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Deposition Process of Dust Microparticles from Aerosol to Snow-Firn Pack on Glacier No. 1 in Eastern Tianshan Mountains, China

Xiaoni You* (尤晓妮)
Tianshui Normal University, *Tianshui* 741001, *China*
Zhiwen Dong (董志文)
State Key Laboratory of Cryospheric Sciences/Tien Shan Glaciological Station, *Cold and Arid Regions Environmental and Engineering Research Institute*, *Chinese Academy of Sciences*, *Lanzhou* 730000, *China*

ABSTRACT: Samples were continuously collected from aerosol, fresh snow, and snow pits on Glacier No. 1 at Urumqi River source in eastern Tianshan (天山) Mountains. The deposition processes and the characteristics of mineral dust microparticles from aerosol to fresh snow, and then evolution to the snow pit were determined. Total dust microparticle concentration in the surface snow and aerosol showed a similar temporal variation trend, which was strongly associated with regional and local atmospheric circulation in the Tianshan Mountains region of Central Asia. Especially from November to February, the correlation coefficient of microparticles concentration in surface snow and aerosol is very high (R^2=0.7). Vertical profiles of microparticles in the snow pits showed that observed dust layers were in high correlation with concentration peaks of large microparticles (d>10 μm), but low correlation with that of fine microparticles (d<1 μm). Moreover, explicit post-depositional process of dust particles was studied by tracking some typical dust concentration peaks in the snow pit. We find that late summer is a key period for post-deposition of dust particles in the snow, as particle concentration peaks in the snow pit evolve intensely during this period. Such evolutional pattern of large particles makes it possible to preserve information of atmospheric dust in the snow, which offers an available proof to reconstruct historical climate using ice cores on Glacier No. 1 and other glaciers in the Tianshan Mountains.

KEY WORDS: Glacier No. 1, dust microparticle, post-deposition.

INTRODUCTION

Insoluble mineral microparticles deposited in Alpine and Arctic snow originate primarily from wind deflation of soils and sediments over continental source regions (Osada et al., 2004; Hinkley, 1992; Kumai, 1977; Murozumi et al., 1969). Changes in the concentration and size distribution of dust particles from ice cores are used to document past changes in

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*Corresponding author: youxiaoni_818@yeah.net

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the atmospheric dust load or the dynamics of airborne dust transport and deposition (Zdanowicz et al., 1998; Petit et al., 1990; Thompson et al., 1989). During the past several decades, atmospheric dust records with high resolution have been developed through microparticle concentration of ice cores in many areas (Wake et al., 1994; Thompson et al., 1975). Moreover, dust storms derived from Central Asia have been of wide concern (Wake et al., 1994; Merrill et al., 1989; Jackson et al., 1973). Some results show that the mid-latitudes (25ºN–40ºN) are most strongly affected by Asian dust (Prospero et al., 1989; Uematsu et al., 1983), especially in the springtime dust period (Gao et al., 1992). Related researches on transformation of dust from aerosol to snow were also processed in many regions (Davidson et al., 1993; Dibb and Jaffrezo, 1993). However, the reports on deposition and post-depositional process of dust microparticle from aerosol to the snow are very limited.

The Tianshan Mountains are 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. Aerosol dust particles deposited in the snow of high mountain glaciers contain information on atmospheric environment at high elevation, and they are an important indicator of global climate change. It is thus very important to research the characteristics of dust deposition in the Tianshan region (Li et al., 2007, 2006; Wake et al., 1994). Chemical analyses and meteorological correlation suggest that the dust layers found in the snow cover of the Tianshan Mountains were formed by deposition of dust storm particles (Li et al., 2010; Dong et al., 2009a, b). However, the processes of formation of the dust layers and characteristics of the dust microparticles in the snow cover on the glaciers of Tianshan Mountains remain unclear. Based on the samples collected from snow pits and aerosol on Glacier No. 1 at Urumqi River source, here we present results of an investigation on the deposition, post-depositional process of dust microparticle from the aerosol, to fresh snow, and then to the snow pit on Glacier No. 1 in eastern Tianshan Mountains.

STUDY AREA

Glacier No. 1, located at 43º06'N, 86º49'E in eastern Tianshan Mountains, is surrounded by vast desert areas; to its south lie the Taklimakan desert in the Tarim basin and the Qaidam basin desert; to its east, lie the deserts in eastern Xinjiang and western Gansu provinces and the Mongolian Gobi plateau; to its north, lie the Gurbantunggut desert in Junggar

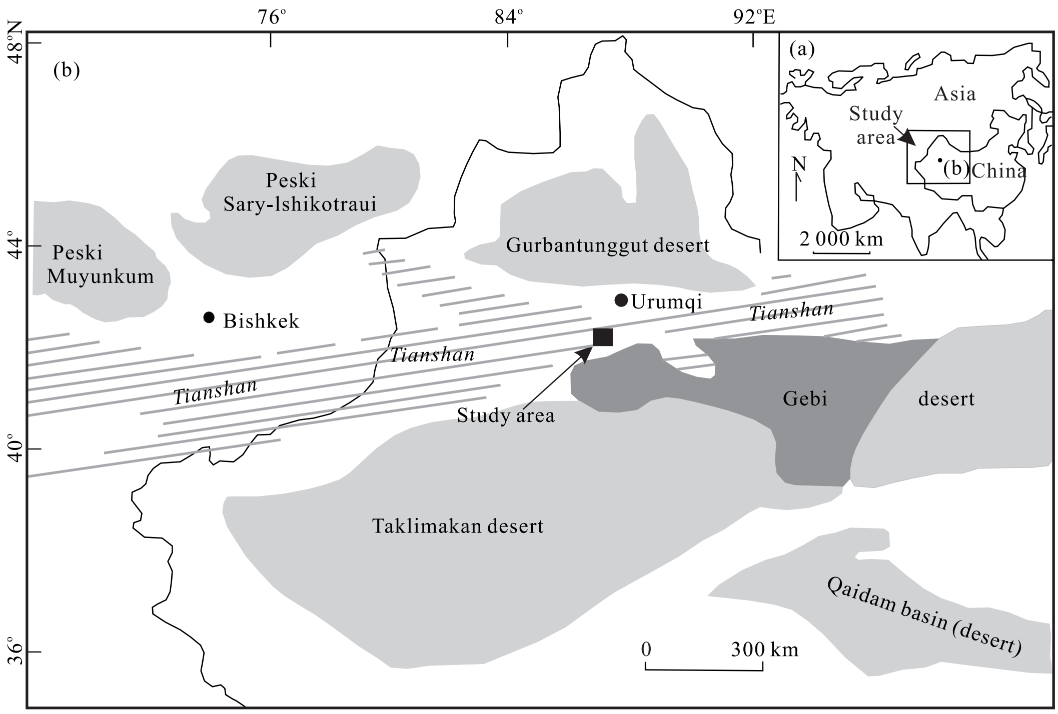

Figure 1. Location of Glacier No. 1 in Tianshan Mountains, Central Asia, China

basin, and Peski Muyunkum and Peski Sary-Ishikotrau deserts lie to the west (Yuan and Mao, 1994). Glacier No. 1 is composed of east and west branches, around which is a mass of bare rock and moraine sediment. A previous study on composition of rock shows that hornblende and epidote are the main heavy minerals; quartz, alkaline feldspar and plagioclase are major light minerals, all of which are abundant in sodium, calcium, magnesium, and iron and so on (Luo, 1983). The main precipitation period occurs from May to September and accounts for about 90% of the annual precipitation (Wang and Zhang, 1985). Concurrent with the precipitation, ablation also occurs during the same period. In this study, the sampling site is located at the percolation zone of the east branch of Glacier No. 1, against a firn basin. Low solar radiation and particular terrain are favorable to preserve complete snow-firn profiles.

METHODOLOGY

This article draws on year-round collections of aerosol and snow on Glacier No. 1 between September 2003 and September 2004. Sampling procedures and site information are described in more detail elsewhere (Li et al., 2006). Aerosol samples were collected from the air about 1.5 m above the snow surface. They were collected on 2 μm pore size, 47 mm diameter ZefluorTM Teflon filters that were placed facing downwards in a cylindrical polyethylene protective cover. The sampling intervals are generally 7 d (but were extended to 8 d during some periods of bad weather).

Surface snow and snow pit samples collection took place in a clean area close to the aerosol sampling site. Prior to sample collection, snow pit wall is refaced using a pre-cleaned scraper. Snow pit samples were collected at 10 cm intervals and surface snow samples were collected approximately the upper centimeter skin. Non-particulating suits and hoods, polyethylene gloves, and masks were worn during all sampling procedures to prevent contamination. All the samples were transported to the Laboratory of the Tianshan Glaciological Station in Lanzhou in frozen state.

The usual instrument for analysis of microparticles is Coulter counter, whose analytical principle and procedures were detailed by Thompson (1977) and Davies (2003). In our study, the microparticles concentration and size distribution are measured using AccuSizer 780A. The basic procedures for analyzing the microparticle were established by Zhu et al., (2006). Equivalent spherical diameter and concentration of insoluble particles from snow and aerosol were measured in a 100-class clean room with a computer driven auto sampler. AccuSizer 780A adopts Single Particle Optical Sensing (SPOS) technology, has 8–512 size channels, with uncertainty less than 5% in 0.57–400 μm measuring range. Prior to analysis, samples are melted at room temperature and pipeline and system of apparatus are cleaned by deionized Milli-Q water until its microparticle concentration is below 50 per mL. Background value of diluent is detected and deducted from the results.

RESULTS AND DISCUSSION

Microparticle Concentration in the Surface Snow and Aerosol

Microparticles of mineral dust are divided into two parts based on the size: small particle with d<1 μm and large particle with d>10 μm. In this article, surface snow includes fresh snow and drifting snow. Drifting snow can affect microparticle concentration in two ways: (1) by scavenging particles from the lower levels of the atmosphere; (2) by moving and redistributing the snow. Figure 2 shows temporal change of concentration of the large particles, small particles and the total particles in the surface snow and aerosol over Glacier No. 1.

For large particles, the high mean value of 238 mL^{-1} in number in aerosol is observed during early winter (November to January), and the mean value of summer is 174 mL^{-1}. In the surface snow, increased dust particle concentration also appeared in winter (November to February) and summer (June to August) with mean concentration of 2.6×10^3 and 2.4×10^3 number mL^{-1}, respectively. Different from the surface snow, in aerosol there is a minor peak value in spring, which suggests strong influence from dust storm occurring in the Central Asian region during springtime (Liu et al., 2003; Wang et al., 2003).

The mean concentration of small particles in aerosol reached the maximum (4.2×10^4 number mL^{-1}

for both) in spring (March to May) and late summer (July to August). In the surface snow, high dust particle mean concentration with 1.4×10^5 and 1.5×10^5 number mL^{-1} appeared in winter and spring, respectively. As an indicator of long distance transport, concentration peak value of small particles in aerosol is as sporadic as the dust storms (Ing et al., 1969), which results in intense fluctuations of dust activity in spring dust period; and the high concentration in summer may attribute to the condensation of moisture. No strong correlation of dust concentration is found between the fresh snow and aerosol, which implies that small particles in surface snow are more sensitive to post-depositional process, such as elution by meltwater and redistribution by drifting snow.

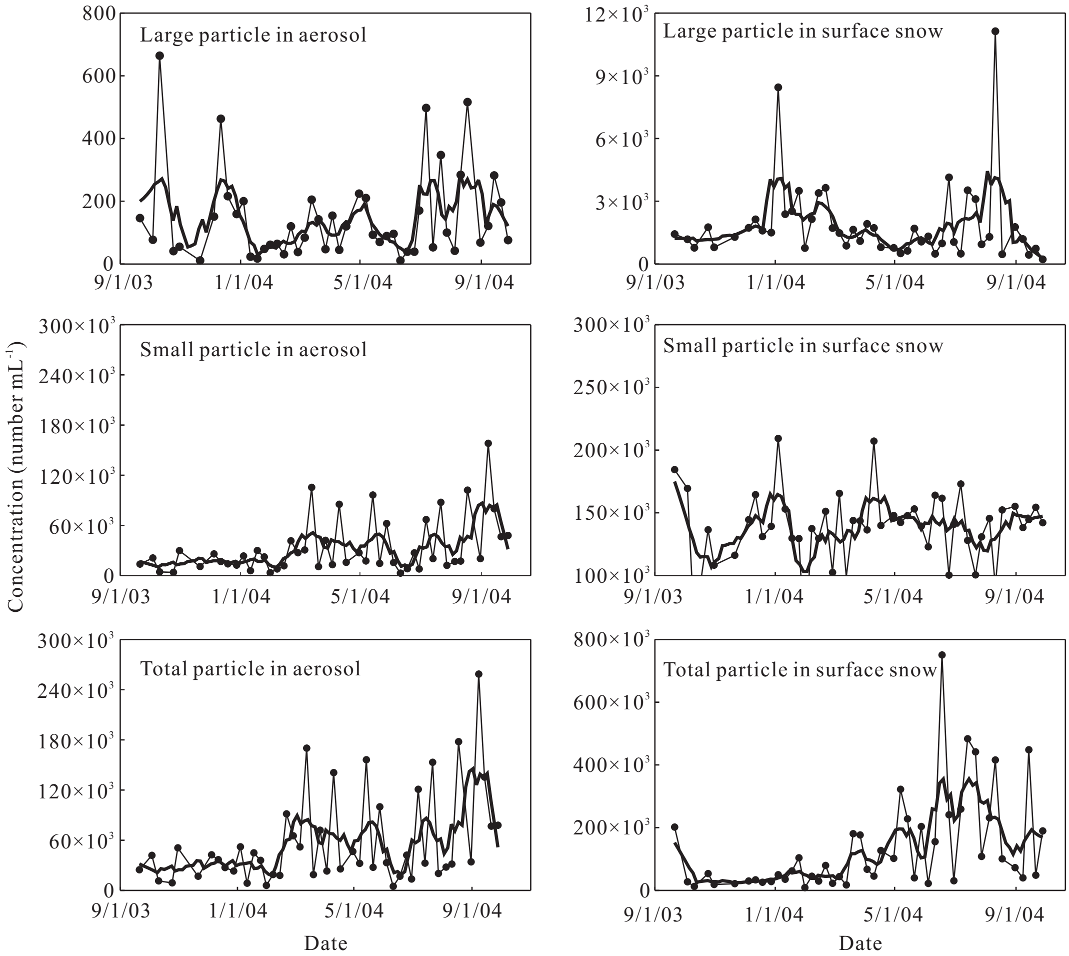

Figure 2. Large, small and total microparticle concentration in surface snow and aerosol. The curves are smoothed through running average technique with sampling proportion of 0.100.

Total concentrations of dust particles, with the intense fluctuations from March to September, have similar trends in surface snow and aerosol. The maximum numbers of concentration in aerosol and fresh snow are found in spring (7.2×10^4 number mL^{-1}) and summer (2.5×10^6 number mL^{-1}), respectively. It indicates that total particle concentration in aerosol is strongly correlated to small particles, because the particles with diameters of d<1 μm are resistant to be scavenged in the atmosphere (Radke et al., 1980). Different from that in aerosol, in the surface snow, great discrepancy exists between small and total particles concentration, which suggests that the middle particles (1–10 μm in diameter) are dominating in total particles after deposition.

Deposition Process of Dust Microparticles from Aerosol to Surface Snow

The ratios of microparticle concentration in surface snow to that in aerosol, and temporal change of microparticle concentration, precipitation, and wind speed during the sampling period are analyzed, to illustrate the effect of the main factors on the relationship between aerosol and surface snow, and then to understand the deposition process of dust particles from atmosphere to snow on the glacier of the Alpine region (Figs. 3 and 4). Intense variations of the ratios suggest a poor relationship between concentration in surface snow and in simultaneous aerosol, and also indicate an intense fluctuation both in surface snow and in aerosol. We could infer that, microparticle concentration in surface snow is an average mean value of dust deposition during sampling intervals; while in aerosol, it reflects an instantaneous condition of atmospheric environment in high mountains.

There were apparent fluctuations for the ratios of particle concentration in surface snow to that in aerosol from late March to late August, which were accordant with frequent precipitation (Fig. 3). Stable variation with low ratios was found from November to February with high correlation coefficient (R^2=0.7) of concentration between the surface snow and aerosol. Dust microparticle transport is associated with cold fronts and depressions with strong barclinic gradients during winter period (Ing, 1969). Most of the dust particles transported throughout the Tianshan Mountains are entrained and transported eastward by the westerly winds in the spring during dust storm period. At the same time, most of the moisture are brought and advected to the Glacier No. 1 by the westerlies (Aizen et al., 1993). Thus, the majority of precipitation and microparticles deposition on Glacier No. 1 occur during the spring and summer. This phenomenon is reflected by the intense variations of ratios of microparticle concentration in surface snow to that in aerosol from late March to late August (Fig. 3). During November to February, there is very little precipitation occurrence; particles are transferred mainly through atmosphere on flow and turbidity as well as their gravity. A balance is maintained between the aerosol and snow depended mostly on atmospheric carrying capacity and particles size. Therefore, high correlation between surface snow and aerosol was found during this period.

Figure 4 shows temporal variation of ratios of large particle concentration in surface snow to that in aerosol, and the speed of prevailing wind during the corresponding period. Two strong fluctuations from December to March and June to August are observed, together with relatively high speed of the prevailing wind. However, during the period marked with S_1, the most stable period for total ratio-curve (Fig. 3), no

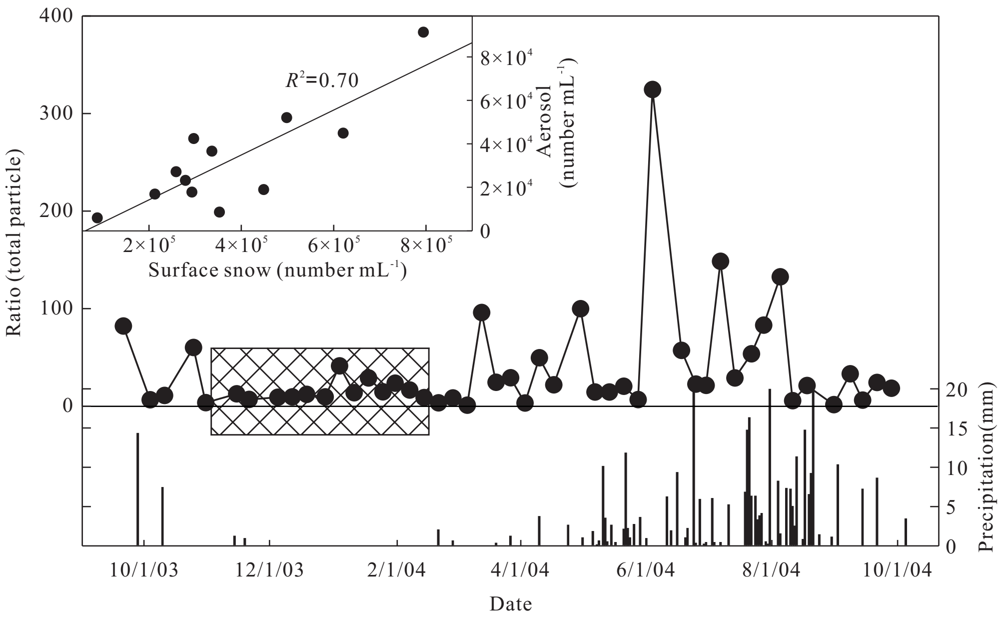

Figure 3. The ratios of microparticle concentration in surface snow to that in aerosol and precipitation against date. The straight lines plot indicates variation of ratios; the vertical bars chart shows precipitation during the corresponding period; the top left corner plot is the linear regression curve of microparticle concentration in surface snow and in aerosol based on the data from rectangular box.

significant fluctuation was found. Large particles are considered as a good indicator of local circulation and atmospheric environment. The wind speed illustrated in Fig. 4 is the wind condition of the northwest and northeast in the glacial region of Urumqi River source, which dominates the region during winter and summer respectively in this region. The high ratios of large particle concentration during the S_1 and S_2 periods are mainly attributed to the prevailing winds, which cause more local coarse particles input into the atmosphere and then increase large particles concentration. In addition, the northeast wind also brings much precipitation due to the frontogenesis when it climbs the high mountain (Li, 1991). However, gravity of large particles is also important for deposition from aerosol to snow on the Glacier No. 1 in Tianshan Mountains.

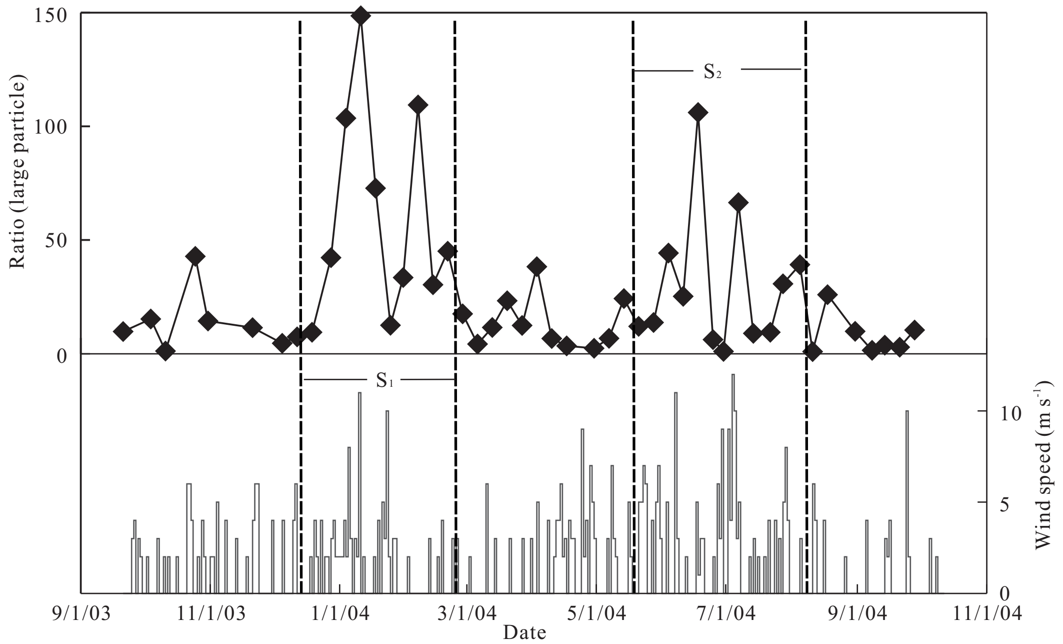

Figure 4. Ratios of large particle concentration in surface snow to that in aerosol and the speed of prevailing wind (sum of speed of northwester and northeaster) against date. The straight lines plot with diamond (◆) shows year-round ratios; the vertical bars chart outlines wind speed during the corresponding period.

Evolutional Process of Dust Microparticles in the Snow-Firn Pack

Much research (Wake et al., 1994; Thompson et al., 1989; Thompsen, 1977) has indicated that, based on the seasonal variation of microparticle concentration, dust layers have been used to date ice cores from glaciers in various sites of the world. However, microparticle concentration in snow-firn pack is significantly affected by post-depositional process of melt water. Therefore, it is necessary and important to learn how the microparticle evolves in the snow-firn pack and is preserved in the ice core. Figure 5 shows a typical example of the profiles of microparticles in the snow-firn pack, which indicates that the visible dust layers in the snow-firn pack are in good coincidence with concentration peaks of large dust particles. Moreover, mean size of dust is a good indicator for dust layer as they are also very coincident with each other in the snow-firn pack. Small particles (d<1 μm) may not be concentrated in dust layers as inferred from Fig. 5, which suggests that they are sensitive to the elution and post deposition by melt water in the snow. According to the coincidence between dust layers and large particle concentration peaks, we try to determine the evolutional process of dust layers in the snow-firn pack based on more than 54 stratigraphy profiles of snow pits and detailed microparticle concentration, by tracing the typical dust concentration peaks (Fig. 6).

In Fig. 6, found in late summer 2002, P_1 was 58 cm above the ice surface on 30th August 2003. It was extremely steady and its input or output of dust particles was rather limited due to little melt water influence. P_2, as a result of strong melting during summer,

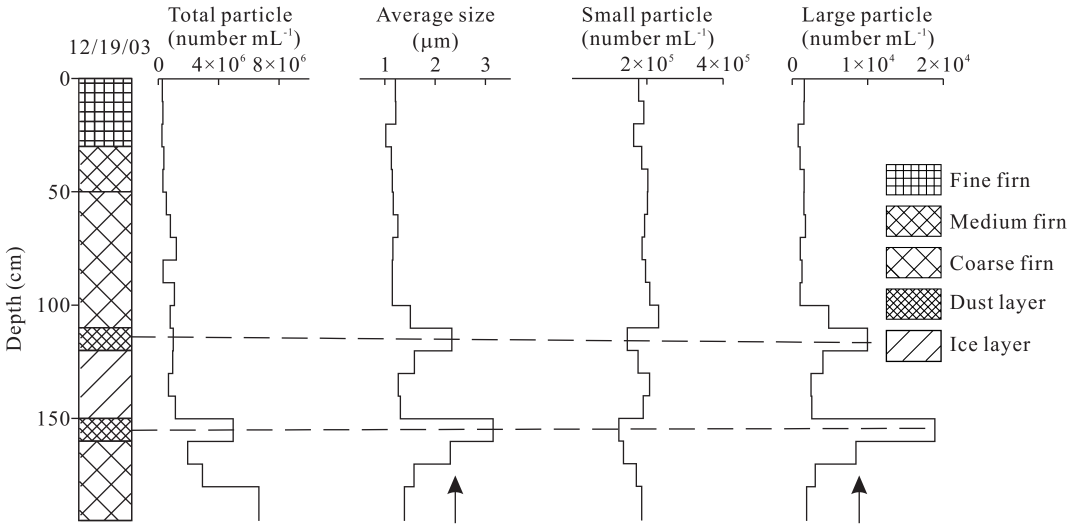

Figure 5. Depth profiles of microparticles in the snow-firn pack of Glacier No. 1. Dashed lines show the relationship between dust layers and peaks. The figures marked by arrows show a strong match between average size and large particles.

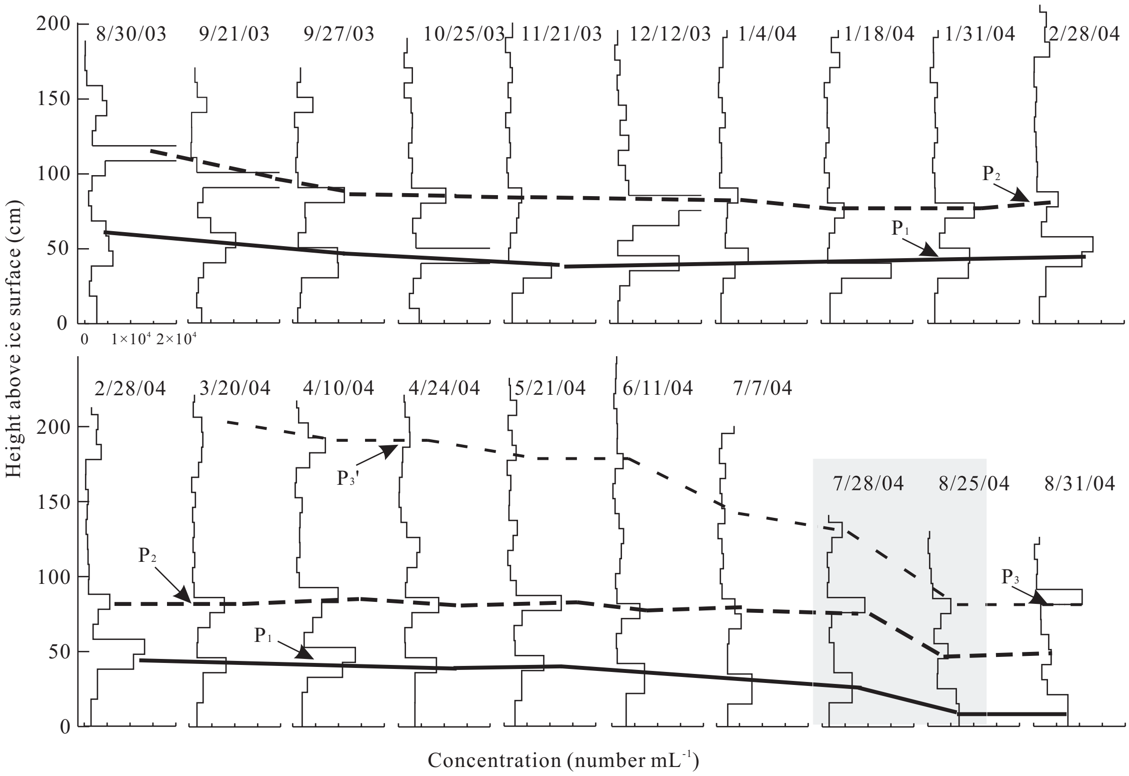

Figure 6. Large particles develop in snow-firn pack. A complete year-round concentration data of large particles (from 30th August 2003 to 31st August 2004) are exhibited here. P_1, P_2 and P_3 indicate three typical dust-peak layers.

was found in late summer 2003 with the initial distance of 108 cm above the ice surface. It can be seen that in winter, spring and late autumn, the entire snow-firn packs were stable and peak P_2 moved towards the ice surface at slow speed forced by densification process. In early summer, along with the increase of air temperature and melt water in the snow, the evolution of P_2 was intensified, characterized by quick transport velocity of microparticles. Some small dust peaks in the upper part of the snow-firn pack, formed by snowfall and wind blowing, moved downwards and then were affiliated to peak P_2 (Fig. 6). In addition, another obvious peak P_3' considered as the results of the frequent dust events, occurred in spring. As a good carrier, P_3' received other new peaks to become more obvious. On the other hand, it acted like a protection layer to block microparticles traversing. From late July to late August (shading area in Fig. 6), intense variations were observed for the three peaks. P_1 arrived at the ice surface and then merged into granular ice around 31st August 2004. During this period, the latent heat, released from melt water percolation and refreezing, is an important thermal source to heat the firn layers at the bottom of the snow pit, which will cause more melt water and further refreezing. As a result, much granular ice was formed and ice surface was enhanced. Meanwhile, P_3' was consolidated at the position 95 cm above the ice surface in 31st August 2004 (P_3). Different from P_3', P_3 was the result of strong eluviations (like P_1 and P_2). The significant information on date and corresponding position of peaks are abstracted from Fig. 6 to show clear evolutional process of dust-peak layers (Fig. 7).

In conclusion, we find that when atmospheric dusts deposit in the surface snow on the glacier, microparticles could be concentrated to particular firn layers because of the influence of melt water percolation, firn characteristics and firnification process, and so on. In the mean time, the particles-rich layers move down and integrate with the neighboring one, and finally consolidate in late summer as a heavy dust layer. Then, the dust layer moves down at a low speed with the dust information of one year, and continuously receives microparticles until a new weak dust layer occurs in the next spring. Finally, the dust layer is well preserved in granular ice of the glacier in the Alpine region. The force to make the lower peaks move down is firnification process under the stress and recrystallization. It could be proven through the similar motional trend between bamboo stakes (a part of the program for glacier processes investigation, on determination of time scale of snow-ice transformation through bamboo stake tracing method; You et al., 2005) and particle peaks. It is emphasized that there was an infrequent high temperature in 2002; strong melt water most probably percolated several annual layers, and may lead to combination and disappearance of some dust layers in the snow pit on Glacier No. 1.

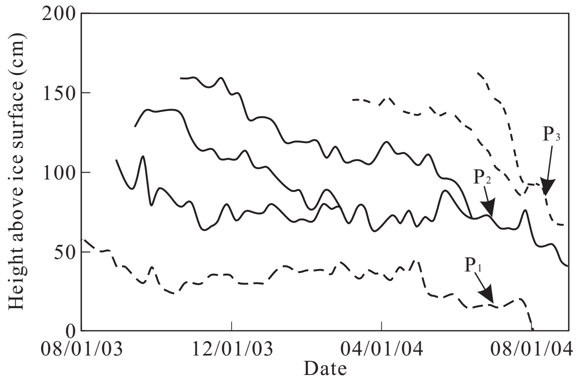

Figure 7. Evolutional graph of large particles with main peaks. More detailed information on incorporation of peaks is laid out. Small fluctuation is probably from man-made error. P_1, P_2 and P_3 indicate three typical microparticles peaks.

CONCLUSIONS

Long-term microparticles data from snow and aerosol are presented to explore the depositional and post-depositional process of dust from aerosol to fresh snow and snow-firn pack on Glacier No. 1 in eastern Tianshan Mountains. Total microparticle concentration in the surface snow and aerosol indicates a similar temporal variation trend, which was strongly associated with large-scale and local atmospheric circulation. Especially from November to February, the correlation coefficient of microparticle concentration in surface snow and aerosol is very high (R^2=0.7). Vertical profiles of microparticle in the snow pits showed that dust layers were in high correlation with concentration peaks of large particles (d>10 μm), but low correlation with that of fine particles (d<1 μm). Moreover, explicit post-depositional process of dust particles was studied by tracking some typical dust concentration peaks. We find that late summer is a key period for dust particle post-deposition in snow, as particle concentration peaks in the snow pit evolved intensely during this period. Such evolutional pattern of large particles makes it possible to preserve information of atmospheric dust in the snow, which offers an available proof to reconstruct historical climate using ice cores on Glacier No. 1 and other glaciers in the Tianshan Mountains. However, the relationship between dust in the ice core and atmospheric environment change, and the effect of the dust content in glaciers on glacier melting in this region remains unclear,and further work is needed in the future.

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