for NH_4^+, NO_3^-, and SO_4^{2-}, which are also correlated with each other. This factor is interpreted as an anthropogenic source component that includes emissions from fossil fuel combustion and biomass burning, livestock manure, and commercial and natural fertilizers. Mineral dust commonly acts as a carrier for these pollutants (Li et al. 1995, 1999; Bernabe et al. 2005). Although the region is relatively unpopulated, Glacier No.51 is situated only 120 km from Kuitun city of Xinjiang Uyger Autonomous Region, with more than 300 thousand inhabitants. Also the town of Dushanzi is only 80 km away from the Haxilegen glacial region. In addition, the Kuitun- Kuche road passes only 500 meters away from the study site. We suspect that these sources must be largely responsible for the anthropogenically derived compounds deposited on the glacier. Atmospheric pollutants from Kuitun may be transported to the glacier by the low-level regional atmospheric circulation. Clouds from the factories in Dushanzi drift over the Kuitun river valley and periodically reach glacier No. 51 by the valley winds. Factor 3 loadings are the highest for Ca^{2+}, Mg^{2+} and dust content, and the three elements are also significantly correlated (see Table 2). This factor is interpreted as a long-distance source component with moisture transport. Potential sources for this group are mainly mineral dust and evaporated aerosols entrained along the trajectory of the air mass to the region (Li et al. 2006).

Moreover, the method of sea-salt ions tracer was also applied in this research. As shown in Table 1, non-marine source of Cl^- and SO_4^{2-} accounted for 66% and 97% respectively in snow on Haxilegen Glacier No.51 of Tian Shan. The

Table 2 Correlation coefficient of major ions, pH, EC and dust in the snowpits (N=66, P≤0.05)

	Cl^-	NO_3^-	$SO4^{2-}$	Na^+	NH_4^+	K^+	Mg^{2+}	Ca^{2+}	pH	EC
NO^{3-}	0.76	-								
$SO4^{2-}$	0.78	0.91	-							
Na^+	0.93	0.53	0.60	-						
NH_4^+	0.81	0.79	0.93	0.65	-					
K^+	0.73	0.18	0.45	0.74	0.67	-				
Mg^{2+}	0.70	0.39	0.68	0.65	0.81	0.93	-			
Ca^{2+}	0.55	0.32	0.64	0.44	0.81	0.83	0.96	-		
pH	0.44	0.16	0.86	0.45	0.36	0.39	0.72	0.41	-	
EC	0.57	0.21	0.83	0.68	0.49	0.63	0.73	0.94	0.89	-
Dust	0.78	0.39	0.75	0.58	0.53	0.49	0.77	0.93	0.71	0.88

Table 3 Factor loading matrix for the elements in surface snow. Factors were extracted by principal components analysis, with varimax rotation to produce the final factor loadings. Bold type indicates the highest factor loading

Element	Communality	Factor loadings		
		Factor 1	Factor 2	Factor 3
NH_4^+	0.750	0.547	**0.695**	0.034
Dust	0.922	0.287	0.226	**0.869**
NO_3^-	0.786	-0.034	**0.839**	0.232
Cl^-	0.931	**0.826**	0.441	0.353
SO_4^{2-}	0.834	0.465	**0.745**	0.252
Mg^{2+}	0.876	0.516	0.045	**0.862**
Ca^{2+}	0.826	**0.669**	0.246	**0.626**
Na^+	0.953	**0.867**	0.263	0.379
K^+	0.733	**0.754**	0.152	0.344
Fraction of variance (%)		33.06	25.61	23.77

descending order of Anion concentration in standard seawater is: $Cl^- > SO_4^{2-} > NO_3^-$, while the order of anion concentration in Haxilegen Glacier No.51 is: $SO_4^{2-} > NO_3^- > Cl^-$, which has great difference with the standard seawaters, reflecting that the non-marine material (also called terrigenous mineral) has great contribution to the anion source in glacier area of Haxilegen at Kuitun river source. Research has indicated that Cl^- in alpine glaciers of the Tibetan Plateau is mainly originated from sea salt, mineral dust and saline lake, while SO_4^{2-} is mainly originated from mineral dust and anthropogenic source (Huang et al. 1998; Kang et al. 2006). However, the source of NO_3^-, more complicated, is mainly from lightning, exchange in stratospheric layer, sea-salt, mineral dust and human pollution, etc. (Xiao et al. 2005; Kang et al. 2000, 2006; He et al. 1999, 2000). We can infer that non-marine source of anion in snow on Haxilegen Glacier No.51 is mainly originated from materials of near source such as dust activity, and also distant source material which is mainly transported by westerly wind. Source of major ions in the ice and snow of alpine glacier is often mainly the mass input from atmospheric circulation, while in research area of Tian Shan is mainly influenced by dust activities as the main atmospheric characteristics. Because Glacier No.51, located in dust source region in central Asia, is very close to the deserts of central Asia such as Taklimakan desert, Gobi desert etc., the ionic source of snow is mainly affected by local atmospheric condition and mineral dust of earth's crustal surface. However, the mountain environment around the glacier (e.g. wind, topography) is also important and may affect the concentration of major ions and mineral dust deposition to the snow on the glaciers.

The correlation coefficient of NO_3^- and SO_4^{2-} in glacier region of this work is R=0.91 (Table 2), and the temporal change of concentration of NO_3^- and SO_4^{2-} is very similar (Figure 5), which may imply that they are originated from the same source. NO_3^- and SO_4^{2-} could be also transported by the air mass from anthropogenic source in this region. The westerly winds passing through many oil industry regions in Xinjiang region, where there is plenty of NO_3^- and SO_4^{2-} diffused in the atmosphere, could transport these ions to the glacier region. Besides the sources mentioned above for NO_3^-, lightning at high altitude may have a considerable contribution to the deposition of NO_3^- in the snow pits. As the altitude of Haxilegen Glacier No. 51 is above 4000 m, precipitation events and lightning on the glacier are very frequent in wet season, from June to September in summer and autumn. However, the relationship between lightning and ionic source in the glacier of Tian Shan is still unclear and further research needs to be carried out to understand the process.

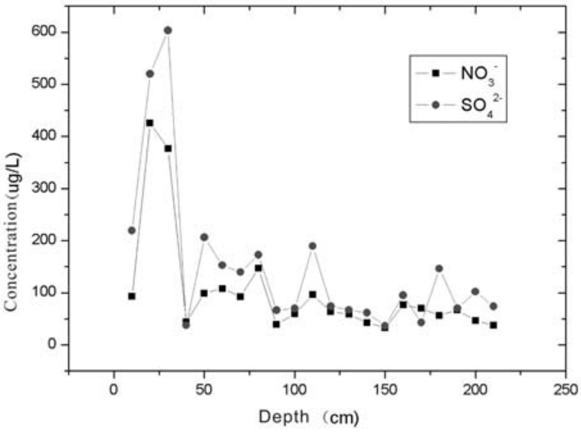

Figure 5 Comparison of NO_3^- and SO_4^{2-} concentration in the snowpit of 2007

Research on chemistry of snow and ice in the Tibetan Plateau and surrounding areas has shown that the spatial distributions of main cation concentration have obvious change trend (He et al. 1994; Yao et al. 1993; Huang et al. 1998). Na^+ concentration has a change trend of increase from central region of the Tibetan Plateau to the northern and southern edge regions; while Ca^{2+} concentration decreases from northern to southern regions. Haxilegen Glacier No. 51 lies in central Asia, spatial distribution of Na^+ concentration in Tian Shan follows the rule above, while Ca^{2+} and K^+ concentration show different situation in spatial distribution, which also indicates that Na^+, as marine sources, follows the basic rule that sea salt ions transfer from the sea to the land. However, other ions from the crustal surface sources are more complicated. The result shows that Na^+ is mostly from marine source in Haxilegen Glacier No. 51 in this work (58%) (Table1). Ca^{2+} is non-marine source (mainly dust source), other cations (Mg^{2+}, K^+) are also non-marine sources. K^+ and Mg^{2+} of non-marine source, respectively, accounted for 99% and 89% in the snow pits. The order of cation concentration in the snow pits is $Ca^{2+} > K^+ > Na^+ >$

Mg^{2+}, basically the same with the order of crustal elements. Correlation between Ca^{2+} and other cations are all high (Table 2), which also show that besides Na^+, other cations mainly derived from terrigenous mineral dust, while Na^+ is primarily from marine source.

Figure 5 shows backward trajectory analysis of air mass transported to the sampling sites of Haxilegen Glacier No. 51 during Asian dust and non-dust periods. During the dust activity period in winter and springtime, the air mass is mainly from the west, which may bring many dust particles from the dust source of central Asia. Moreover, the wind speed is often strong in springtime in this region, and dust storms are quite frequent, which have made big contributions to the deposition of mineral dust and major ions to the snow in Tian Shan. However, the westerly wind may also bring plenty of moisture from the west Ocean, thus it also contributes to the marine source ions in the snow and ice of alpine glaciers. During the non-dust period in summer and autumn (from June to September) (Figure 6), besides those ions sources from west, the air mass from southwest also accounts for a large proportion, which may indicate that precipitation is not only affected by moisture from the west Oceans and lakes of central Asia, but also from the Indian Ocean in the southwest, having great influence on the sources and transport of mineral dust and major ions in the snow of Haxilegen Glacier No. 51 in Tian Shan.

4 Conclusions

Snow chemistry in alpine glaciers is a good indicator for climatic and atmospheric environment change. In this work, we mainly

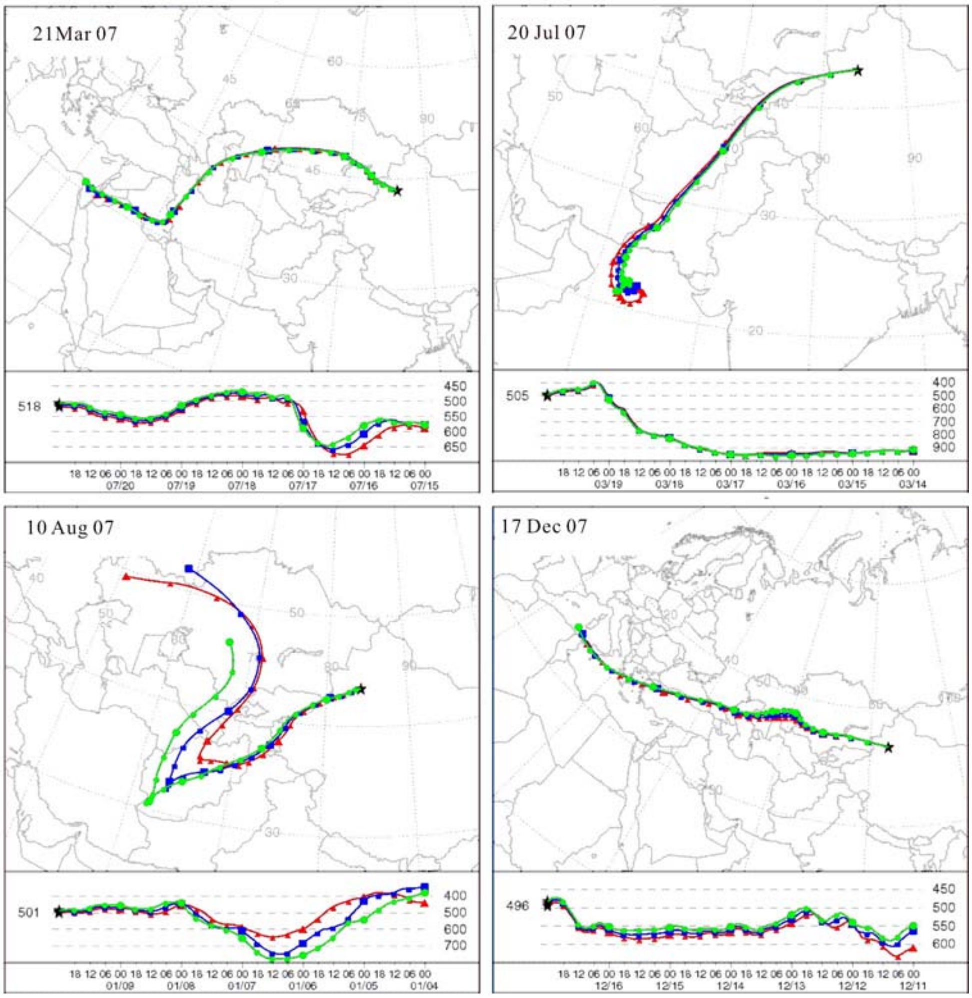

Figure 6 Backward trajectory analysis of air mass in Glacier No.51, Tian Shan, China, during different seasons

discuss the characteristics and environmental significance of mineral dust particles and major ions in the snow pits at Haxilegen Glacier No. 51 in Tian Shan. Results show that mineral dust particles and chemical ions vary seasonally in the snow pits. Dust particle concentration in the snow during Asian dust period (generally in winter and spring), is obviously higher than that in the non-dust period (in summer and autumn), which indicates that the glacier is significantly affected by Asian dust activity occurred in springtime; the concentration of major ions in snow pits during the dust period is obviously higher than that of the non-dust period. The order of average mean ionic concentration in the snow pits was determined to be $Ca^{2+} > SO_4^{2-} > NH_4^+ > NO_3^- > Cl^- > Na^+ > Mg^{2+} > K^+$. Ca^{2+} was the dominant cation; SO_4^{2-} was the dominant anion. We find, with the exception of NO_3^-, that the variabilities of ionic concentrations are highly correlated. The high correlation between dust particle, Ca^{2+} concentration and electrical conductivity shows that the chemical characteristics in the snow are significantly influenced by atmospheric dust activity in central Asia. Moreover, using the methods of correlation analysis， factor analysis and sea salt tracer to examine the sources of major ions in the snow, results show that major ions in the Haxilegen Glacier No. 51 is significantly affected by both mineral dust of the crustal surface and anthropogenic source. Also, as the air mass of the glacier region is mainly from the west of central Asia, major ions in the snow pits, especially Na^+, is originated from mineral dust particles and from Ocean, transported by the westerly winds.

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