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Glaciological observations on the plateau of Belukha Glacier in the Altai Mountains, Russia from 2001 to 2003

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Abstract

In order to reconstruct past climate and environment changes from ice cores, the US-Russia-Japan joint research was carried out on the west plateau of Belukha Glacier in the Altai Mountains from 2001 to 2003. After two years reconnaissance researches, an ice core to the bottom (171 m) was successfully extracted in August 2003. We report in this paper the observational results during 3 years (2001-2003) with respect to mass balance, changes in surface level, surface flow velocities, meteorological and climatological data, and pits.

1. Introduction

Runoff from southwestern Siberia plays a part in regulating the global thermohaline circulation through the hydrological cycle of the Arctic Ocean (Wang and Cho, 1997). Seasonal snow covers and glaciers of the Altai range are sources of water of the Ob and Yenisey rivers, which are the largest western Siberian rivers flowing into the Arctic Ocean. The continental runoff amounts to about 54% of the total freshwater into the Arctic Ocean (Barry *et al.*, 1993) and the water flowing from the Ob and Yenisey rivers accounts for 40% of the total river inflow into the Arctic (Aagaard, 1980). We expect, therefore, that climate change has a significant influence on the freshwater budget of the Arctic Ocean through impact on glacier and snow runoff in the headwaters of these rivers. During the last half of the 20th century, the volume of glaciers in the central high Asia has decreased tremendously (IPCC, 2001a) in association with remarkable rapid warming in Siberia (Chapman and Walsh, 1993; Weller, 1998; IPCC, 2001b).

Well-dated, high-resolution ice core records will improve our understanding of past climate and hydrological environment and help to predict possible future changes (Taylor *et al.*, 1993). Although Tibetan/Himalayan ice core records have been recovered in regions dominated by monsoon circulation (*e.g.* Mayewski *et al.*, 1984; Thompson *et al.*, 1988; 1989; 1990; 1993; 1995; 1997; 2000; Yao *et al.*, 1995; 1996; 1999; Kang *et al.*, 2000; Duan and Yao, 2003), paleo-climatic records from the Altai Mountains are relatively few. The Altai Range lies on the northwestern periphery of the central Asia (Fig. 1a) and acts as the initial barrier to the westerly jet stream and Siberian high. In recent years, several observations with respect to ice cores and glacier dynamics have been carried out in the region (*e.g.* Eyrik *et al.*, 2001; Blaser *et al.*, 2002; Fujii *et al.*, 2002; Schwikowski *et al.*, 2002; De Smedt and Pattyn, 2003; Pattyn *et al.*, 2003). Despite of many glaciers in the Altai Mountains, suitable snow accumulation sites to extract ice cores are few. The west plateau of Belukha Glacier (49° 49′ N, 86° 34′ E; 4000-4100 m a.s.l., Fig. 1b and 1c), the observation site of this study, is located at so high elevation that disturbances of meltwater on climatic signals in snow are expected to be small.

In order to examine climatic and environmental records through ice core, we have started the US-Russia-Japan joint research on the west plateau of Belukha Glacier in the Altai Mountains since July 2001. After two years reconnaissance researches, an ice core to the bottom (170 m) was extracted in August 2003. Observational results during 3 years (2001-2003) with respect to mass balance, changes in surface level, surface flow velocities, meteorological and climatological data, and snow pits, which will be helpful for analysis of ice core, are reported in this paper.

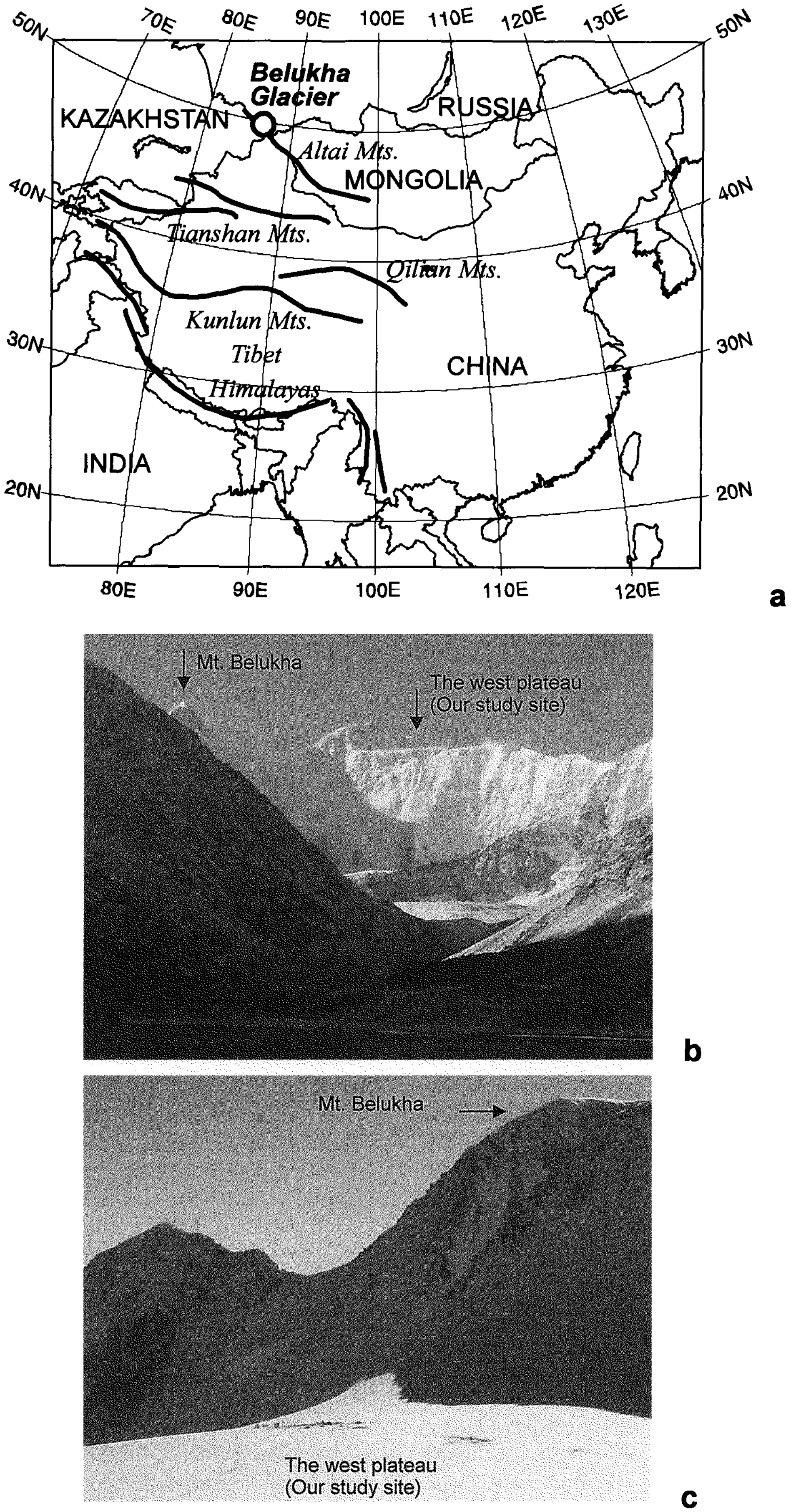

Fig. 1. Location of Belukha Glacier (a) and photographs of research area (b: Mt Belukha from Akkem base camp taken on 13 August 2003, c: The west plateau taken from a west hill on 9 August 2003).

2. Observations and results

In July 2001, a reconnaissance research expedition was carried out. Two bench marks and five stakes were installed on the west plateau of Belukha Glacier. Several snow pits were dug and shallow and deep ice cores were extracted during the succeeding two years. Participants in the field observation during three years are listed in Table 1. Relative locations of the bench marks (BM), stakes (ST), snow pits (P, JP, RP), drilling site (DS), and glacier camp (GC) are shown in Fig. 2. The locations of the bench marks, stakes, pit JP and drilling site were measured precisely with a carrier-phase differential GPS (GP-SX1, TOPCON in 2001 and 2003; Allstar, CMC electronics in 2002). Locations of the snow pits (P and RP) and glacier camp were measured with a handy-type GPS (Garmin, U.S.A.). In addition, daily precipitations were sampled at the Akkem meteorological station, located at 12 km north of the plateau of Belukha Glacier, for stable isotope analysis from July 2002 to July 2003 (136 samples). Samples are under analysis at present.

2.1. Climatological data at Akkem

Long-term meteorological records (air temperature and precipitation since 1950s) are available at the Akkem meteorological station (2040 m a.s.l.) operated by the Russian government. It is valuable to compare climatic signals in ice cores with long-term climatological data in order to improve reliability of the climate information reconstructed from the ice cores. Changes in annual mean air temperature and annual amounts of precipitation, and their seasonal changes observed at Akkem are shown in Fig. 3. In the long-term records (Fig. 3a), annual mean air temperature tends to rise since the mid 1980s, while there is no clear tendency in annual precipitation. Seasonal change in monthly precipitation (Fig. 3b) shows that fairly large amounts of precipitation occur during summer season (May to September), suggesting that Belukha Glacier is a summer-accumulation type glacier. It has been known that mass balance and fluctuation of summer-accumulation type glacier in the Asian highland are very sensitive to change in air temperature (Kayastha *et al.*, 1999; Fujita and Ageta, 2000;

Table 1. List of participants in the field observation

Period (in/out Akkem)	Participants
11 to 23 July 2001	V. Aizen[1], S. Nikitin[2], L.D. Cecil[3], K.J. Kreutz[4], K. Fujita[5], Y. Matsuda[5], K. Matsuki[5], A. Surazakov[2], A. Lushnikov[2], A. Chebotarev[2], T. Prokopinskaya[2], S Polesskiy[6]
10 to 18 July 2002	V. Aizen[1], S.A. Nikitin[2], K. Fujita[5], N. Takeuchi[7], A. Surazakov[2], A. Lushnikov[2], A. Chebotarev[2], T. Prokopinskaya[2]
22 July to 13 August 2003	V. Aizen[1], S. Nikitin[2], N. Takeuchi[7], J. Uetake[8], A. Takahashi[9], T. Yamazaki[10], M. Sawahata[11], A. Surazakov[1], D. Joswiak[1], A. Lushnikov[2], A. Chebotarev[2], T. Prokopinskaya[2]

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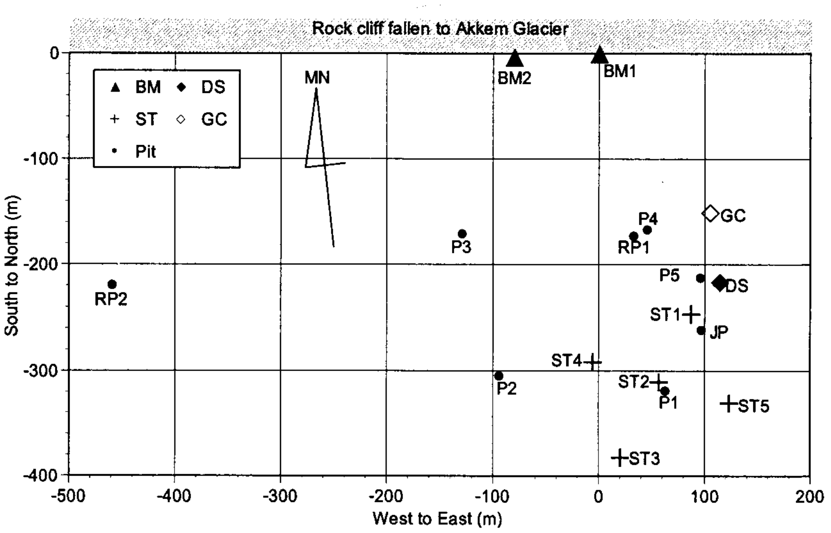

Fig 2. Locations of bench marks (BM), stakes (ST), pits (P, JP and RP), drilling site (DS), and glacier camp (GC) on the plateau of Belukha Glacier. MN denotes the direction of magnetic north.

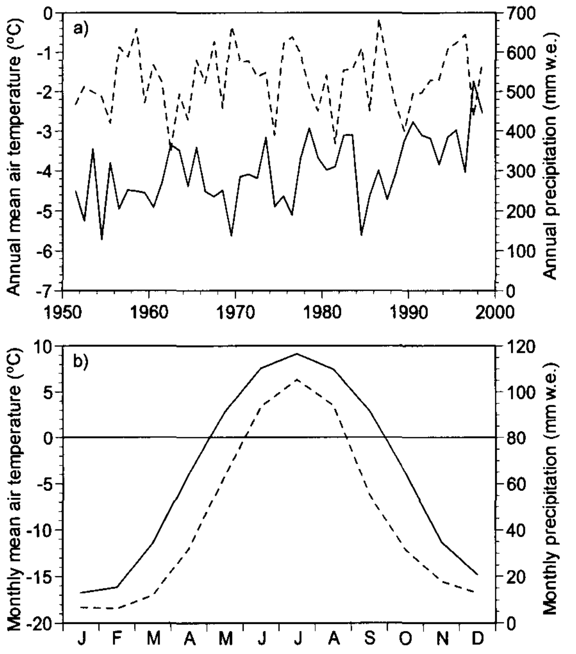

Fig. 3. Records of air temperature (solid lines) and precipitation (broken lines) at Akkem meteorological station. Annual changes from 1951 to 1998 (a) and seasonal change of monthly mean values from 1951 to 1998 (b).

Naito *et al.*, 2001). It is interesting, therefore, to investigate how the glaciers in the Altai Mountains are sensitive to climate change. It is, therefore, valuable to compare climatic records derived from ice cores, instrumental climatic records around glaciers, and fluctuations of glaciers and river discharges.

2.2. Surface level

In order to measure annual snow accumulation on the plateau, five stakes were installed in July 2001 and re-installed in July 2002 (Fig. 2). Measurements of these stakes provide surface accumulation in snow thickness (Table 2).

An automatic snow gauge (KADEC-SNOW, Kona System Co. Ltd., Sapporo, Japan) was installed in 2001 and 2002 at Stake 2 (ST2 in Fig. 2) to measure daily accumulation throughout the years on the plateau. It provides daily surface level with a resolution of 0.01 m. Unfortunately, the data loggings were stopped at the end of October 2001 and at the end of November 2002 due to a battery trouble. Figure 4 shows the daily mean surface level as results of the 2 year measurement. The surface levels are represented as relative levels to that in July 2001 (the first day of the measure-

Table 2. Changes in surface level (m) at five stakes from July 2001 to July 2003. Locations of stakes are shown in Fig. 2. Stake 1 was lost and re-installed in July 2002. Ice thicknesses (m) measured by a radio echo sounding system (Tomsk State Univesrity, Russia) are also shown.

	Snow accumulation from 18 July 2001 to 13 July 2002	Snow accumulation from 16 July 2002 to 30 July 2003	Ice thickness (m)
Stake 1 (ST1)	–	1.53	151
Stake 2 (ST2)	2.13	1.58	168
Stake 3 (ST3)	2.36	1.73	185
Stake 4 (ST4)	2.15	1.50	143
Stake 5 (ST5)	2.39	1.65	193
Averages and standard deviation	2.26 ± 0.14	1.60 ± 0.09	168 ± 21

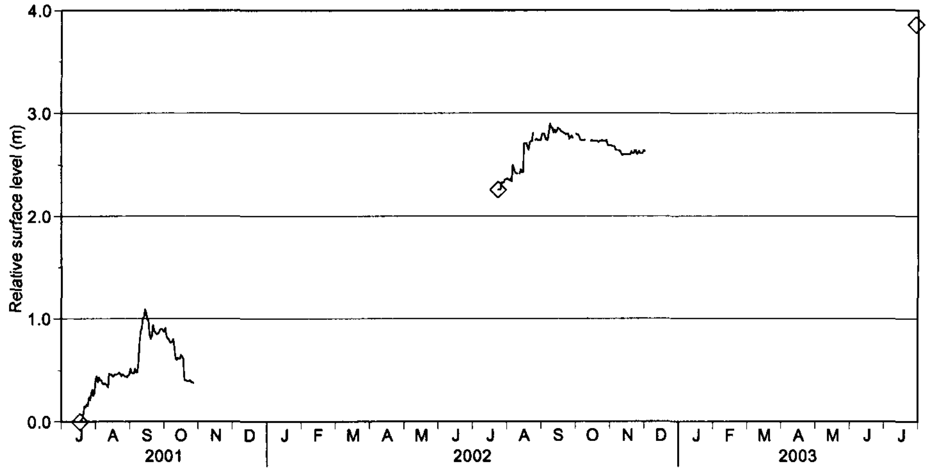

Fig. 4. Changes in relative surface levels based on the level on July 2001 (the first day of the measurement) on the plateau of Belukha Glacier from July 2001 to July 2003. Lines and squares denote surface levels measured by automatic snow gauges and by stakes.

ment).

According to the snow gauge data, the surface level increased more than 1 m from July to September 2001, and then decreased rapidly in October. The decrease in the surface level may be due to compaction of snow, melt of snow, or wind erosion. However, the decrease is unlikely due to compaction of snow or melt of snow. The decrease in October was approximately 50 cm in a month, which is too large to result from snow compaction. Furthermore, in the snow pit observation in 2002, no heavy melt feature was found in snow layer, suggesting that significant snow melting did not occur in 2001. Therefore, wind erosion is the most plausible possibility for the decrease of the surface level. In contrast to the result in 2001, no such rapid subsidence was found in 2002. It is important whether such wind erosion occurred or not when net-balance estimated from an ice core is regarded as regional precipitation. Although a possibility of wind erosion has been vaguely pointed out at many 'ice coring sites', this is the first evidence of wind erosion. This result suggests that it is necessary to discuss net-balance from ice core on the plateau with precipitation and wind speed recorded at the Akkem meteorological station.

Although we failed to collect surface level from winter to spring in both 2002 and 2003, large amounts of accumulation should have occurred in this season. Based on the stake measurements and snow gage data, the accumulation in this season was 1.9 m in 2002 and 1.2 m in 2003, which are more than half of annual accumulations in each year. Seasonal change in monthly precipitation at Akkem (averages for the period from 1951 to 1998; Fig. 3b) suggests that the rest of the annual snow accumulation occurs mainly in May and June. In order to analyze an individual precipitation event at Akkem and surface level change on the plateau in detail, it is necessary to obtain meteorological records at Akkem after 1999.

2.3. *Surface flow velocities*

Since the plateau is located at the top of the glacier, ice movement is likely small enough for an ice core study. In order to measure ice movement at the drilling site, locations of the five stakes on the plateau and two bench marks installed on rocks were surveyed with the differential GPS. Changes in the locations of Bench Mark 2 and five stakes between study years are summarized in Table 3. The origin of the surveys was set at Bench Mark 1. Since both of the bench marks were installed on rocks, the changes in relative location of Bench Mark 2 indicate measurement errors, which were less than 0.2 m in horizon and 0.05 m in vertical. The result shows that the surface flow velocities increased downstream and that the grid of 5 stakes strained convergently (Fig. 5). Since the drilling site in 2003 was located upstream of Stake 1 (DS in Fig. 2) horizontal surface flow at the site was expected less than 1.5 m a^{-1}.

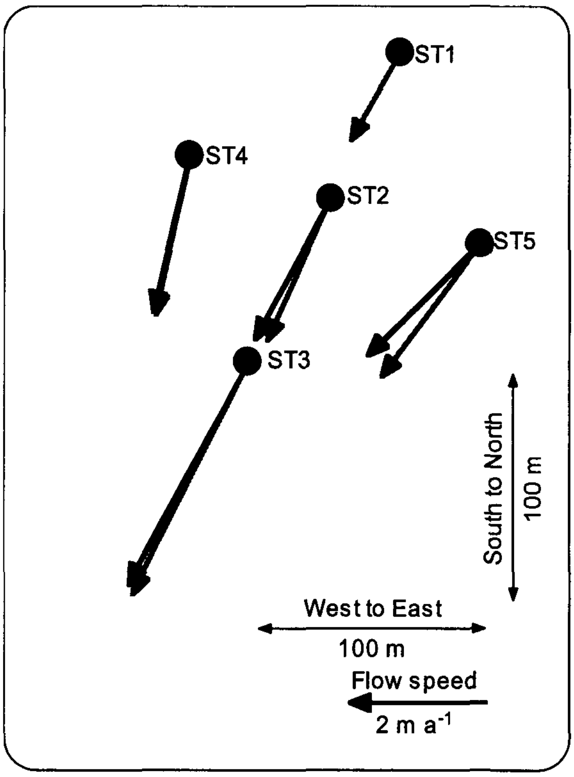

Fig. 5. Surface flow velocities on the plateau of Belukha Glacier. Circles, and black and gray arrows denote relative positions of stakes (ST), and flow velocities between 2001 and 2002, and between 2002 and 2003, respectively.

Table 3. Changes in locations (m) of bench mark and five stakes from July 2001 to July 2003. Abbreviations dN, dE, dZ and dH denote the northward, eastward, vertical and horizontal components of the changes, respectively. The origin is set at Bench Mark 1. Velocities in Fig. 5 are converted into annual values.

Duration	18 July 2001 to 14 July 2002				14 July 2002 to 30 July 2003			
	dN	dE	dZ	dH	dN	dE	dZ	dH
Bench mark 2 (BM2)	0.10	0.13	−0.01	0.16	−0.02	0.02	−0.04	0.02
Stake 1 (ST1)	–	–	–	–	−1.36	−0.76	0.09	1.56
Stake 2 (ST2)	−2.11	−1.16	1.20	2.40	−2.19	−0.98	−0.89	2.39
Stake 3 (ST3)	−3.38	−1.80	0.22	3.83	−3.58	−1.78	−0.90	4.00
Stake 4 (ST4)	−2.36	−0.54	0.94	2.42	−2.47	−0.53	−1.04	2.53
Stake 5 (ST5)	−1.68	−1.69	0.78	2.38	−2.05	−1.52	−0.30	2.55

Table 4. Slope angle (a), effect of slope (SE) and submergence velocities (SV and SV_a) at each stake from 2001 to 2003. Averages of each period are also shown.

	18 July 2001 to 14 July 2002				14 July 2002 to 30 July 2003			
	a (°)	SE (m)	SV (m)	SV_a (m a^{-1})	a (°)	SE (m)	SV (m)	SV_a (m a^{-1})
Stake 1 (ST1)	3.28	–	–	–	3.41	−0.09	−1.34	−1.29
Stake 2 (ST2)	4.13	−0.17	−0.75	−0.76	4.32	−0.18	−2.29	−2.19
Stake 3 (ST3)	4.98	−0.33	−1.81	−1.83	5.24	−0.37	−2.26	−2.17
Stake 4 (ST4)	4.13	−0.18	−1.03	−1.04	4.32	−0.19	−2.35	−2.25
Stake 5 (ST5)	4.13	−0.17	−1.44	−1.45	4.32	−0.19	−1.75	−1.68

	Average and standard deviation	
SV_a (m a^{-1})	−1.27 ± 0.47	−1.91 ± 0.42

Since the measurement errors of the carrier-phase differential GPS survey are small, submergence velocity can be calculated by subtracting accumulation height and effect of slope from vertical change in surface. Values at each stake and averages are summarized in Table 4. It is considered that most part of the submergence velocity is caused by compaction of snow layer accumulated in previous year.

2.4. *Temporal change in snow temperature*

Snow temperature record is useful to interpret post-depositional changes in stratigraphy, chemical, and stable isotopes near the surface. A temperature sensor was installed at Stake 2 (ST2 in Fig. 2) and snow temperature was monitored from July 2002 to July 2003 at an interval of one hour (Fig. 6). Since the sensor was fixed at the surface level in July 2002, depth of the sensor below the surface has changed with snow accumulation. Snow temperature was 0 °C during the first two months (July and August). This constant temperature is likely due to an aquifer keeping meltwater isolated by snow accumulation from the surface (Fig. 4). The aquifer probably became an ice layer during the succeeding winter. However, no heavy melting feature was found in the snow pit of July 2003. Therefore, the aquifer may have formed only at the site around the sensor. Meltwater may have flowed down along the stake then froze the sensor. In the early June of 2003, the snow temperature increased drastically up to 0 °C. This is probably due to melt of the ice around the sensor.

Air temperature, relative humidity, wind speed and direction, and atmospheric pressure were measured beside Bench Mark 1 from July 2002 to August 2003. The meteorological data will be compared with atmospheric circulation patterns. It will help to understand vapor sources and origins of chemical species, dust, and pollens preserved in snow (see the next sub-chapter). Detailed discussion will be published elsewhere.

2.5. *Ice cores and snow pits*

Several snow pits were dug every year from 2001 to 2003. Many thin ice layers but no heavy melt feature were observed in all of the pits. This suggests that annual snow layers on the plateau are not disturbed by melt water percolation. Therefore, the plateau is likely to preserve well information of atmosphere when snow was deposited. In contrast to this plateau of Belukha Glacier, significant melt and melt water percolation have been observed at the drilling site of Sofiyskiy Glacier (3435 m a.s.l., 49° 47′ N, 87° 44′ E, located 80 km east from Belukha Glacier), where an ice core has been drilled in 2001 by Fujii *et al.* (2002). This fact implies that the suitable sites to extract ‘dry ice core’ are limited even if the Altai Mountain Range

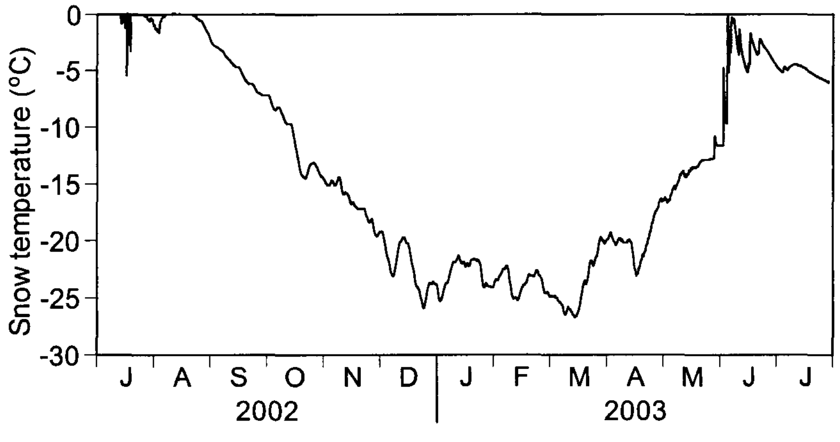

Fig. 6. Snow temperature at Stake 2 (ST in Fig. 2). Depth of the sensor was fix at the surface in July 2002 (see Fig. 3).

Table 5. Accumulations in snow thickness and water equivalent on the plateau of Belukha Glacier. Accumulation between 2000 and 2001 are estimated from depth of ice layer and density profiles in pits (P in Fig. 2). Accumulations from 2001 to 2003 are obtained from stake measurements (ST in Fig. 2) and density profiles in pits (JP in Fig. 2). Averaged densities of surface layer are also shown.

	Snow thickness (m)	Water equivalent thickness (m)	Averaged density ($\times 1000$ kg m^{-3})
from summer of 2000 to July 2001	1.78 ± 0.06	0.69 ± 0.05	0.39
from July 2001 to July 2002	2.26 ± 0.14	0.87 ± 0.06	0.38
from July 2002 to July 2003	1.60 ± 0.09	0.56 ± 0.04	0.35

lies at high latitude. Comparison of the ice cores from two locations of different conditions in Altai may yield some information which is not obtained from one ice core.

In 2001, five pits (P in Fig. 2) were dug to understand spatial distribution of chemical species, oxygen and hydrogen stable isotopes, and other variables on the plateau. The results will be published elsewhere. In these pits, an obvious ice layer was observed. The ice layer is considered to be formed in the previous summer of 2000. Based on the depth of the ice layer, the accumulation in the previous year (2000 to July 2001) was estimated to be 1.78 ± 0.06 m in snow thickness and 0.69 ± 0.05 m water equivalent. Accumulations in snow thickness, that in water equivalent, and averaged surface snow densities from 2000 to 2003, which were obtained from the stake and pit observations (ST and JP in Fig, 2) are summarized in Table 5.

In addition to the snow pits, a shallow ice core in 21 m depth was extracted with a hand auger (PICO, U.S.A.) at the site of pit P5 in 2001. Chemical species, stable isotopes, and dust concentrations in the ice core were analyzed and will be published elsewhere. Results of the analysis showed seasonal variations of major soluble ions and suggest that the 21 m core covers 8 years. The results also suggest that NH_4^+ and solid particles in the ice core may reflect biomass burning events around the glacier.

In order to evaluate the effect of seasonal melt on chemical species and stable isotopes in snow, a snow pit was dug at the exactly same place (JP) in 2002 and 2003. Snow samples were collected at the same vertical snow plane at one year interval. It is important to know the post-depositional changes in chemical species and stable isotopes in snow for the interpretation of deep ice core records. Samples collected in 2003 are now under analysis. The results and discussion will be published elsewhere.

In July 2003, an ice core down to the bottom (171 m depth) was successfully recovered at drilling site (DS in Fig. 2) with a mechanical ice core drill (Takahashi, 1996, Geo Tecs Co. Ltd., Nagoya, Japan). The depth was almost the same as the ice thicknesses obtained with a radio echo sounding system (Tomsk State University, Tomsk, Russia; Table 2). Another core of 48 m depth was also drilled. Stratigraphy, density, oxygen and hydrogen stable isotopes, major ions, heavy metals, dust, pollens, organic matters, and microbes will be analyzed in order to comprehensively understand an environmental history around the Altai Mountains.

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