Reevaluation of the reconstruction of summer temperatures from melt features in Belukha ice cores, Siberian Altai

Sachiko Okamoto,[1] Koji Fujita,[1] Hideki Narita,[2] Jun Uetake,[3] Nozomu Takeuchi,[4] Takayuki Miyake,[3] Fumio Nakazawa,[3] Vladimir B. Aizen,[5] Stanislav A. Nikitin,[6] and Masayoshi Nakawo[7]

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[1] In a previous study, past summer temperatures were reconstructed from melt features in the Belukha ice core, Siberian Altai. We evaluated the climatic representativeness of net accumulation and melt features by comparing two Belukha ice cores retrieved at neighboring sites by different institutions and dated by different methods. Melt features in both cores showed a significant correlation, but the trends of net accumulation were different between the cores. Melt features corresponded to the retreat rate of a glacier terminus in a neighboring mountain range. These findings demonstrate the spatial representativeness of melt features in the ice cores. We reevaluated an equation formulated for reconstructions of summer temperature, as used in a previous study, and found that it underestimates temperature. We propose an alternative equation to obtain more reliable summer temperatures from melt features and net accumulation records for the period from 1914 to 2003.

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1. Introduction

[2] In recent years, glaciers in various parts of the world have been reported to be retreating, probably because of global warming [e.g., *Oerlemans*, 2005]. In particular, areas at high elevations in Asia have seen a marked reduction in the volume of glaciers [*De Smedt and Pattyn*, 2003; *Yao et al.*, 2004], and remarkably rapid warming has occurred in the Russian Arctic and Siberia [*Weller*, 1998; *Johannessen et al.*, 2004] because of albedo–snow cover–temperature and permafrost–trace-gas–temperature feedbacks [*Kellogg*, 1975], which act to amplify the greenhouse effect. It is therefore important to retrieve records from valuable natural archives that preserve environmental data such as precipitation and temperature.

[3] Analyses of well-dated, high-resolution ice core records will improve our understanding of the past climate and hydrological environment, and help to predict future climate change [*Taylor et al.*, 1993]. However, few paleoclimate records have been determined from Siberia, compared with many records available for the Tibetan/Himalayan region [e.g., *Thompson et al.*, 1989, 1997, 2000; *Yao et al.*, 1996; *Kang et al.*, 2000; *Kaspari et al.*, 2008]. Therefore, studies of ice cores recovered from Siberia are important in terms of understanding recent warming in the region and the response of glaciers to such warming.

[4] This study focuses on the Siberian Altai, the most continental northern periphery of the central Asian mountain system and the southern periphery of the Asian Arctic basin. This region, settled by humans during the Palaeolithic [*Arkhipov*, 1999], is an area of relatively high biodiversity [*Mutke and Barthlott*, 2005]. The highest part of the Siberian Altai Mountains (the Katun, South Chuya, and North Chuya ranges) contains about 70% of south Siberian glaciers (by area), which provide fresh water to the upper tributaries of the Ob and Yenisey rivers [*Narozhniy and Okishev*, 1999]. Accordingly, this region is a suitable setting for investigations of interactions among climate, the hydrological system, vegetation, and humans.

[5] Two previous expeditions obtained ice cores from Mt. Belukha (4499 m above sea level (asl)), the highest peak in the Siberian Mountains. In July 2001, a Swiss-Russian group recovered a 140 m deep ice core (covering the entire thickness of ice) from the saddle located between the East and West Belukha peaks (49°48′N, 86°34′E; 4062 m asl; Figure 1) [*Olivier et al.*, 2003]. The upper 86 m of the core, covering the past two centuries, contains a record of atmospheric plutonium fallout [*Olivier et al.*, 2004], temporal variations in ion concentrations [*Olivier et al.*, 2006], and temporal variations in accumulation and temperature, as

[1]Graduate School of Environmental Studies, Nagoya University, Nagoya, Japan.
[2]Network of Snow and Ice Specialists, Sapporo, Japan.
[3]National Institute of Polar Research, Tachikawa, Japan.
[4]Graduate School of Science, Chiba University, Chiba, Japan.
[5]College of Science, University of Idaho, Moscow, Idaho, USA.
[6]Department of Glacio-Climatology, Tomsk State University, Tomsk, Russia.
[7]National Institutes for the Humanities, Tokyo, Japan.

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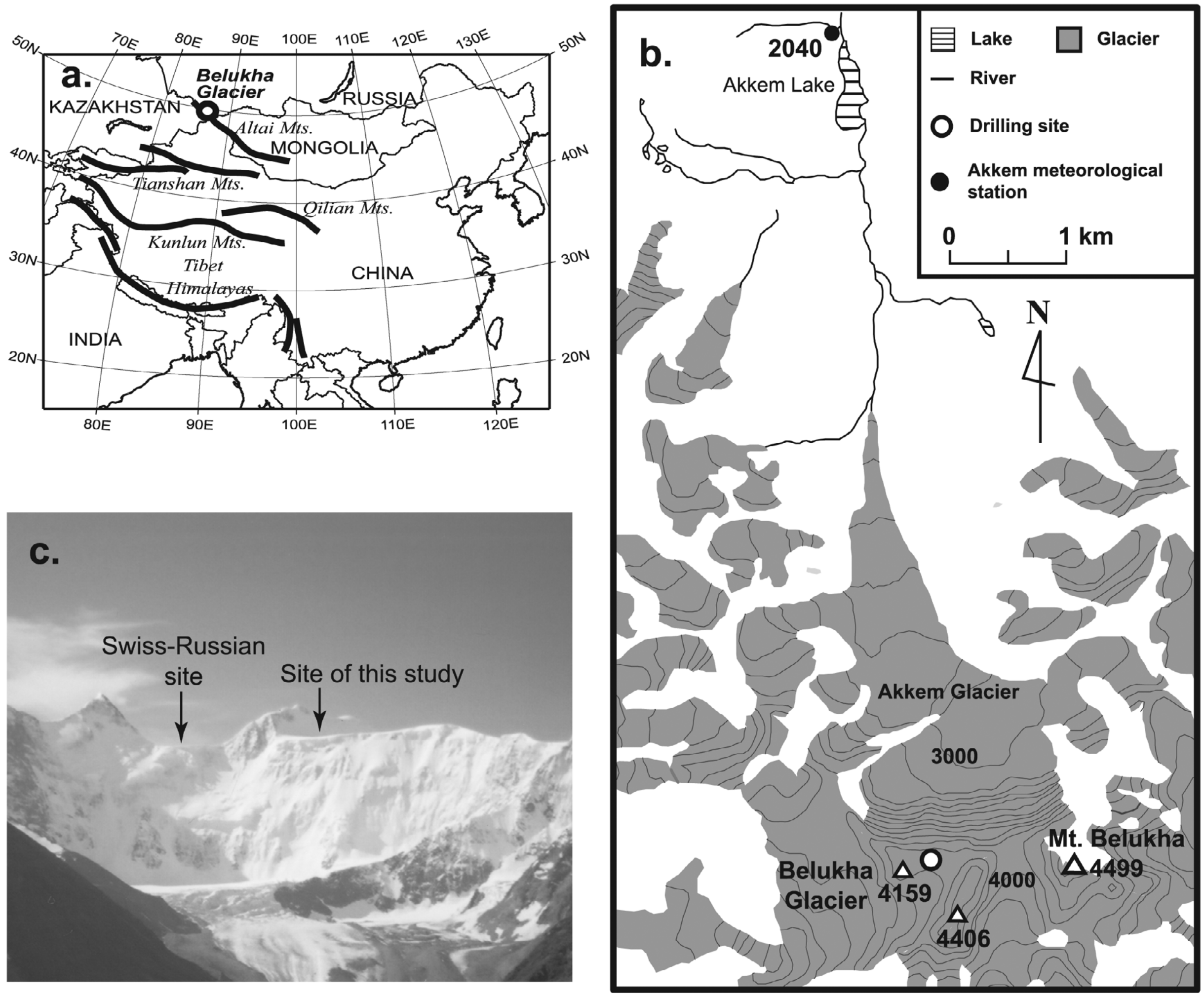

Figure 1. (a) Regional map showing the location of the Belukha Glacier. (b) Location of the Akkem meteorological station. (c) Photograph of the locations of the drilling sites of the present study and a Swiss-Russian group [*Olivier et al.*, 2003] viewing from Akkem meteorological station.

deduced from oxygen stable isotope data and melt features [*Henderson et al.*, 2006]. The upper 138 m, covering the period from 1250 to 2001, records the influence of the sun on climate variability, as deduced from oxygen stable isotope data [*Eichler et al.*, 2009a], and the history of biogenic emissions related to changes in temperature linked to variations in solar activity [*Eichler et al.*, 2009b]. In the summer of 2001, a U.S.-Japanese-Russian group recovered a 21 m deep snow/firn core in the West Belukha Plateau. On the basis of an analysis of this core, clustering analysis of δ^{18}O and d-excess records, and an examination of synoptic atmospheric patterns showed that two-thirds of the origin of precipitation nourishing the Belukha Plateau was transferred from the Atlantic, Pacific and Arctic Oceans and the rest of the precipitation was recycled over Aral-Caspian sources [*Aizen et al.*, 2005, 2006]. In the summer of 2003, a 171 m deep ice core (covering the entire thickness of ice) was recovered from the West Belukha Plateau by the U.S.-Japanese-Russian group. (49°49′N, 86°34′E; 4100 m asl; Figure 1) [*Takeuchi et al.*, 2004]. Dating has been completed for the upper 48.25 m of the ice core.

[6] Temporal changes in melt feature percentage (MFP) have been successfully applied worldwide as a proxy record of summer temperature [e.g., *Koerner*, 1977; *Herron et al.*, 1981; *Koerner and Fisher*, 1990; *Fisher and Koerner*, 1994; *Tarussov*, 1992; *Shiraiwa et al.*, 1997]. It has been assumed that the amount of surface snowmelting in summer is related to the summer air temperature. However, few studies have reconstructed the record of quantified temperature [*Alley and Anandakrishnan*, 1995; *Kameda et al.*, 1995; *Henderson et al.*, 2006], whereas many studies have reconstructed the record of relative warmness/coldness.

[7] In this paper, we assess the representativeness of accumulation and melt features by comparing two neighboring ice cores that were independently analyzed and dated using different methods. Many previous studies have compared ice core records in low-latitude and midlatitude regions [e.g., *Aizen et al.*, 2006; *Henderson et al.*, 2006; *Yao et al.*, 2008]; however, no such comparisons have been attempted for nearby sites. Such a comparison would enable us to confirm the regional representativeness of signals retrieved from ice cores, and to assess the reliability of analytical

methods and results obtained regarding climatic variation. We also reevaluate methods of reconstructing summer temperatures from melt features in a Belukha ice core, as proposed by *Kameda et al.* [1995] and *Henderson et al.* [2006].

2. Data and Methods

2.1. Location and Meteorological Data

[8] The Altai region, in the central part of the Eurasia continent, has a continental climate. Most of the annual precipitation occurs during the short summer (June–August). The Atlantic Ocean is the main moisture source for the Siberian Altai, although around 33% of precipitation in the region originates from internal moisture sources, mainly evaporation from continental sources such as the closed Aral and Caspian drainage basins, or local river basins [*Aizen et al.*, 2005]. One of the main factors that determines the climatic regime in this region is interaction between the Siberian High and western cyclonic activity [*Surazakov et al.*, 2007].

[9] The Altai region is located at the southern margin of Siberia. Mt. Belukha, located near the junction between Russia, China, Mongolia, and Kazakhstan, contains the West Belukha Plateau on the west side of its summit. This plateau was selected for the ice core drilling site because of its flatness and high elevation based on a 2 year preliminary investigation [*Fujita et al.*, 2004; *Takeuchi et al.*, 2004]. *Aizen et al.* [2005] described that this plateau was the only location in Siberian where the Altai glaciers experienced sufficiently cold temperatures and enough snow accumulation to preserve climatic and environmental records according to the results of the glaciological and meteorological observations.

[10] We obtained a long-team meteorological record (daily air temperature and precipitation since 1950) from the Akkem meteorological station (49°54′N, 86°32′E; 2045 m asl; Figure 1b), located 10 km north of the Belukha Glacier, whereas *Henderson et al.* [2006] and *Eichler et al.* [2009a] used instrumental temperature data from Barnaul, Russia (52°26′N, 83°31′E; 184 m asl; 360 km northwest of Belukha), covering the period from 1851 to 1999. Precipitation data shows that Akkem receives 55% of its annual precipitation (537 mm on average for the period 1951–2002) during summer (June–August, JJA) and only 5% during winter (December–February).

[11] An automatic weather station (AWS) was installed in the West Belukha Plateau near the drilling site on 26 July 2002 to measure hourly air temperature, atmospheric pressure, net radiation, relative humidity, wind speed, and wind direction; however, operation of the station ceased on 28 April 2003 because of battery malfunction. Daily accumulation was measured by automatic snow gauge from July 2001 to July 2003. The maximum temperature had not exceeded 0°C near the drilling site during 2000/2001, as measured by AWS, and it indicates that the West Belukha Plateau lies in the cold recrystallization zone [*Aizen et al.*, 2005]. According to the snow gauge data, a rapid decrease in surface level occurred in October 2001 (approximately 50 cm in 1 month), which is too large a decrease to have resulted from snow compaction [*Fujita et al.*, 2004]; in addition, meteorological data indicate that no melting occurred at this time. These observations suggest a significant influence of wind erosion on the surface level [*Nakazawa et al.*, 2005]. *Olivier et al.* [2003] also reported that a portion of the fresh snow at the exposed saddle site might be eroded by wind.

2.2. Measurements and Dating of the Ice Core

[12] The age scale was derived from the seasonal distribution of pollens validated by the 1963 tritium peak (Figure 2). Ice core samples were cut by a band saw at intervals of 4–6 cm, and 1 cm of the core surface was scraped off with a precleaned ceramic knife to eliminate contamination. The samples were then packed into cleaned plastic bags. After melting at room temperature, all samples were poured into clean plastic bottles upon a clean bench. For the pollen analysis, 10 mL of water sample was filtered through hydrophilic PTFE membrane filters with a pore size of 0.2 μm, and pollen grains on the filters were counted using a microscope by following a manner proposed in the previous studies [*Nakazawa et al.*, 2004, 2005].

[13] Alpine glaciers contain many species of pollen grains that show peaks in concentrations at certain times of the year. In ice from the Belukha Glacier, the most abundant pollens are classified into the following four groups: Betulaceae, *Pinus*, *Abies* + *Picea*, and *Artemisia*. The ice that occurs between the pollen peaks that mark May (Betulaceae and *Abies* + *Picea*) and the summer–autumn boundary (i.e., the boundary between *Pinus*-rich and *Artemisia*-rich layers) is the summer layer [*Nakazawa et al.*, 2004, 2005]. *Nakazawa et al.* [2004] cited the following three advantages of pollen dating: (1) pollen is well protected from decay by an outer shell of sporopollenin; (2) the large grain size helps the pollen to remain at its original depth despite meltwater incursion; and (3) this method can also distinguish seasonal boundaries by using different pollen species. *Nakazawa et al.* [2005] showed the results of snow pit observation near drilling site and concluded that pollen dating is a useful tool and other conventional methods of dating are unreliable because of wind erosion and low winter precipitation. Consequently, the upper 48.25 m of the ice core is considered to cover the period from 1914 to 2003.

2.3. Melt Features

[14] The bulk density of the ice cores increase with depth and reached 900 kg m^{-3}, the density of pure ice, at approximately 50 m depth [*Takeuchi et al.*, 2004]. The density almost linearly increased with depth from 7 m to 42 m and thus the core from the surface to approximately 50 m consists of firn with occasional ice.

[15] Melt features are formed when some of the meltwater produced by high summer air temperatures and solar radiation percolates downward along vertical channels and spreads laterally, via capillary action, along impermeable layers marked by a discontinuity in firn grains. In the present study, the measurement of melt features was carried out in a cold laboratory. Ice cores were cut in half-lengthways, set on a light table, and subjected to detailed megascopic examination. Melt feature shapes were recorded on graph paper, being clearly distinguishable under transmitted light. With illumination, snow and ice look the darkest, and ice looks brighter with decreasing number of air bubbles. Melt feature is distinguishable from its brightness. In this study, we regarded melt feature as bubble-free or sparse bubble layer, and did not adopt the layer with large air bubbles formed under less

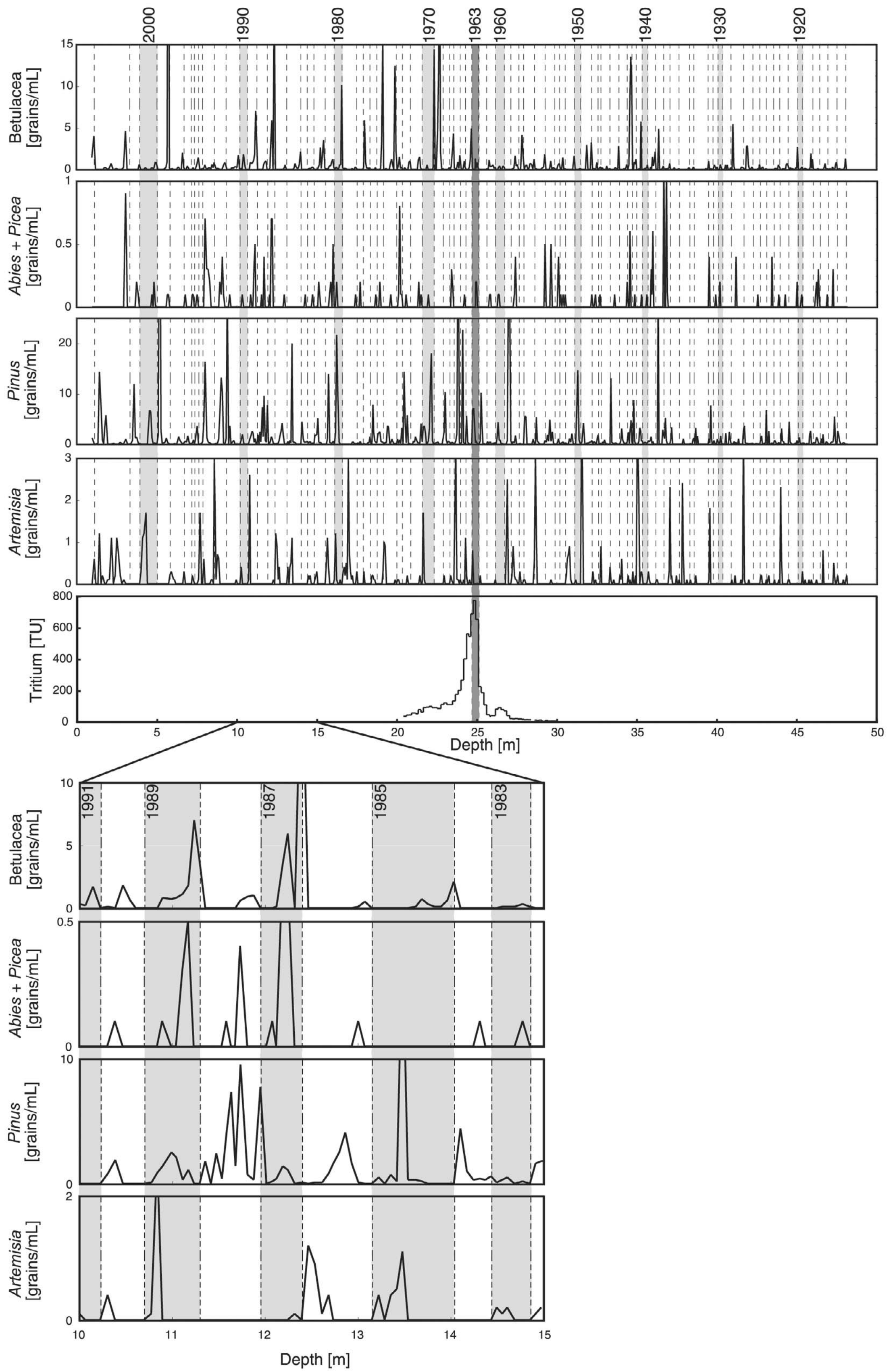

Figure 2. Vertical profiles of pollen from four species (Betulaceae, *Abies* and *Picea*, *Pinus*, and *Artemisia*) and tritium concentration. The dashed line represents the annual boundary between autumn and spring. The maximum peak of tritium (shaded in gray) can be observed in the 1963 layer. Bottom plot shows the enlarged vertical profile from 10 to 15 m. The areas shaded in gray indicate the layers from odd years.

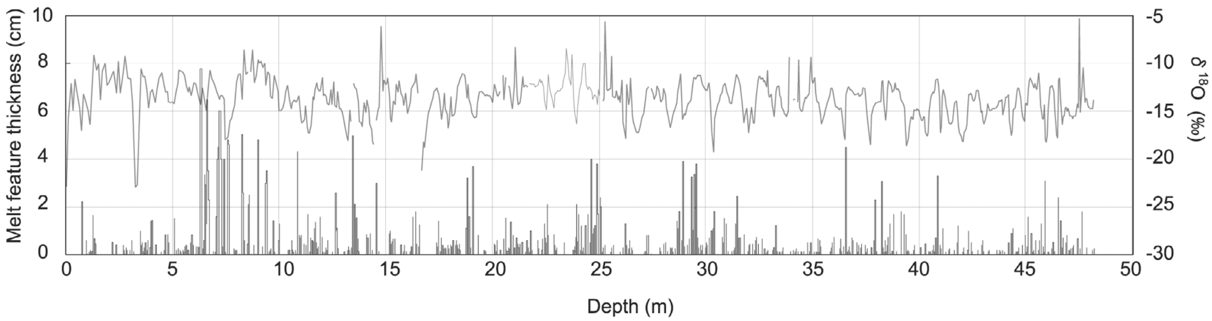

Figure 3. Distribution of melt features and vertical profile of oxygen isotope ratio in the upper 48.25 m of the Belukha ice core.

meltwater condition. The percentage of melt layers relative to annual layer was defined as the melt feature percentage (MFP).

[16] The West Belukha Plateau lies in the cold recrystallization zone, where any meltwater subsequently refreezes below the surface. Snow pit and borehole temperatures was recorded as 0°C at snow surface (noontime of August 2003) to −10°C at 2 m depth, to −15.8°C at 50–70 m depth and −14.2°C at the bottom. [*Takeuchi et al.*, 2004; *Aizen et al.*, 2005]. Figure 3 shows the distribution of melt feature thickness and vertical profile of oxygen isotope ratio in the upper 48.25 m of the Belukha ice core. There exist melt features of greater than 4 cm in thickness (although most are less than 1 cm thick), and the most remarkable melt features occur at a depth of around 7 m. At nearby Akkem meteorological station, most of the precipitation (90%) occurs from April to October. Even if remarkable snowmelt occurs, little meltwater would percolate to the layer of the previous year. Additionally, the profile of δ^{18}O shows well-preserved signals even the part of remarkable melting. The obtained profiles reveal negligible snowmelt and meltwater percolation. Thus the present drilling site was identified as a suitable location for the recovery of ice core and subsequent reconstruction of climatic records.

2.4. Reference Temperature

[17] Long-term air temperature at the drilling site was derived from temperature data recorded at Akkem (Figure 1b) and validated by AWS temperature. Summer temperature (JJA) at Akkem increased by 1.1°C for the period 1951–2000. There exists a significant correlation between the daily temperature at Akkem and that at the drilling site ($r = 0.97$, $p < 0.001$). Lapse rates between the two sites show a clear relationship with temperature (Figure 4). The lapse rate decreases with air temperature, suggesting that a strong inversion layer is formed during winter at Akkem. Using the trend line in Figure 4, we derived daily mean air temperature at the drilling site, which was used as the reference temperature (T_{ref}) for the period 1951–2000 to evaluate the accuracy of summer temperatures reconstructed from the ice core. We confirmed that T_{ref} has remained below 0°C for nearly all of the past 50 years except for a few days a year (Figure 5). The winter temperature shows large year-to-year variation, whereas summer temperature shows a rather stable variation. This feature is also found in the original Akkem temperature so that a short period of observation at the plateau does not account for this feature.

2.5. Reconstruction of the Accumulation Record

[18] In comparing the two ice cores obtained at neighboring sites upon the Belukha Glacier, the accumulation history was reconstructed using the same method as that employed by *Henderson et al.* [2006]. Both accumulation histories were calibrated from thickness profiles of the annual layer using a glacier flow model [*Nye*, 1963] to correct for the nonlinear thinning of layers with depth. This model is based on an estimate of the representative surface accumulation and a constant value for the vertical strain rate [*Haefeli*, 1961]. Accumulation was determined from the ratio of the layer thickness for each year to the modeled thickness, multiplied by the surface accumulation rate [*Henderson et al.*, 2006]. In this study, the calculation of accumulation was repeated twice. At the first calculation, average annual layer thickness was substituted for the value of surface accumulation. Then the result of first calculation was resubstituted. However, an influence of wind erosion, which was observed at drilling site [*Fujita et al.*, 2004; *Nakazawa et al.*, 2005], was not considered.

2.6. Methods of Reconstructing Summer Temperature

[19] *Henderson et al.* [2006] reconstructed the past summer temperature at the Belukha Glacier using the method

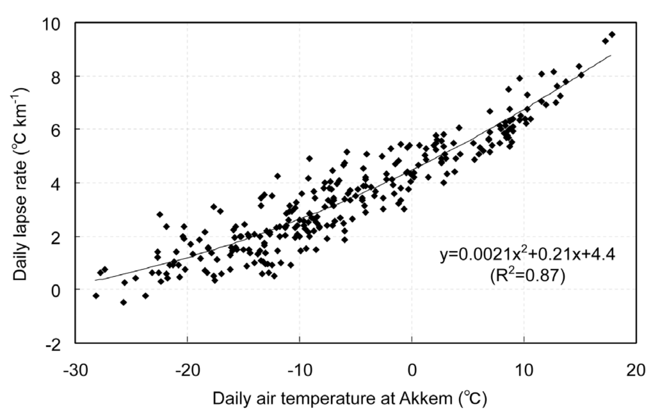

Figure 4. Relation between daily temperature at the Akkem meteorological station and the lapse rate between Akkem and the West Belukha Plateau (AWS) for the period from July 2002 to April 2003.

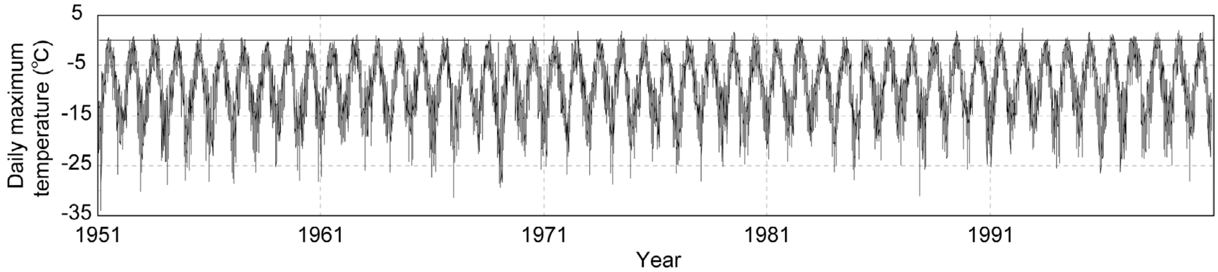

Figure 5. Daily maximum reference temperature (1951–2000) estimated for the West Belukha Plateau.

proposed by *Tarussov* [1992], which comprises two equations. The first is the Krenke-Khodakov equation, in which meltwater formed during a given summer is estimated from the mean JJA temperature [*Krenke and Khodakov*, 1966]. This equation was derived from observational data obtained for glaciers worldwide in the 1960s. In the second equation, the total annual meltwater is derived from annual MFP and reconstructed accumulation for the same year, based on the assumption that melt layers themselves form within firn layers that initially contain approximately 50% pore volume. The Krenke-Khodakov equation is as follows:

$$T_{JJA} = (0.50 MFP_a\, b_a)^{1/3} - 9.5 \qquad (1)$$

where T_{JJA} is JJA temperature, MFP_a is the annual MFP, and b_a is the reconstructed annual accumulation (mm w.e.) for the same year.

[20] *Kameda et al.* [1995] examined the relation between annual melt thickness (AMT) and monthly mean temperatures in the Site J ice core, Greenland. AMT is equal to MFP multiplied by the annual layer. Past summer temperature was reconstructed using a liner regression formula obtained from the relation with the strongest correlation (June temperature at Jakobshavn and AMT).

[21] The amount of surface snowmelt in summer is expected to correlate not only with summer air temperature, but also solar radiation. In particular, the contribution of solar radiation should be significant because the daily temperature on the Belukha Plateau has not exceeded 0°C except for a few days a year during the past 50 years (Figure 5). Although solar radiation is an important factor in terms of melting, especially at the cold Belukha Glacier, the record of solar radiation is unavailable in the ice core. Consequently, we adopted the accumulation record as a proxy for solar radiation. *Matsuda et al.* [2006] examined the relation between precipitation and the ratio of solar radiation at the surface to that at the top of the atmosphere (the authors defined this ratio as "transmissivity"), using measured records for the Asian highland. The authors found that transmissivity showed an exponential decrease with increasing precipitation when examining monthly bases. These findings indicate that the reciprocal of accumulation should correlate with ice layer thickness. In other words, we can retrieve a temperature index from AMT by subtracting the effect of solar radiation. Accordingly, in the present study, we used a multiregression formula composed of AMT and the reciprocal of accumulation to reconstruct summer temperatures.

3. Results

3.1. Comparison of Accumulation and MFP Between the Two Belukha Ice Cores

[22] Figures 6a and 6b show comparison of accumulation and MFP in the two ice cores obtained at neighboring sites upon the Belukha Glacier for the period 1915–2000. The distance between two drilling sites is about 1 km. The average accumulation for this period in the Russian-U.S.-Japanese (BLC03) and Swiss-Russian (BLC01) cores was 464 and 478 mm, respectively. The annual and 5 year running mean accumulation records show no significant correlation ($r = 0.004$ and $r = -0.2$, respectively). This discrepancy is considered to reflect the contrasting effects of wind erosion at the two sites [*Olivier et al.*, 2003; *Nakazawa et al.*, 2005].

[23] In contrast, the annual MFPs show a significant correlation between the BLC03 and BLC01 cores (Figure 6b; $r = 0.47$, $p < 0.001$), with average values of 10.4% and 12.7%, respectively. This consistency suggests that melt features in the cores provide a useful record of climate signals because the refrozen surface, which is observed as melt features in ice cores, is more resistant to persist wind erosion than are soft firn and fresh snow. MFPs of the two core remained low until 1950 but increased thereafter, showing peaks in the early 1950s, mid-1960s, and mid-1970s, respectively. A remarkable warming trend is evident from the 1980s onward. Significant differences between the two records are seen in the early 1920s and around 1980, probably because of dating uncertainties: the two ice cores were analyzed independently and assigned time scales using different methods. The harmonic fluctuations in MFP between the two cores indicate the robustness of both time scales and the representativeness of MFP as a climatic proxy.

[24] The recorded temporal variations in MFP are consistent with the rate of terminus retreat of the Maliy Aktru Glacier in the Siberian Altai. This glacier is located in the northern Chuya Range, about 90 km northeast of the Belukha Glacier. The area of Maliy Aktru Glacier is 2.61 km^2 in 2006 [*Surazakov et al.*, 2007]. The mass balance of this glacier has been monitored since 1960s and the data can be obtained from the World Glacier Monitoring Service (http://www.wgms.ch/). *Surazakov et al.* [2007] estimated the rate of terminus retreat of the Maliy Aktru Glacier based on analyses of remotely sensed images (Figure 6c), reporting

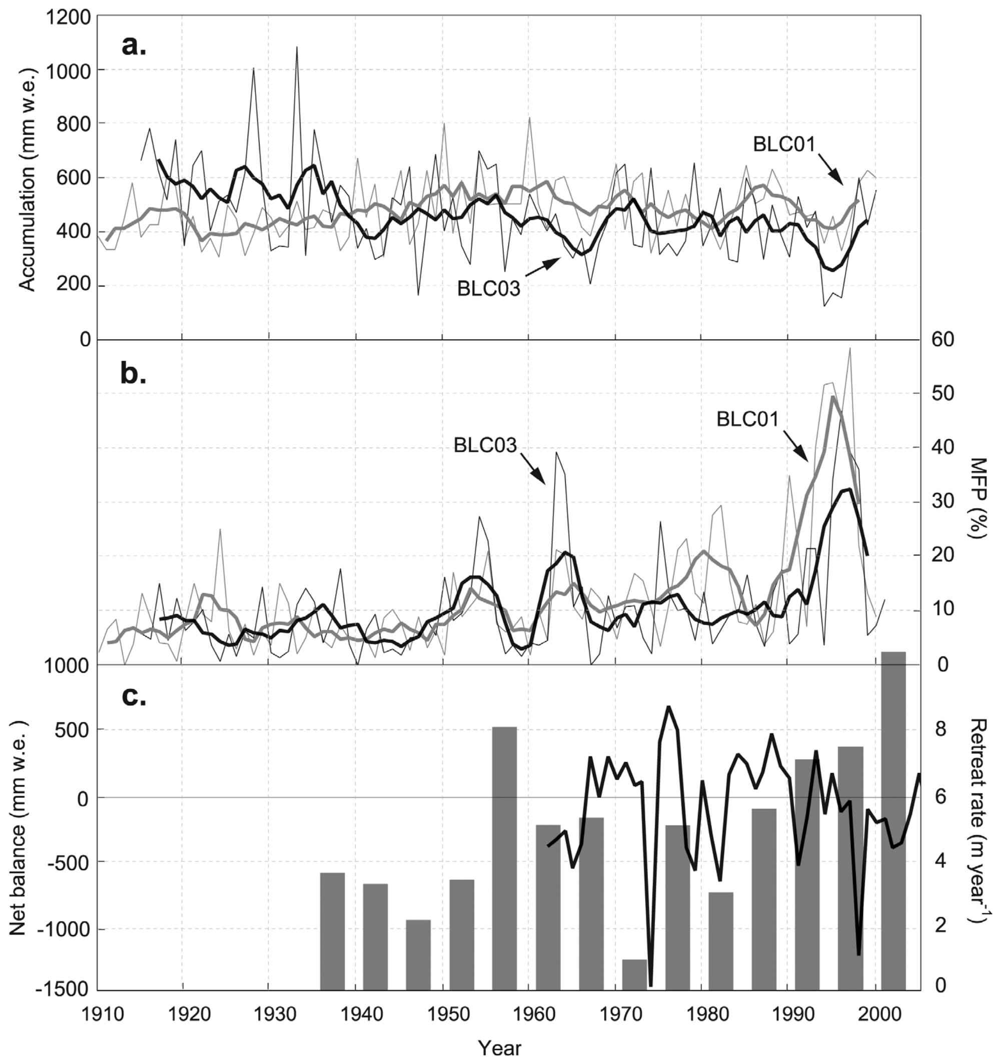

Figure 6. Temporal changes in (a) accumulation and (b) melt feature percentage (MFP) in cores recovered by a U.S.-Japanese-Russian group (black line) and a Swiss-Russian group (gray line). Thin and thick lines denote annual values and the 5 year running mean, respectively. (c) The 5 year averaged rates of terminus retreat (gray bars) [*Surazakov et al.*, 2007] and mass balance (black line) of Maliy Aktru Glacier from World Glacier Monitoring Service.

that the main cause of observed loss in glacier area within the Aktru Basin was an increase in summer air temperature. Figures 6b and 6c show that the rate of terminus retreat has accelerated with the warming of summer temperatures indicated by MFP data. The data in Figure 6 also suggest that melt features in ice cores preserve a record of the summer climate and that these temporal variations are applicable not only to the Belukha Glacier but also to the broader region.

[25] In addition, *De Smedt and Pattyn* [2003] showed an agreement between summer air temperature at Aktru meteorological station and mean annual surface mass balance variation in Maliy Aktru Glacier ($r = -0.61$). The mass balance of Maliy Aktru Glacier responds to summer temperature within the year. Figure 6c shows that the rate of terminus retreat has accelerated after decreases of mass balance. In Maliy Aktru Glacier, the response time of terminus retreat seems to be a few years delay to the mass balance. *Surazakov et al.* [2007] pointed out that the mean summer air temperatures are high correlated between Aktru and Akkem meteorological stations ($r = 0.83$). However, there is no significant correlation between temporal variations of MFP and mass balance of Maliy Aktru Glacier (Figure 6c; $r = -0.006$). On the other hand, we can obtain the best significant correlation when the MFP is moved +2 years ($r = 0.35$, $p < 0.05$). It suggests that our dating result has about 2 years error. Retreat rate of the terminus and mass balance are function of air temperature and precipitation. We also examined relation between reconstructed accumulation in our ice core and mass balance of Maliy Aktru Glacier. The two records show a weak significant but negative correlation ($r = -0.36$, $p < 0.05$). It becomes no significant when date is moved +2 years like MFP. *De Smedt and Pattyn* [2003] also showed no significant relations

Table 1. Correlation Coefficients for Annual Melt Thickness (AMT) and Summer Reference Temperature (1951–2000; Degrees of Freedom is 50)

	June	July	August	JA[a]	JJA[a]
Coefficient	0.10	0.14	0.37[b]	0.33[c]	0.31[c]

[a]JA and JJA represent July–August and June–August mean temperature, respectively.
[b]$p < 0.01$.
[c]$p < 0.05$.

Table 2. Average Temperatures, Warming Trends, and Standard Deviation of Reconstructed Temperatures (1951–2000)[a]

	Average	Warming Trend	Standard Deviation
T_{ref}	−4.8°C	+0.52°C/50 a	±0.36°C
T_{SO10}	−4.8°C	+0.34°C/50 a	±0.27°C
T_{KH06}	−6.8°C	+0.36°C/50 a	±0.91°C

[a]T_{SO10} and T_{KH06} represent the reconstructed temperatures by SO10 and KH06 method.

between mass balance and annual or summer precipitation at Aktru station. These results suggest that the main cause of the observed glacier shrinkage in Altai Mountains is an increase in summer air temperature.

3.2. Reconstruction of Summer Temperature

[26] Table 1 lists the correlation coefficients obtained between AMT in the Belukha ice core and monthly T_{ref} AMT showed the strongest correlation with August T_{ref} ($r = 0.37$, $p < 0.01$), followed by June–August T_{ref} (JJA, $r = 0.31$, $p < 0.05$) and July–August T_{ref} (JA, $r = 0.33$, $p < 0.05$) for the period 1951–2000. However, the summer temperature reconstructed based on a linear regression between JJA T_{ref} and AMT showed less variability ($\sigma = 0.11$°C) than did the reference temperature ($\sigma = 0.36$°C) for the period 1951–2000. Taking into account the uncertainties involved in dating, we reconstructed summer temperature based on a simple linear regression between the 5 year running mean JJA T_{ref} and AMT ($r = 0.31$, $p < 0.05$); this resulted in improved variability ($\sigma = 0.34$°C). This improvement might be the result that the influence of dating error was suppressed by using 5 year running mean. Correlation between 5 year running mean of JJA T_{ref} and AMT is so significant ($r = 0.78$, $p < 0.01$) that the annual variability of reconstructed temperature might be improved.

[27] We also performed a multiregression analysis by adding the accumulation record to the AMT-temperature equation. The temperature obtained from the multiregression formula derived from AMT and the reciprocal of annual accumulation showed small variability ($\sigma = 0.13$°C), similar to that obtained above using simple linear regression. This value was also improved by using the 5 year running mean AMT and the reciprocal of annual accumulation ($\sigma = 0.27$°C). Summer accumulation actually accounts for more than 55% of annual because of wind erosion on winter accumulation [*Fujita et al.*, 2004; *Nakazawa et al.*, 2005]. Because it is difficult to distinguish summer layer from annual layer, we use annual accumulation as the proxy of summer solar radiation. Ultimately, we adopted the following multiregression formula:

$$T_{JJA} = 0.0045 AMT_{5a} + \frac{77}{b_{5a}} - 5.3 \qquad (2)$$

where AMT_{5a} and b_{5a} are the 5 year running mean AMT (mm) and reconstructed annual accumulation (mm w.e.), respectively. The result obtained using this formula showed the strongest correlation with the reference temperature ($r = 0.35$, $p < 0.01$). A benefit of this approach is that both AMT and annual accumulation can be obtained from the analyzed ice core.

[28] Figure 7 shows summer temperatures reconstructed using the equation proposed by *Henderson et al.* [2006] (KH06) and using the multiregression formula (SO10). Average temperatures, warming trends, and standard deviations are listed in Table 2. It seems that T_{KH06} and T_{SO10} show similar trends as T_{ref}, however they have different average and variability. These reconstructed temperatures showed warming trends since 1990s. *Shahgedanova et al.* [2010]

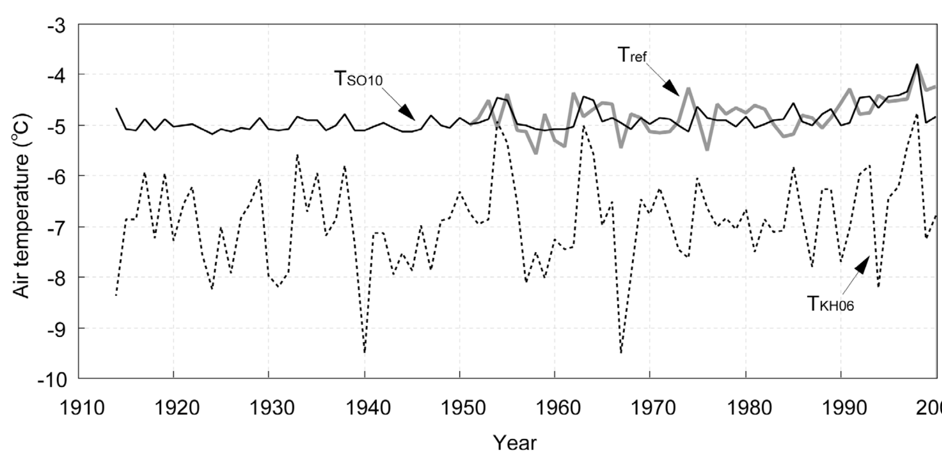

Figure 7. Reconstructed summer temperatures (black solid line is based on multiregression formula, black dashed line is based on equation proposed by *Henderson et al.* [2006], and gray line is our summer reference temperature).

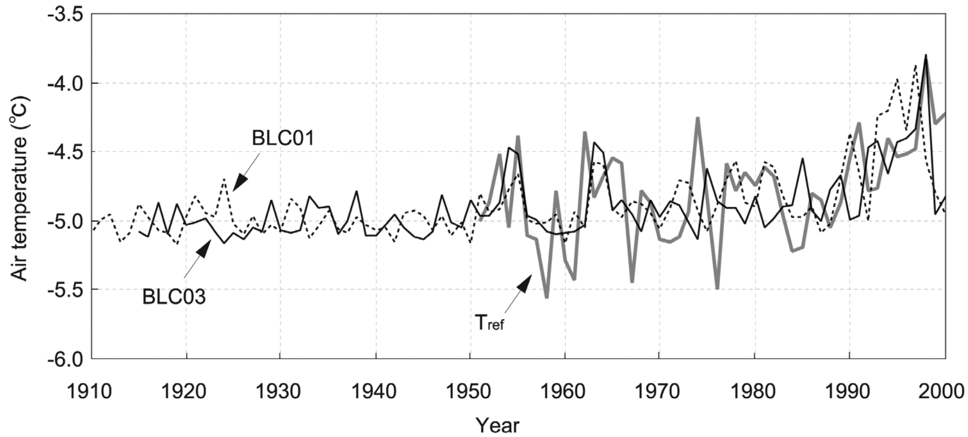

Figure 8. Reconstructed summer temperatures derived from multiregression formula (black line is based on the results of BLC03, black dashed line is based on those of BLC01, and gray line is our summer reference temperature).

reported that Altai glacier front fluctuations and mass balance records showed their acceleration of shrinkage since the 1990s. This agreement supports that the main cause of the observed glacier shrinkage in Altai Mountains is an increase in summer air temperature.

4. Discussion

[29] KH06 yielded underestimated temperatures, perhaps reflecting the fact that annual accumulation in the ice core (average, 464 mm) is less than annual precipitation recorded at the Akkem meteorological station (average, 537 mm) because of wind erosion. However, the result is not improved even if a greater amount of accumulation is assumed, as low temperatures are still obtained for low-MFP years (e.g., 1940). The Krenke–Khodakov equation used in KH06 was derived from observational data obtained for glaciers worldwide [*Krenke and Khodakov*, 1966], probably including ablation areas, where the albedo is lower than in the accumulation area. For a given temperature, larger amounts of ablation would occur in the ablation area (with lower albedo) than in the accumulation area (with a higher albedo). In addition, the same AMT would be produced under the colder environment of the ablation area than in the accumulation area. Therefore, temperatures reconstructed using KH06 are underestimated because of the lower albedo effect.

[30] SO10 yields temperature with low variability partly because temperatures below −5.3°C cannot be obtained according to intercept of multiregression formula. Figure 8 shows reconstructed temperatures derived from SO10 by using accumulation and AMT obtained each ice core. Two temperatures show a significant correlation ($r = 0.55$, $p < 0.01$) despite uncertainty and disagreement between two reconstructed accumulations. It suggests that uncertainty of accumulation has no great influence on reconstruction by SO10. In addition, we calculate root mean square differences (RMSD) of AMT and reciprocal of annual accumulation between BLC01 and BLC03 as 57.9 (mm) and 0.00128 (mm w.e.$^{-1}$), respectively. These RMSDs correspond to 0.26°C for AMT and 0.10°C for annual accumulation. It suggests that the contribution of AMT is greater than that of annual accumulation.

[31] If long-term instrumental temperature data are available, SO10 should be appropriate for glaciers such as the Belukha Glacier, where summer temperatures approach 0°C. For cold glaciers, where summer melting has never occurred, it is not feasible to reconstruct summer temperatures using this method, as it relies upon melt features.

5. Conclusions

[32] We reconstructed the record of summer temperature from melt features and compared the results with those obtained using different methods (as reported in previous studies) for the uppermost 48 m of an ice core recovered from the Belukha Glacier, Siberian Altai Mountains. We compared records of accumulation and melt feature percentage (MFP) with the results of a Swiss-Russian group who drilled an ice core at a nearby site upon the Belukha Glacier, which was analyzed independently and assigned a time scale using different methods to those employed in the present study. The two sets of MFP data showed similar trends ($r = 0.45$, $p < 0.001$), whereas there was no significant correlation between the annual accumulation ($r = 0.004$) reported in the two studies. Temporal variations in MFP are consistent with the rate of terminus retreat (with a lag time of several years) of the Maliy Aktru Glacier in Siberian Altai, northeast of the Belukha Glacier. The finding of harmonic fluctuations in MFP between the two cores demonstrates the robustness of both time scales and the representativeness of MFPs as a climatic proxy, not only for the Belukha Glacier but also for the broader region.

[33] Temperatures reconstructed using the equation proposed by *Henderson et al.* [2006] are underestimated, probably because the equation was derived using data from ablation areas, where albedo is lower than in the accumulation area and where larger amounts of ablation occur (compared with the accumulation area) for a given temperature. We successfully reconstructed past summer temperatures using a multiregression formula derived from a

5 year running mean of melt feature thickness and the reciprocal of annual accumulation.

Notation

T_{ref} reference temperature, °C.
T_{JJA} June–August mean temperature, °C.
MFP_a annul melt feature percentage, %.
b_a reconstructed annual accumulation, mm w.e.
AMT_{5a} 5 year running mean AMT (annual melt feature thickness), mm.
b_{5a} 5 year running mean reconstructed accumulation, mm w.e.

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V. B. Aizen, College of Science, University of Idaho, PO Box 443025, Moscow, ID 83844, USA.

K. Fujita and S. Okamoto, Graduate School of Environmental Studies, Nagoya University, Furocyo F3-1, Chikusa-ku, Nagoya, Aichi 464-8601, Japan. (sokamoto@nagoya-u.jp)

T. Miyake, F. Nakazawa, and J. Uetake, National Institute of Polar Research, 10-3 Midoricho, Tachikawa, Tokyo 190-8518, Japan.

M. Nakawo, National Institutes for the Humanities, Kamiyacho Central Place, 4-3-13 Toranomon, Minato-ku, Tokyo 105-0001, Japan.

H. Narita, Network of Snow and Ice Specialists, Sapporo 064-0804, Japan.

S. A. Nikitin, Department of Glacio-Climatology, Tomsk State University, 634050 Tomsk, Russia.

N. Takeuchi, Graduate School of Science, Chiba University, 1-33 Yayoicho, Inage-ku, Chiba 263-8522, Japan.