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Microscopic Analyses of Insoluble Particles in an Ice Core of Ürümqi Glacier No. 1: Quantification of Mineral and Organic Particles

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ABSTRACT: Insoluble particle concentration in ice cores is commonly analyzed as a proxy for variations in atmospheric mineral dust (aerosol concentration). However, recent studies have revealed that the mineral dust is not only a constituent of the particles but that biogenic organic particles are also contained. We microscopically analyzed insoluble particles in a shallow ice core drilled on a mountain glacier, the Ürümqi Glacier No. 1, in eastern Tienshan, China. We distinguished different morphological particles in the ice core and quantified them separately. Results showed that the insoluble particles in this ice core consisted mainly of mineral particles, amorphous organic particles, pollen, and microorganisms. Mineral particles were the most dominant, accounting for approximately 67% of total particles, and amorphous organic particles were the second most dominant, accounting for approximately 33% of the total. The annual variation in the particles for the last 11 years differed between mineral and amorphous organic particles. The results suggest that the total insoluble particle concentration in the ice core reflects not only the atmospheric mineral dust but also the organic particles blown from ground soil or produced by microbes on the glacial surface.

KEY WORDS: ice core, insoluble particle, mineral dust, microbes, organic particles.

INTRODUCTION

Ice cores drilled from glaciers in polar regions and high mountains can provide a wealth of information on past climate and environment. Insoluble particles in ice cores are commonly analyzed in order to know variations in the atmospheric dust concentration (e.g., Yang et al., 2006; Delmonte et al., 2002; Thompson et al., 1989). The atmospheric dust concentrations reflect dust storms, dryness of climate, and also atmospheric circulation patterns, vegetation, and other environmental conditions. Atmospheric dust also has a significant effect on radiative forcing in the climate system (e.g., Liao and Seinfield, 1998). There-

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fore, reconstructions of temporal variations in atmospheric dust concentrations are important to understand past and recent climate change.

On Asian glaciers, the concentration of insoluble particles in ice is significantly higher than those of polar glaciers or icesheets because the glaciers are located close to sources of mineral dust. For example, the insoluble particle concentration of the East Antarctic ice core was 3.9×10^3 number mL^{-1}, whereas that of the Asian ice core was 2.9×10^5 number mL^{-1} during the Holocene, which is two orders of magnitude higher than those of the polar ice core (Delmonte et al., 2002; Thompson et al., 1989). Vast deserts located in Asia, such as the Taklimakan, Gurbantunggut, and Gobi, are major sources of windblown mineral dust. In these regions, dust storms usually occur in spring and deposit enormous amounts of fine desert particles on the glacier surface in the high mountains. Such annual deposits form dust layers and can be visibly observed in ice cores. The insoluble particle concentrations in the ice cores have been used to determine annual layers (e.g., Takeuchi et al., 2009a; Han et al., 2006) and have revealed the frequency of dust storms, droughts, and dryness in the regions (e.g., Yang et al., 2006; Thompson et al., 1989).

Recent studies have revealed that such insoluble particles in ice cores consist not only of mineral dust but also of biologenic organic particles, such as pollens, microbes, and other organic matter. Many studies have reported that there are biological communities consisting of snow algae, microfauna, insects, and bacteria growing on the glacier surface (e.g., Hoham and Duval, 2001; Kohshima, 1987). These organisms are specialized taxa that have adapted to extremely cold environments. Such microbes have been found in ice cores. For example, significant amounts of snow algal cells and organic particles have been found in ice cores drilled from Himalayan, Tibetan, Altay, and Patagonian glaciers (e.g., Takeuchi et al., 2009b; Kohshima et al., 2007; Uetake et al., 2006; Yoshimura et al., 2000; Kohshima, 1989). A number of pollen grains have also been commonly found in ice cores drilled in Asian mountains (e.g., Nakazawa et al., 2004).

In most studies, insoluble particle concentrations in ice cores are measured electrically with a Coulter counter or optically with a laser particle counter. Such equipment can measure the particle concentrations separately in different size ranges. However, they cannot distinguish between mineral and organic particles. Although the particle concentrations obtained by the above equipment have been regarded as involving mineral dust, the concentrations possibly include organic particles. Thus, they may be overestimated as a proxy for atmospheric mineral dust. However, quantities of each constituent of the mineral and organic particles in the ice core are unknown.

This study aims to investigate constituents of insoluble particles in a shallow ice core drilled from the Ürümqi Glacier No. 1, in western China. We microscopically distinguished different morphological particles and quantified them separately. The variations in each of the different particles are discussed in terms of their sources.

STUDY SITE AND METHODS

Ürümqi Glacier No. 1 is located at the headwaters of the Ürümqi River in eastern Tien Shan of Central Asia (Fig. 1). The glacier is surrounded by vast deserts; the Taklimakan in the Tarim basin to the south, the Gurbantunggut in the Junggar basin to the north, and the Gobi desert to the east. With a typical continental climate, the westerly jet stream prevails across these high mountains. Ürümqi Glacier No. 1 is a northwest-facing valley glacier composed of east and west branches covering 1.73 km^2 and lies between 3 740 and 4 486 m above sea level (a.s.l.). The recent mean equilibrium line altitude was measured as 4 110 m a.s.l. (1997–2003, Ye et al., 2005).

An ice core was drilled on the snow surface of this glacier at 4 130 m a.s.l. in November 2006. This was the experimental site of a research program for glacier process investigation (PGPI) carried out by the Tien Shan Glaciological Station, Chinese Academy of Sciences. This program investigates the effects of deposition and meltwater-related post-depositional processes on chemical signals recorded in glacial snow and ice (e.g., Li et al., 2006). The site was selected in a percolation zone where there was no direct wintertime exposure to sunshine due to the shadowing effect of the mountain ridges. The mean annual air temperature and precipitation at the site were -9.1 ℃

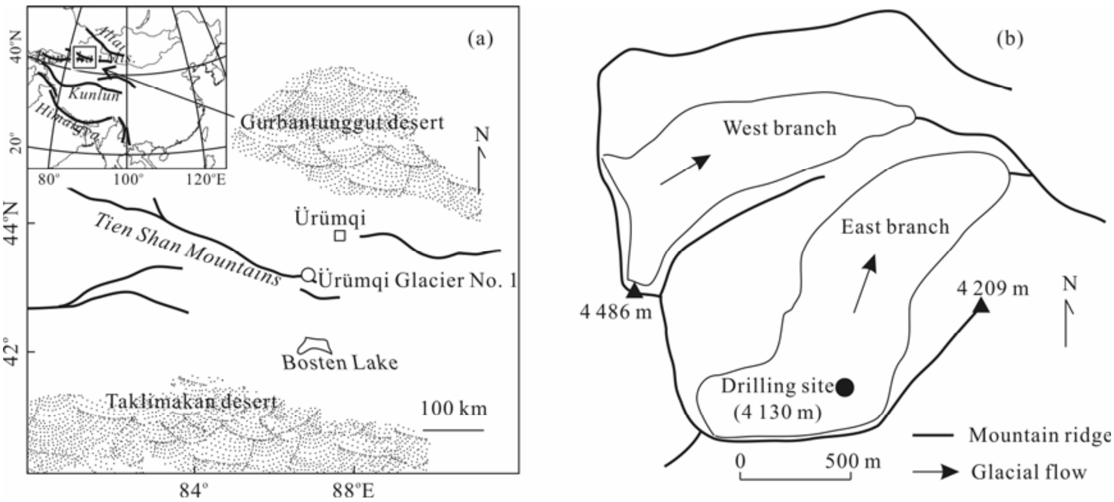

Figure 1. Geographical location (a) and map (b) of the Ürümqi Glacier No. 1 in the Tien Shan Mountains, China. Ice core drilling site is shown on the map.

and 700 mm (water equivalent) during the experimental period (Li et al., 2007). Maximum precipitation and snow melt occur in the summer. The ice core was drilled from the bottom of a snow pit 2.6 m below the surface down to 7.7 m (total length: 5.1 m). The ice core was obtained at intervals of about 50 cm, with 11 sections in total. While frozen, they were transported by truck to a cold room of the Cold and Arid Regions Environmental and Engineering Research Institute in Lanzhou, China, and cut in half lengthwise. They were then flown by air cargo to a cold laboratory in the Research Institute for Humanity and Nature in Kyoto, Japan. In the laboratory, all core sections were weighed to obtain their densities. The density was calculated by dividing the weight of each core section by its semicircular columnar volume. The visual stratigraphy of all core sections was recorded. The core was then cut about every 5.5 cm. The surface of core samples was scraped off to eliminate contamination with ceramic knives. The samples were packed into sterilized plastic bag and transported while frozen to the laboratory of Chiba University. Snow pit samples were also collected at the drilling site every 5–15 cm from the surface to 3.7 m deep. The pit samples were also transported while frozen state to the laboratory of Chiba University. The total number of samples was 123 (ice core: 96; snow pit: 27). Both the ice core and snow pit samples were melted, dispensed into clean bottles, and preserved as a 3% formalin solution at room temperature.

Insoluble particle concentrations in each sample were quantified by microscopy. The 200 μL of sample water was filtered through a membrane filter (pore size 0.2 μm, 13 mm diameter, H020A013A), which became transparent with the addition of water, and the number of insoluble particles on the filter was counted under an optical microscope at 200× magnification (Olympus, BX51TF). The range in size of particles counted in this study was from 5 to 200 μm. Particles smaller than 5 μm were not counted because they could not be distinguished from each constituent by microscopy at the given magnification. From the particle count number on the filter and filtered sample water, the particle concentration (number mL^{-1}) of each sample was obtained. The estimated error in this procedure is 15%. The number of autofluorescent algae on the filter was counted with a fluorescence microscope. However, since for the estimated error in this cell count, it was too large to evaluate the depth profile of cell concentration, their concentrations were represented by relative abundances in this study. To confirm whether the insoluble particles were organic matter, some samples were placed in a 30% hydrogen peroxide solution for 24 h. Changes in particles from the samples after this treatment were observed with a microscope. Only organic particles should have dissolved in the solution.

RESULTS

Visual Stratigraphy and Density of Snow Pit and Ice Core

The stratigraphies of the snow pit and ice core are shown in Fig. 2. There was fresh snow at (0–0.14 m depth) and compacted snow at (0.14–0.80 m) near the surface. The remaining lower part was a mix of firn and ice layers. Twelve dust layers were visibly apparent in the stratigraphy. Ten of them were observed in the ice layers and two in the firn layers (depth: 2.3 and 4.3 m).

The density of the ice core ranged from 470 to 917 kg·m^{-3} (mean: 710 kg·m^{-3}, Fig. 2). The density of the firn layers ranged from 470 to 660 kg·m^{-3}, while that of the ice layers ranged from 694 to 917 kg·m^{-3}.

Morphology of Insoluble Particles

Microscopy of the pit and ice core samples revealed that they contained various insoluble particles. The particles observed were mineral particles, amorphous organic particles, pollens, and microbes, such as cyanobacteria and green algae (Figs. 3 and 4).

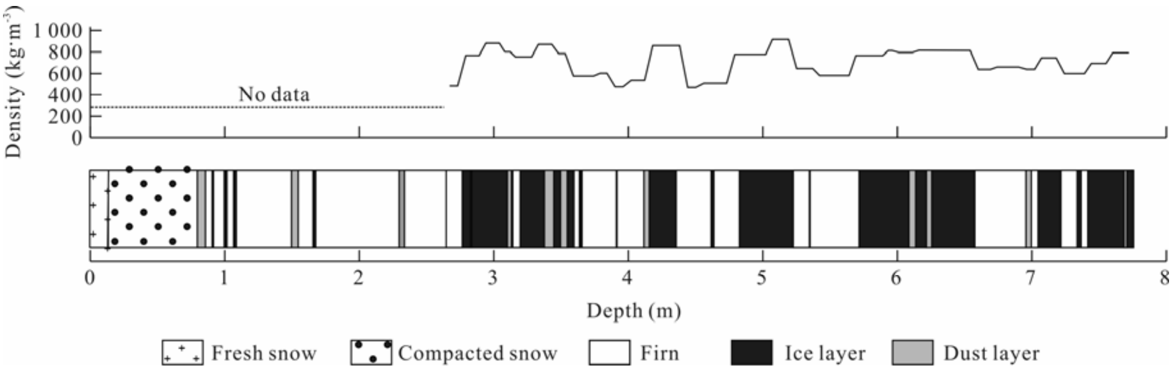

Figure 2. Stratigraphy and density profile of the snow pit and ice core of the Ürümqi Glacier No. 1.

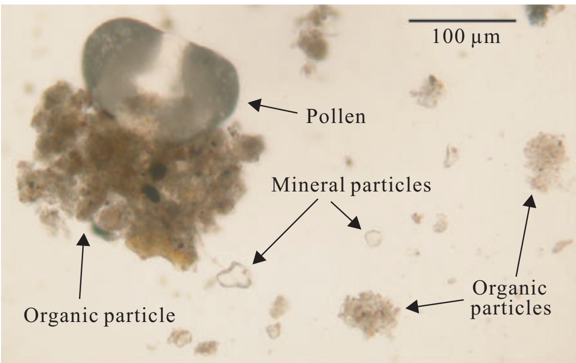

Figure 3. Microscopic photograph of the constituents of the insoluble particles in the ice core of the Ürümqi Glacier No. 1.

Most of the mineral particles were transparent or yellow, with the size of the mineral particles ranging from 5 to 120 µm. Most of the mineral particles appeared to be quartz, feldspar, mica, calcite, and clay minerals. The smaller particles (5–10 µm in diameter) were generally round, whereas the larger particles (over 50 µm) were mostly flat plate-shaped mica.

Amorphous organic particles were clearly distinct from mineral particles in morphology. The outlines of the organic particles were not straight, like mineral particles, but were obscure curved lines. They were brown or dark brown in color. The size of the organic particles ranged from 5 to 300 µm. The large-sized organic particles mostly seemed to be aggregates of smaller organic particles and mineral particles, pollens, and/or microbes. These particles completely disappeared after treatment in hydrogen peroxide solution, confirming that they were organic matter.

The pollens, cyanobacteria, and green algae were observed in the samples under a fluorescence microscope. The pollens observed in samples included taxa of Pinaceae, Betula, Ephedra, Artemisia, and Chenopodiaceaed. Most cyanobacteria and green algae were found to be aggregates with amorphous organic particles (Fig. 4). The cyanobacteria in the samples were filamentous or unicellular. Filamentous cyanobacteria ranged 2 µm in width, and the unicellular ones were 5–10 µm in diameter. The green algae were spherical, 10–20 µm in diameter.

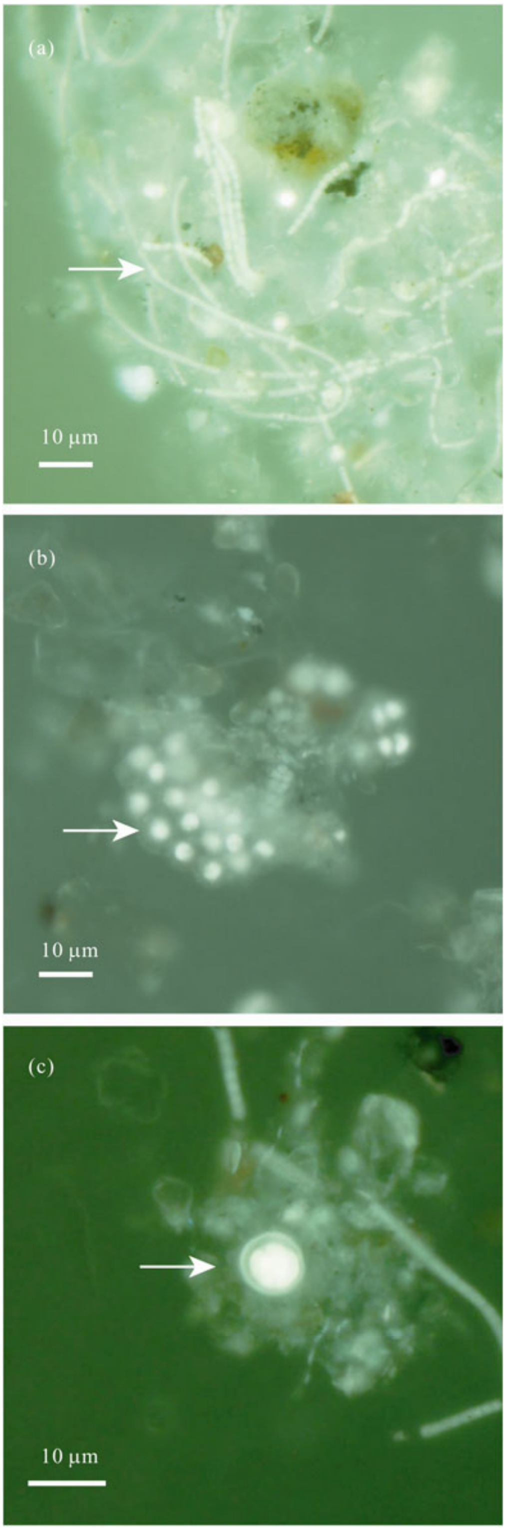

Figure 4. Fluorescent microscopic photographs of the cyanobacteria and snow algae observed in the ice core of the Ürümqi Glacier No. 1. (a) Filamentous cyanobacteria; (b) coccoid cyanobacteria; (c) green algae.

Concentrations of Insoluble Particles

The total particle concentration in the 7.7 m of the snow pit and ice core significantly varied with depth (Fig. 5a). Particle concentrations ranged in 8.2×10^2–1.6×10^5 number mL^{-1} (mean: 3.0×10^4 number mL^{-1}). The profile showed 13 prominent spikes. The largest four spikes exceeded 1.0×10^5 number mL^{-1} and occurred at 0.9, 2.2, 3.1, and 6.1 m depth.

The depth profiles of the two most abundant constituents (mineral and organic particles) showed that they were significantly different from each other (Figs. 5b, 5c. The concentration of mineral particles ranged in 8.2×10^2–1.5×10^5 number mL^{-1} (mean: 2.0×10^4 number mL^{-1}). The mineral particle profile was generally similar to that of the total particle concentration and showed 13 prominent peaks (P1–P13 in Fig. 5). The concentrations of amorphous organic particles were generally lower than those of mineral particles. They ranged in 0–4.2×10^4 number mL^{-1} (mean: 9.8×10^3 number mL^{-1}), and their profile was completely different from those of mineral and total particle concentrations. The prominent spikes observed in total, and mineral particles were not as apparent as those seen in organic particles. The relatively higher concentration of organic particles occurred at 3.1–3.6 m and 6.1 m depth. There were small peaks in the particles, which tended to be located just below the peak of mineral particles.

The percentage of organic particles within the total particle concentration ranged from 0 to 86% (mean: 42%, Fig. 5d). The samples with high total particle concentration (the 13 prominent peaks) tended to have a lower percentage of organic particles (7%–27%) with the exception of the peak at the depth of 3.54 m (45%). The relatively higher percentages (more than 60%) were observed in the samples of 3.1–5.4 m and 6.8–7.3 m depth.

The relative abundances of cyanobacteria (filamentous and coccoid) and green algae in 5.1 m ice core were shown in Figs. 5e, 5f, and 5g. The samples that contained filamentous, coccoid cyanobacteria, and green algae were 54, 91, and 79, respectively, out of 96 samples. Their cell concentrations ranged in 0–1.6×10^4 filaments mL^{-1} (mean: 7.8×10 filaments mL^{-1}) for filamentous cyanobacteria, 0–5.0×10^3 cells mL^{-1} (mean: 2.0×10^2 cells mL^{-1}) for coccoid cyanobacteria, and 0–6.0×10 cells mL^{-1} (mean: 1.6×10 cells mL^{-1}) for green algae. The filamentous bacteria were relatively abundant from 2.5 to 3.6 m. The coccoid cyanobacteria showed two abundant layers at 0.8 and 7.1 m. The green algae were relatively abundant at 3.0, 3.5, 4.4, 5.1, 6.1, and 7.7 m.

Dating of Ice Core and Annual Flux of Particles

Annual layers were dated using the variations in mineral particle concentrations and stratigraphy. There were 13 prominent peaks (P1–P13 in Fig. 5) in the mineral particles, and the peaks are likely to correspond to spring maximum of mineral dust deposition on the glacier, which is a common phenomenon in this region (e.g., Li et al., 2007). However, two peaks (P7 and P12 in Fig. 5) out of the 13 seem to be subpeaks

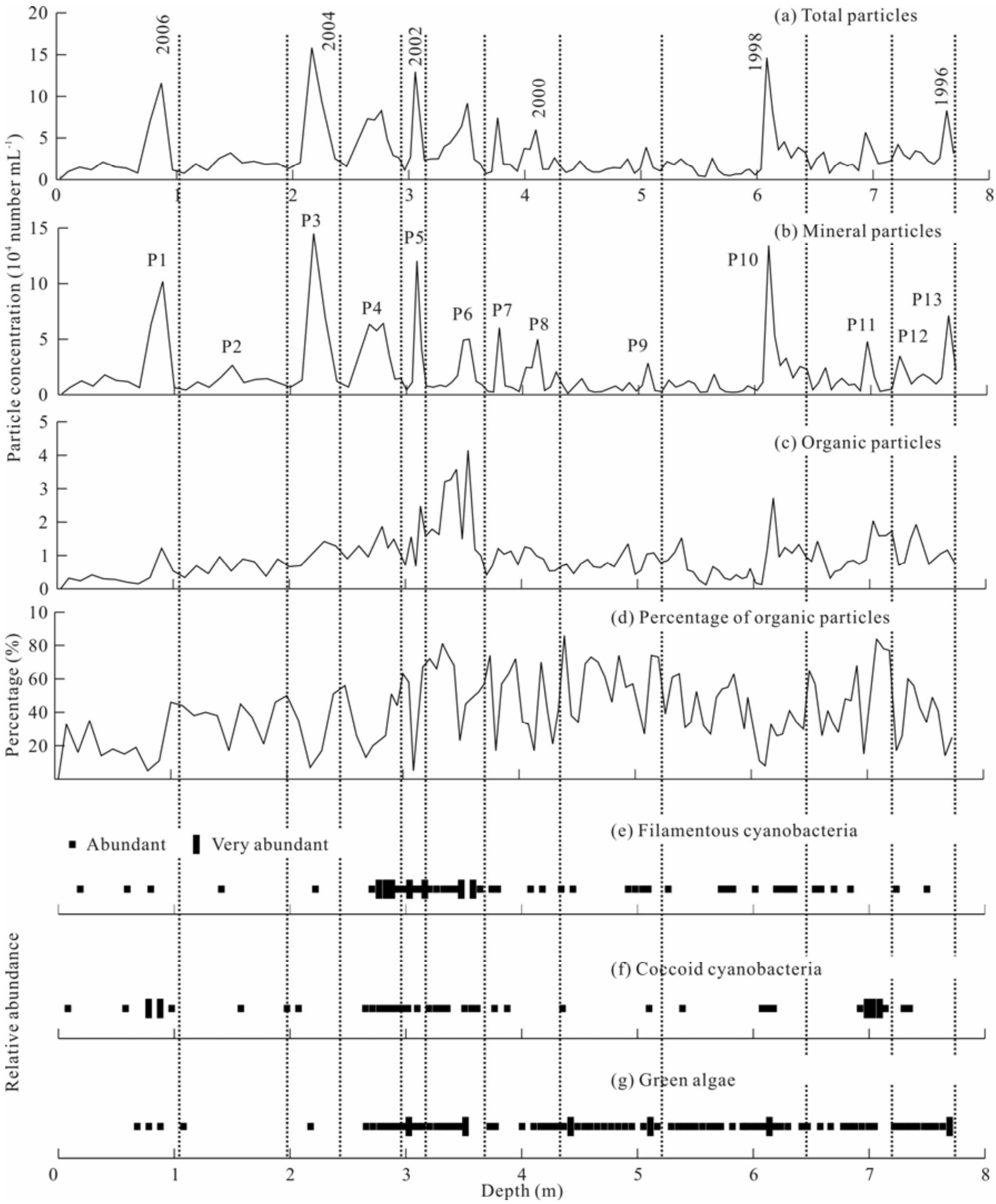

Figure 5. Profiles of concentrations of (a) total insoluble particles (>5 µm), (b) mineral particles, (c) organic particles, (d) percentage of organic particles, and relative abundances of (e) filamentous cyanobacteria, (f) coccoid cyanobacteria, and (g) green algae in the ice cores of the Ürümqi Glacier No. 1.

formed in winters, because they were found at firn layers. Therefore, we used 11 mineral particle peaks and stratigraphy as annual signals to determine the boundary of the annual layers. The dating showed that this 7.7-m-deep record covered the last 11 years from 1996 to 2006. However, there were some unclear peaks of the particle concentration that may cause ambiguous identification of annual layers. Thus, the dating uncertainty at the end of the core is possibly 2 years or less.

Based on the dating, the annual flux of the total particles on the glacier was found to range from 17×10^4 to 65×10^4 number $cm^{-2}\cdot a^{-1}$ (mean: 33×10^4 number $cm^{-2}\cdot a^{-1}$, Fig. 6). The highest flux of the total particles was in 1998. The flux in mineral particles ranged from 11×10^4 to 45×10^4 number $cm^{-2}\cdot a^{-1}$ (mean: 22×10^4 number $cm^{-2}\cdot a^{-1}$). The highest flux of the mineral particles was in 1998, as it was for the total particles. In 1998, an extreme dust storm took place in this region (e.g., Murayama et al., 2001). The highest flux of the mineral particles in 1998 corresponded with this event, suggesting the consistency of the dating.

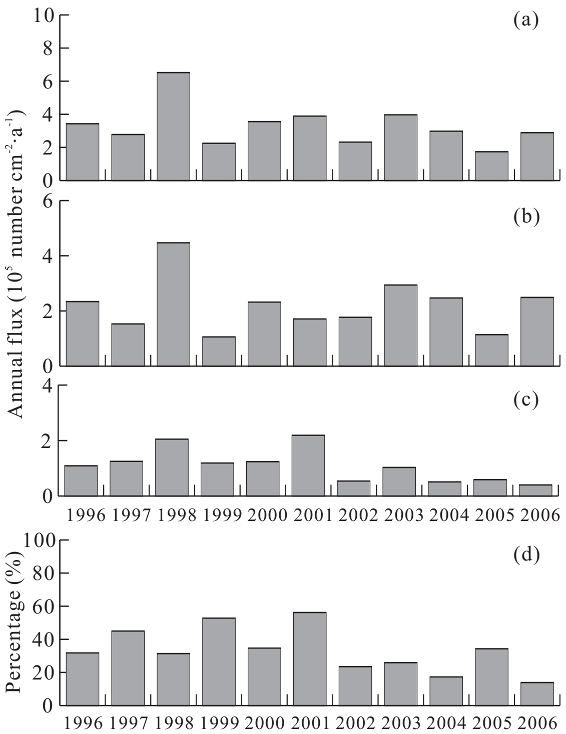

Figure 6. Annual variations in (a) total insoluble particle flux (>5 μm), (b) mineral particle flux, (c) organic particle flux, and (d) percentage of organic particles reconstructed the ice core of the Ürümqi Glacier No. 1.

The flux of organic particles ranged from 40×10^3 to 22×10^4 number $cm^{-2}\cdot a^{-1}$ (mean: 11×10^4 number $cm^{-2}\cdot a^{-1}$). The flux was relatively high in 1998 and 2001. The proportion of organic particles also significantly varied, with percentages ranging from 13.9% (2006) to 56.2% (2001). The percentages differed significantly between the two high flux years (31.4% in 1998 and 56.2% in 2001).

DISCUSSION

Results showed that mineral dust particles were not the only constituents of the insoluble particles in the ice core of this glacier. Mineral and organic particles were the two major constituents, accounting on the average, for 67% and 33% of the total insoluble particles in the ice core, respectively. This fact indicates that the total particle concentrations measured with an automatic particle counter would be overestimated if used as a mineral dust proxy. However, the depth profile of the total particle concentration in the ice core was generally similar to the profile of the mineral particles. The depths of prominent spikes and the relative values between them were in good agreement (Fig. 4). Hence, the variation in the total insoluble particles can mostly be explained by the variation in mineral dust supply on the glacier.

The depth profile of the particle concentrations significantly differed between mineral and organic particles, suggesting that each particle was derived from a different source. The variation in the annual flux on the glacier also significantly differed between mineral and organic particles. Windblown dust is the only source of the mineral particles. However, it is unlikely to be the source of organic particles because it is in a different depth profile. The proportion of the organic particles to the total particles varied significantly within the depth profile. The percentage of organic particles at the total particle peaks tended to be lower, suggesting that the spring dust event mostly involved mineral particles. By contrast, the variation in organic particles changed little with the seasons.

The mineral dust particles are likely to be blown in from a distant desert, probably the Junggar desert located north of the glacier, judging by the major wind direction (Sun, 2002). The difference in the size distribution of the mineral particles among layers suggests that they come various distances from their source. Size distribution particularly differed between the spring peaks and other layers. The mineral particles smaller than 10 μm were dominant in most of the layers including spring peaks and other low concentration layers. This suggests that smaller particles constantly fall on the glacier throughout seasons of the year. The mineral particles of the spring peaks contained particles larger than 15 μm. Particles larger than 100 μm were also found in the samples of the two large peaks (P5 and P9), but they would be too large to be wind-carried here from a distant desert. Such particles are probably derived from nearby ground surface and/or rock walls surrounding the glacier.

There are some possible sources of organic particles on the glacier, one of them being the ground soil around the glacier. Organic soil was distributed on grassland in downstream basins of the glacier. Soil organic matter usually consists of fine particles and could be blown to the glacier surface by wind.

Another possible source of organic particles is microbial activity on the glacier surface. Autotrophic microbes, such as cyanobacteria and green algae, are known to commonly live throughout glaciers in the world (e.g., Takeuchi et al., 2006). They photosynthetically produce organic matter on the surface snow and ice of the glaciers. Furthermore, heterotrophic organisms, such as rotifers, tardigrada, ice worms, copepods, insects, and bacteria, also live on the glaciers (e.g., Kohshima, 1987). Their biomass has been reported particularly abundant on Asian glaciers compared to those in other parts of the world (Takeuchi et al., 2006). Abundant filamentous and coccoid cyanobacteria have been reported on glaciers in the Himalayas, Kunlun, Qilian, and Tien Shan mountains, including Ürümqi Glacier No. 1 (Takeuchi and Li, 2008; Takeuchi et al., 2008, 2005, 2001; Kohshima, 1989). They form significant amounts of cryoconite granules, which are small spherical aggregates of cyanobacteria, bacteria, and mineral particles, and cover the ablation surface (Takeuchi et al., 2001). Therefore, biological activity on these Asian glaciers is likely to be high, and microbes, their dead bodies, and the decomposed granules could be among the organic particles in the ice core. Cyanobacteria and algal cells were contained in some organic particles in the ice core (Fig. 4). Such particles are likely to be derived from algae.

Proportions of the soil and microbial particles in total organic particles of the ice core are unknown. Most of the two organic particles are difficult to distinguish microscopically, because their specific characteristics including their size and morphology, could not be identified in this study. If most of the organic particles were windblown organic soil, the depth profile of the organic particle concentration would be similar to the mineral particles, which consisted only of windblown particles. However, the profile was significantly different from that of mineral particles, although some peaks between the two profiles were in agreement. On the other hand, if most of the organic particles were derived from snow algal production on the glacier surface, the depth profile of the organic particle concentration would be similar to that of the algal cell abundance. However, the relative abundances of algae were different from that of organic particles, and the concentration of algal cells was much smaller than that in the total organic particles. The organic particles are probably a mixture of both organic particle groups.

The profiles of algal cells indicate that green algae appeared every year, whereas cyanobacteria appeared in certain years on the glacier (Fig. 5). According to previous studies, cyanobacteria are usually distributed on the ablation ice surface of glaciers (e.g., Takeuchi and Li, 2008; Yoshimura et al., 1997). Therefore, the layers in which cyanobacteria were observed are likely to be formed during a significant melt. The high concentration of organic particles at 3.1–3.6 m depth (year: 2001) may be due to high algal production during that year, since algae were also relatively abundant in this area. On the other hand, the high concentration of organic particles at 6.1 m depth may consist mainly of soil organic particles, because the concentration of mineral particles was also high at that depth, and the percentage of organic particles was smaller than average (8%–33%). The reason for the high algal production in 2001 is uncertain. That may be due to a warm summer and/or the favorable chemical conditions of the snow. The variety of microbial productivity may reflect certain environmental conditions, such as melt intensity, nutrients, and solar radiation. However, further studies are necessary to identify the source of organic particles in the ice core.

The constituents of particles smaller than 5 μm were not analyzed in this study. The optical particle counter revealed that the insoluble particles smaller than 1.5 μm in diameter were abundant in snow on the Ürümqi Glacier No. 1 (Li et al., 2006). Such counters can usually measure particles larger than 0.5 μm. However, the constituents of particles smaller than 5 μm are unknown. Significant amounts of bacteria, usually measuring 1 to 5 μm, found in Asian ice cores (e.g., Xiang et al., 2009), are likely to account for a certain part of the small insoluble particles. Understanding constituents of insoluble particles in ice cores is important for interpreting the results of their measurements.

CONCLUSIONS

Microscopy of snow pit and ice core samples collected from Ürümqi Glacier No. 1 in western China revealed that insoluble particles in the samples had two main constituents: mineral and amorphous organic particles. The depth profile of the total particle concentration in the ice core was generally similar to the profile of the mineral particles; therefore, the variation in the total insoluble particles can mostly be explained by the variation in mineral dust supply on the glacier. However, the variation of organic particles significantly differed from those of mineral particles. The organic particles may be derived from ground soil around the glacier and/or microbes on the glacier surface. They may be potential indicators of the past environment; thus, further studies are warranted to understand the ongoing transportation and formation process of organic particles on the glacier.

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