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Establishing the Timing of Chemical Deposition Events on Belukha Glacier, Altai Mountains, Russia, Using Pollen Analysis

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Abstract

In this study, we used a 4.00-m pit on Belukha glacier in Russia's Altai region and attempted to establish the timing of chemical deposition events by analyzing pollen profiles. As the pollen deposition of each examined taxon on the glacier surfaces followed a distinct seasonal phenology, seasonal layers could be identified over a two-year period. The seasonal layer boundaries reconstructed from the pollen analyses were in close agreement with the *in situ* observations and indicated that the snow deposition on the glacier originates mainly from summer precipitation. The record of oxygen isotope ratios showed a relatively high mean value of -13.3‰ , which was attributed to the absence of winter depositions. The formate (HCOO^-) concentration records displayed seasonal variation with the highest emissions occurring in the spring, and a dust event in the spring of 2003 was detected from the Mg^{2+} , Ca^{2+} , and dust concentration profiles. Taken together, these results suggest the analysis of pollen profiles in combination with chemical data in snow pits and ice cores may lead to better reconstruction of seasonal variation.

Introduction

Studies of deep ice cores from Greenland and Antarctica have provided valuable long-term (greater than 100,000 years) paleoclimatic and environmental information (e.g., Watanabe et al., 2003; EPICA community members, 2004; North Greenland Ice Core Project members, 2004). Although covering shorter time scales, ice cores from mountain glaciers in mid and low latitudes allow for high-resolution analysis due to high snow accumulation rates, as shown by Thompson et al. (1985, 1988), Fujita et al. (2004), and Reese and Liu (2005). Another advantage of analyzing these glaciers is that they typically contain greater than 1000 pollen

grains per liter because they are often situated within a few tens of kilometers from pollen sources (Godwin, 1949; Heusser, 1954; Ambach et al., 1966; Haeberli et al., 1983; Liu et al., 1998, 2007; Reese and Liu, 2005; Reese et al., 2003; Nakazawa et al., 2004, Santibáñez et al., 2008).

Pollen grain production and liberation follow a distinct seasonal phenology depending on the taxon. Several studies have identified seasonal pollen variations in firn pits and ice cores (Ambach et al., 1966; Short and Holdsworth, 1985; Bourgeois, 1990, 2000). Moreover, recent studies of pits and an ice core in Russia's Altai Mountains demonstrated the potential for identifying and separating seasonal layers with high resolution by

analyzing pollen taxa in samples as small as 10 mL (Nakazawa et al., 2004, 2005). In particular, Nakazawa et al. (2005) verified the accuracy of the identified seasonal layers by comparing pollen-dated profiles with meteorological data and *in situ* measurements of surface snow levels. Although this study indicated the potential usefulness of pollen stratigraphy for identifying seasonal layers, it was based on only one year of data and should be further verified.

Pollen analysis in glaciers is expected to complement chemical, biological, and physical analyses with seasonal resolution and may be useful for understanding past climates and environments by allowing more accurate reconstruction of seasonal variation. The purpose of the present study was to verify the findings of Nakazawa et al. (2005) by replicating their study one year later, using a pit on the same (Belukha) glacier. In addition, in order to facilitate the interpretation of a 171-m ice core record obtained on Belukha glacier (Takeuchi et al., 2004), we attempted to interpret in detail the oxygen isotope ratios ($\delta^{18}\text{O}$) and ion concentration profiles of the pit in reference to the pollen profiles.

Study Site and Methods

Belukha glacier (49°49'N, 86°34'E; 4110 m a.s.l.) is located on the west side of Mt. Belukha (4500 m a.s.l.) in the Russian Altai Mountains and is situated in the border region between Russia, Mongolia, China, and Kazakhstan (Fig. 1). To date, a 171-m-deep ice core drilling and pit observations have been conducted on the plateau of the glacier, which was located hundreds of meters from the present study site (Fujita et al., 2004; Takeuchi et al., 2004). Furthermore, a 140-m-deep ice core was retrieved at the saddle between Mt. Belukha and west Belukha peak (Olivier et al., 2003). The observation site (4100 m a.s.l.) is in the percolation zone where positive air temperatures have never been observed and only surface melting from solar radiation is considered to occur (Aizen et al., 2005). Therefore, summer meltwater percolation within the firn is likely an insignificant factor in this study.

Long-term meteorological records dating from the 1950s are available at the Akkem meteorological station (2040 m a.s.l.), which is located 7 km north of the Belukha glacier and within the same basin (Fig. 1). Akkem receives 55% of its annual precipitation (534 mm on average) during summer (June–August) and only 5% during winter (December–February). Thus, similar to other Altai glaciers, Belukha glacier is characterized as a summer-accumulation-type glacier. The major types of vegetation surrounding the glacier are tundra and steppe, including *Artemisia* and forest consisting of *Betula*, *Pinus*, *Picea*, and *Abies*. The tree line is approximately 2400 m a.s.l., with tundra predominating above this point.

The daily and annual depositions of snow between July 2001 and July 2003 were measured using an automatic snow gauge and five stakes on the accumulation area of the glacier. However, due to problems with the logger batteries, daily deposition data could only be obtained from 18 July to 27 October 2001 and from 14 July to 1 October 2002.

On 1 August 2003, snow was sampled from a 4.00-m pit at the observation site for analyses of pollen, $\delta^{18}\text{O}$, ion species, and microparticles (dust). The samples were taken consecutively at intervals of 0.10 m. The lower part of the pit (1.60–4.00 m) covered the same period as the one presented in our previous study (Nakazawa et al., 2005). For the pollen analysis, 10-mL samples were filtered through a hydrophilic PTFE membrane filter with a pore size of 0.2 μm , and the pollen grains on the filters were then counted under a microscope. To simplify the process and prevent

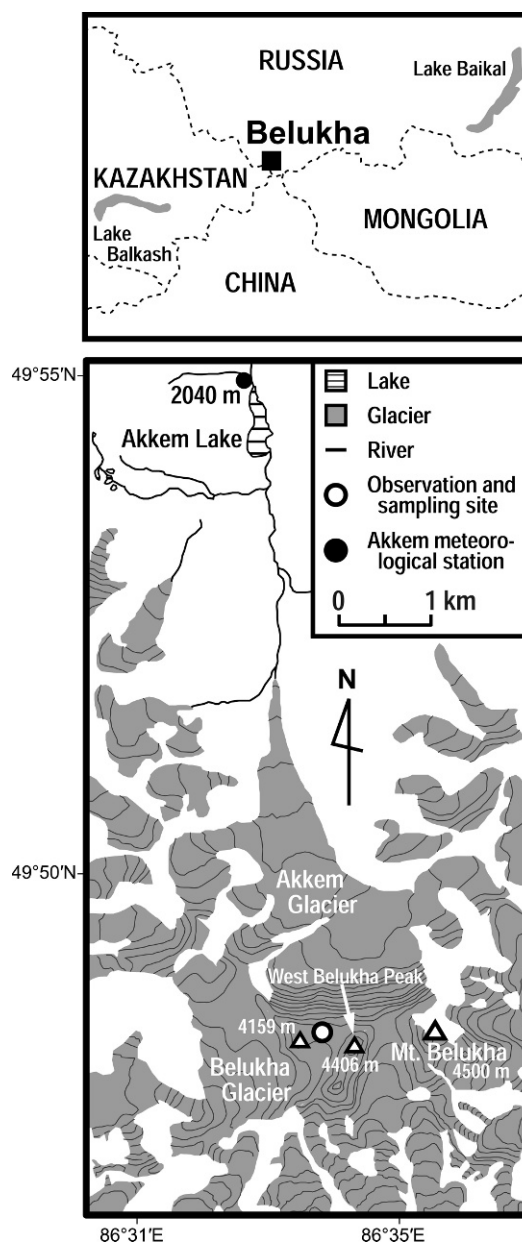


FIGURE 1. Location of Belukha glacier in Russia's Altai Republic. The observation and sampling site used in this study was located to the west side of Mt. Belukha.

pollen loss, the samples were subjected to neither chemical treatment nor centrifugation. As the cytoplasm in the pollen grains was not chemically removed, *Betulaceae*, which appeared to include *Betula* and *Carpinus*, could only be identified at the family level. Similarly, we purposely did not distinguish between *Abies* and *Picea* as the identification was complicated by the grain orientation. The classification and enumeration were only performed for the major pollen types (*Betulaceae*, *Abies*, *Picea*, *Pinus*, and *Artemisia*) as this study was focused on the seasonality of pollen deposition. Moreover, as *Abies* and *Picea* have the same flowering season, they were grouped together. In our samples, the total pollen counts ranged from 0 to 524 grains (mean \pm SD: 63 ± 124 ; median: 24).

Oxygen isotopes in the snow samples were measured with a dual-inlet isotope mass spectrometer (Thermo Electron, Finnigan

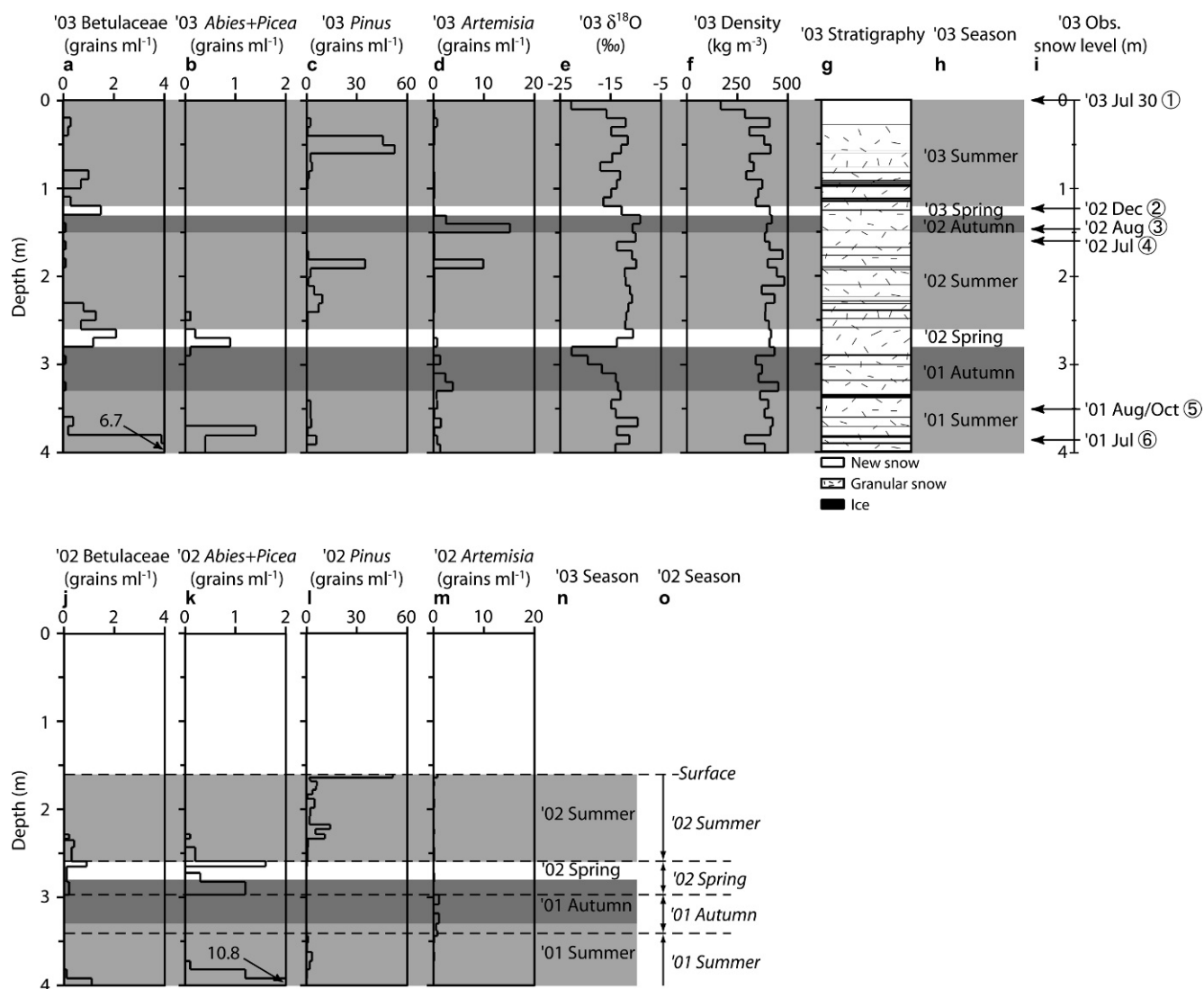


FIGURE 2. Vertical profiles determined from 2003 pit samples on Belukha glacier. Pollen concentrations of (a) *Betulaceae*, (b) *Abies + Picea*, (c) *Pinus*, and (d) *Artemisia*; (e) oxygen isotope ratios ($\delta^{18}\text{O}$); (f) density profiles; (g) physical stratigraphy; (h) seasonal layers: white, light gray, and dark gray shaded areas indicate spring, summer, and autumn layers, respectively; (i) observed changes in snow depth originating from the surface level of 30 July 2003. Pollen concentrations of (j) *Betulaceae*, (k) *Abies + Picea*, (l) *Pinus*, and (m) *Artemisia* measured in 2002 (Nakazawa et al., 2005). (n) Seasonal layers determined from the 2003 pit. (o) Seasonal layers estimated from the 2002 pit (Nakazawa et al., 2005). The numbered depths in Figure 2i correspond to the numbered surface levels in Figure 3a. The recorded depths in 2002 are adjusted to the depth scale in 2003 on the basis of annual snow deposition of 1.60 m determined by snow stake measurements.

Delta Plus). Concentrations of nine major ionic species (Na^+ , NH_4^+ , K^+ , Mg^{2+} , Ca^{2+} , Cl^- , formate (HCOO^-), NO_3^- , and SO_4^{2-}) in the samples were determined by ion chromatography (Dionex, DX-500). Concentrations of dust in the samples were analyzed with a laser particle counter (MetOne, Model-211) equipped with a high concentration sensor using the method described by Fujii et al. (2003).

Results and Discussion

RESULTS OF POLLEN ANALYSIS

Although the most common snow type in the 4.00-m pit is granular snow, ice layers with thicknesses ranging from a few millimeters to 5 cm occasionally appear (Fig. 2g). The observed snow stratigraphy suggests that meltwater percolation is insignificant at this elevation, and therefore the pollen, $\delta^{18}\text{O}$, and ion concentrations are expected to be well preserved.

The pollen profile extracted from the 2003 snow pit revealed the presence of several pollen-rich layers (Figs. 2a–2d). It was found that the *Pinus*-rich layers occurred above both the *Betulaceae*-rich and *Abies + Picea*-rich layers, whereas the *Artemisia*-rich layers were observed above the *Pinus*-rich layers and below the *Betulaceae*-rich and *Abies + Picea*-rich layers. Since the three pollen-rich layers of *Betulaceae* and *Pinus* appear at regular intervals, the pollen records indicate that the 4.00-m pit contains an entire two years of snow deposition between 2001 and 2003. Because the pollen profiles of the present and previous snow pit studies on the Belukha glacier are in good agreement (Figs. 2a–2d, 2j–2m), the spatial and temporal reproducibility of pollen deposition on the glacier surface was confirmed.

POLLEN-ASSIGNED SEASONAL LAYERS

It is considered that the observed pollen layers would have formed on the snow surface during the flowering season. The

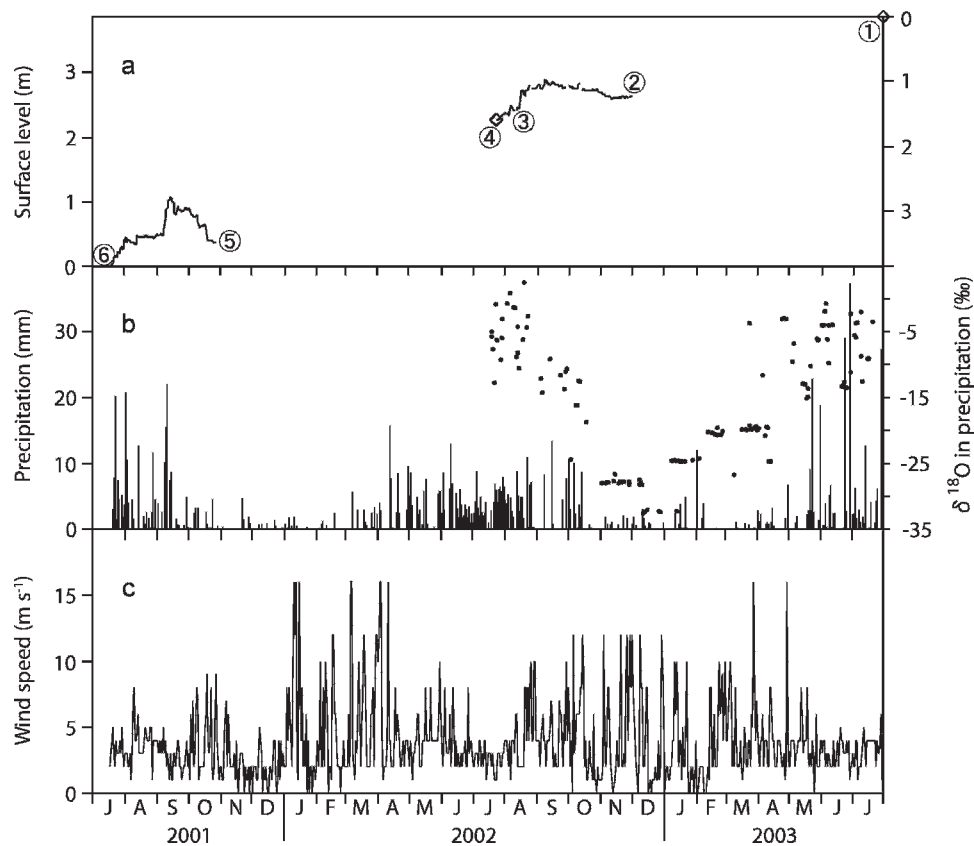


FIGURE 3. Snow levels on Belukha glacier and meteorological conditions at Akkem station. (a) Daily changes in relative surface levels on the plateau of Belukha glacier. Ordinates on the left side are relative to the surface level of 18 July 2001; ordinates on the right are relative to the surface level of 30 July 2003. The plotted points include 18 July through 27 October 2001 and 14 July through 1 October 2002, as measured with an automatic snow gauge; diamonds indicated the surface levels on 24 July 2002 and 30 July 2003, as measured with stakes. The numbered surface levels correspond to the numbered depths in Figure 2i. (b) Daily precipitation at Akkem meteorological station between 18 July 2001 and 30 July 2003, and $\delta^{18}\text{O}$ values (dots) for precipitation between 20 July 2002 and 22 July 2003. Ordinates on the left indicate daily precipitation, whereas those on the right show $\delta^{18}\text{O}$ values. (c) Daily maximum wind speeds at Akkem meteorological station between 18 July 2001 and 30 July 2003.

flowering and pollen seasons in Russia's Altai region occur mainly in May for Betulaceae, *Abies*, and *Picea*; typically in June for *Pinus* (Luchik, 1970); and from late August to early September for *Artemisia* elsewhere in Asia (Satake et al., 1981; Polunin and Stainton, 1984; Qiao, 2004). Based on the position of each pollen peak and the known flowering season, seasonal layers in the pit could be identified, as shown in Figure 2h. Although the pollen peaks formed a regular profile among the four groups of pollen analyzed, a few anomalies were observed. For example, an *Abies* + *Picea* peak was not detected in the upper layers of the pit. In addition, the *Artemisia* peak at 1.8–1.9 m in depth was regarded as a second peak within the summer layer of 2002 because no other pollen peak appears between the two *Artemisia* peaks at depths of 1.40–1.50 and 1.80–1.90 m. Despite these anomalies, the seasonal pollen depositional patterns show that snow depositions increase during summer and diminish during winter.

Based on the pollen profiles, the depths of 1.30 m and 2.80 m are thought to have been deposited between the autumn and spring of 2002/2003 and 2001/2002, respectively. The dispersal of airborne pollen grains is typically at a minimum in winter because of the lack of plants flowering at this time. However, it was observed that each *Artemisia* layer is in direct contact with the Betulaceae and *Abies* + *Picea* layers, which are indicative of autumn and spring layers, respectively, without an intervening pollen-poor layer. This indicates that the snow depositions during

the winters of 2001/2002 and 2002/2003 were either negligible or mostly eroded by wind.

COMPARISON OF POLLEN PROFILES WITH METEOROLOGICAL AND IN SITU MEASUREMENTS

We next examined if the annual and seasonal layers determined from the pollen analyses were consistent with the *in situ* measurements of surface levels and the meteorological data. Figure 3a shows the daily changes in the surface levels relative to

TABLE 1

Observed and reconstructed annual snow thickness and depth of seasonal layer boundaries for a two-year accumulation from 2001 to 2003.

	Observed value	Reconstructed value
Annual snow deposition, 2001/02	0.87 ± 0.06 m w.e.	0.86 m w.e.
Annual snow deposition, 2002/03	0.56 ± 0.04 m w.e.	0.51 m w.e.
Summer–autumn boundary, 2001	1.29 ± 0.04 m w.e.	1.26 m w.e.
Autumn 2001–spring 2002 boundary	1.07 ± 0.04 m w.e.	1.06 m w.e.
Spring–summer boundary, 2002	0.94 ± 0.04 m w.e.	0.98 m w.e.
Summer–autumn boundary, 2002	1.40 m s.e.	1.50 m s.e.
Autumn 2002–spring 2003 boundary	1.23 m s.e.	1.30 m s.e.

Note: “w.e.” and “s.e.” represent water and snow equivalents, respectively.

TABLE 2

Precipitation at Akkem meteorological station during the spring and summer of 2003.

Period	Precipitation (mm)	% of total precipitation (289 mm) from 1 March through 31 July 2003
1 May–31 July 2003	262	91
31 May–31 July 2003	198	69

that on the first day of measurements (18 July 2001). The surface level increased more than 1 m from July to September 2001, and then decreased rapidly to 0.35 m in October, returning to the level of the first half of August. The observation site then received more

new snow, reaching 2.26 m on 13 July 2002, 2.46 m on 16 August, and 2.63 m on 2 December 2002. After 2 December, the observation site again received new snow and reached a level of 3.86 m on 30 July 2003. The changes of the snow level originating from the surface level of 30 July 2003 are shown in Figure 2i. When compared to the seasonal layer boundaries reconstructed from the pollen analyses, the observed layers correspond closely to these values for each date (Table 1, Figs. 2h, 2i). In addition, the observed and reconstructed values for the annual depositions between 2001 and 2002 and between 2002 and 2003 are also in good agreement. For this comparison, the *Pinus* peaks were selected because they are nearly contemporaneous with the stake observations. The water-equivalent thickness calculated from the density profiles in Figure 2f is shown in Table 1.

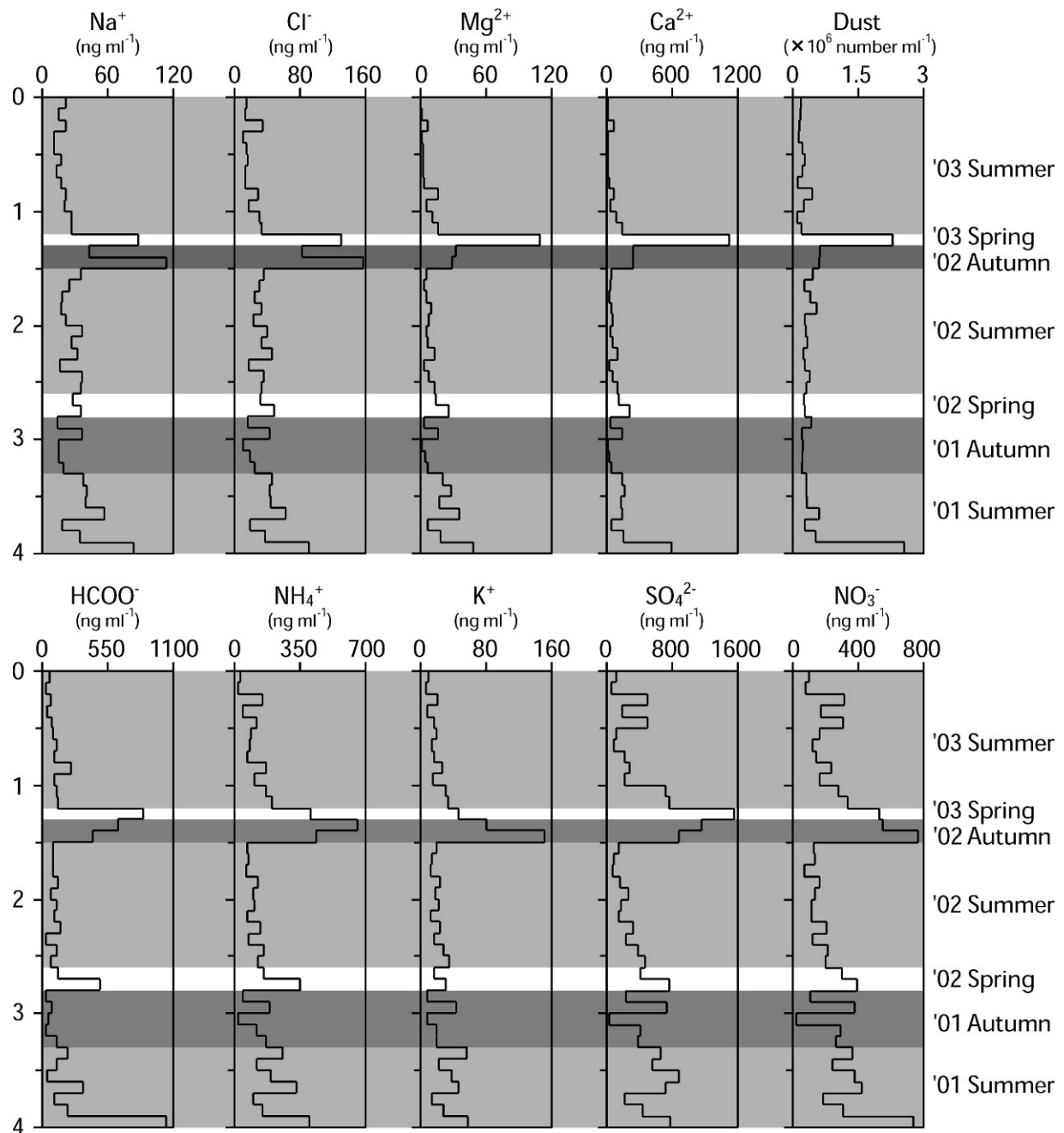


FIGURE 4. Vertical profiles from pit samples on Belukha glacier. Ion concentrations of sodium, chloride, magnesium, calcium, formate, ammonium, potassium, sulfate, and nitrate; and dust concentrations measured in August 2003. As indicated to the right of the profiles, the white, light gray, and dark gray shaded areas indicate spring, summer, and autumn layers, respectively.

The reliability of each seasonal boundary between summer 2001 and summer 2002 determined in this study was confirmed by adding one year of deposition (1.60 m), between July 2002 and July 2003, to the earlier results of Nakazawa et al. (2005). Figures 2n and 2o show the seasonal layers determined in the present and previous studies, respectively. From this comparison, it is clear that the depths of each seasonal boundary are in good agreement. Since the results from the 2002 pit study were supported by the meteorological data and *in situ* measurements of the surface levels, it is considered that the seasonal boundaries between the summers of 2002 and 2003 identified in the present study are also accurate and indicate the reproducibility of the pollen dating method.

The results of the pollen analyses indicate that the winter layers of 2002/2003 and 2001/2002 are missing or are negligible. To examine the accuracy of this determination, the wind speed and precipitation data at Akkem station were analyzed (Figs. 3b, 3c). The daily maximum wind speeds during the winter (December–February) were higher than those of the other seasons and even exceeded a wind erosion event that occurred on the glacier during September and October 2001 (Nakazawa et al., 2005) (Fig. 3c). Furthermore, there may have been little or no snow deposition on the glacier during the winter of 2002/2003 since the total precipitation from December to February (46 mm) at Akkem amounted to only 9% of the annual precipitation (509 mm) between August 2002 and July 2003 (Fig. 3b). Taken together, these results indicate that the negligible or nonexistent winter layers resulted from a combination of negligible snowfall and wind erosion, and support the conclusions of the pollen analyses.

Finally, we examined the 2003 spring-summer boundary for which the daily deposition data were unavailable due to a technical failure. Precipitation at Akkem gradually increased from March after the 2003 winter season (Fig. 3b). The total precipitation from 1 March through 31 July, representing the period of the 2003 spring and summer, was 289 mm. The ratio of precipitation from May, which corresponded to the Betulaceae pollen season, through 31 July to the total amount ranged from 69 to 91% (Table 2). These values agree with the estimated ratio of 91%, which represented the ratio of the deposition in the 2003 summer layer (0.40 m w.e. [water equivalent]) to the total deposition in the spring and summer layers in 2003 (0.44 m w.e.). Therefore, our interpretation that summer deposition is dominant in the pit after the 2003 winter season appears to be reasonable. Comparisons between the pollen data and the observed data presented in this section indicate that pollen data can be used to precisely identify annual and seasonal boundaries.

INTERPRETATION OF CHEMICAL PROXIES AT THE SEASONAL LEVEL

Seasonal information derived from the pollen analyses enabled detailed interpretations of $\delta^{18}\text{O}$ signals in the snow pit. The observed $\delta^{18}\text{O}$ profile shows that although strong winter minima are absent, a minimal value (2.80 to 2.90 m), which is nearly identical to that in the 2003 summer layer (0 to 0.10 m), occurs at the boundary between autumn 2001 and spring 2002 (Fig. 2e). However, the winter minimal value of 2002/2003 was not observed in the $\delta^{18}\text{O}$ record. The lack of winter minima results in a relatively small amplitude of the $\delta^{18}\text{O}$ variation. In contrast, the $\delta^{18}\text{O}$ values in the precipitation collected at the Akkem meteorological station from July 2002 to July 2003 show a clear seasonal variation, with high and low values in the summer and winter, respectively (Fig. 3b). Moreover, the $\delta^{18}\text{O}$ values at

Akkem vary between 2.4 and -32.6‰ , whereas the $\delta^{18}\text{O}$ values from the snow pit only vary between -9.2 and -22.8‰ (mean value of -13.3‰). In the snow pit, 33 of the 40 samples had values higher than -15‰ , whereas high values at Akkem station were only observed during July–September 2002 and April–July 2003. As the value of $\delta^{18}\text{O}$ in precipitation is generally expected to decrease with altitude because of the so-called altitude effect, the $\delta^{18}\text{O}$ values in the pit are considered to represent mainly summer precipitation. Therefore, by combining the $\delta^{18}\text{O}$ values with the summer layers determined from the pollen analysis, the $\delta^{18}\text{O}$ records in the glacier may provide reliable mean summer temperature variations from the past.

The HCOO^- concentration records displayed the most distinct seasonal variation among the major ions examined (Fig. 4). Upon comparison with the seasonal layers identified from the pollen analysis, the HCOO^- concentrations exhibited spring maxima, suggesting biogenic emissions as their source (Kesselmeier and Staudt, 1999). Interestingly, the peaks for all ion species are located between 1.30 and 1.50 m in depth, which corresponds to the period between autumn 2002 and spring 2003. Although variations between the different ion peaks were observed, the highest peaks in Mg^{2+} , Ca^{2+} , and dust concentrations were found only in the spring 2003 layer, indicating that a dust event occurred during this time. This also suggests that the enhanced concentrations of the other ion species in the 2002 autumn layer were likely caused by a separate event. However, identifying the causative event here is difficult with only biennium data and more data are needed for further interpretation.

Conclusions

This study has confirmed that pollen analysis can be used to identify seasonal layers in the Belukha glacier located in Russia's Altai Mountains. Moreover, the seasonal layers allowed us to detect clear seasonal variation in the HCOO^- concentrations, which have the highest emission in spring, as well as to identify a dust event in the spring of 2003. As the pollen analysis was performed with water samples as small as those typically obtained from core samples (10 mL), this high-resolution analysis technique can be extended to the identification of various chemical, biological, and physical signals in ice cores. Climate proxies, such as tree ring width and ice cores, are often considered to be representative of particular seasons rather than complete years (IPCC, 2007). Although this fact is widely recognized, numerous ice core studies continue to report annual fluctuations, such as in annual mean temperatures determined from the mean $\delta^{18}\text{O}$ values in annual layers. However, the use of pollen analysis in ice core studies may allow for more accurate reconstruction of seasonal variation and assignment of seasons, and lead to a more precise understanding of past climates and environments.

Acknowledgments

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