Bulletin of Glaciological Research 17 (2000) *43 – 50*

Glaciological research of Bilchenock Glacier in Kamchatka, 1998

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(Received August 5, 1999 ; Revised manuscript received December 1, 1999)

Abstract

Bilchenock Glacier is a surging glacier in the Kamchatka Peninsula, Russia, which most recently surged in 1982 and is currently in its quiescent phase. To get information on the quiescent phase behavior of Bilchenock Glacier, a preliminary research on the glacier dynamics and meteorological features was carried out from July 18 to August 17, 1998.

The surface of the ablation area of Bilchenock Glacier exhibits repeated patterns of a ridge and a gentle slope, and the distribution of flow speeds was considerably irregular ranging from about 0.05 m day^{-1} to 0.17 m day^{-1} within a 2-km part in the lower reach. The terminus has risen by about 250 -350 m from 1984 to 1998. Daily mean air temperature varied from 7 to 17 °C and relative humidity was often close to 100 % near the glacier terminus. Averaged daily amount of icemelt was 56 mm water equivalent near the glacier terminus. Though the next surge may be predicted to occur in the near future based on its interval of surge about 23 years, no remarkable premonition of surge was found during this research.

1. Introduction

Bilchenock Glacier is known as a unique surging glacier in Kamchatka (Paterson, 1994), which has been in a phase of quiescence since a surge in 1982/84 (Muravyev *et al.*, 1987). At some surging glaciers, quiescent-phase evolutions were studied to evaluate causes of surge, and the results indicated that many surging glaciers showed some premonitions of surges toward the end of the quiescent-phase (Raymond and Harrison, 1988; Clarke and Blake, 1991; Heinrichs *et al.*, 1996; Lawson, 1996). However, the behavior varies from glacier to glacier, so we need more examples to discuss the processes of surges. The main aim of the present research at Bilchenock Glacier is to get information of its quiescent-phase behavior and to clarify the dynamic characteristics of the glacier. We also paid attention for hydrological characteristics of a runoff stream to know the subglacial hydrological condition which is regarded as another important key in surge mechanisms.

Several glaciological studies aiming at reconstruction of the past climate over Kamchatka have been carried out on the summit of Ushkovsky ice cap which is the accumulation area of Bilchenock Glacier (Shiraiwa *et al.*, 1997; Shiraiwa *et al.*, 1999; Salamatin *et al.*, 1999). Because the dominant mass output from this ice cap is undertaken by Bilchenock Glacier, dynamics and ablation processes of Bilchenock Glacier are also important to reconstruct a mass-balance history of the ice cap. In the persent research, to make clear ablation processes of this glacier, we also attempted to obtain meteorological features on the debris-covered surface in the ablation area.

According to Muravyev (1999), 38% of glaciers in Kamchatka Peninsula are located in active volcanic

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areas. Thus, the influence of volcanic and geothermal activities upon mass balance, hydrological condition and glacier dynamics might be very important to understand glaciers in Kamchatka.

From these issues, we carried out a preliminary research on glacier dynamics, meteorological conditions and hydrological processes at Bilchenock Glacier from July 18 to August 17, 1998. In this paper, we present first the historical records of researches at Bilchenock Glacier by Russian scientists, and secondly the distribution of surface velocities, the surface topography of the glacier and the weather conditions. Results of observations and analyses on hydrological processes will be presented by a separate paper in the near future.

2. Regional settings

Bilchenock Glacier (Fig.1) is located in the central part of the Kamchatka Peninsula. In this area, the highest and very active volcanoes in Kamchatka exist, most of which exceed 3000 m a. s. l. Ushkovsky volcano has an altitude of 3900 m and an ice cap of 4 km in diameter is located at the summit. Bilchenock Glacier is the main outlet glacier from this ice cap. According to Dolgoushin and Osipova (1975), Bilchenock Glacier had a length of 19.2 km and the area of 24.4 km^2, with the terminus altitude of 650 m a. s. l. (According to the survey in 1998, the terminus altitude was 750 m a. s. l.) and the firn line altitude of 2800 m a. s. l. The accumulation area is now located between 3300 and 3900 m a. s. l. in a caldera of Ushkovsky and the ice fall extends from 2950 to 1400m a. s. l. The average surface slope below the ice fall is about 5°, and it is 9°near the glacier terminus. The glacier surface of the ablation area is covered with thick and dark debris composed of volcanic rocks and ashes of which thickness exceeds 1 m at some place (Fig. 2a).

The glacier surface in the ablation area shows repeated patterns of a transverse ridge (Fig. 2b) and a following gentle slope as shown in Fig. 3. The relative

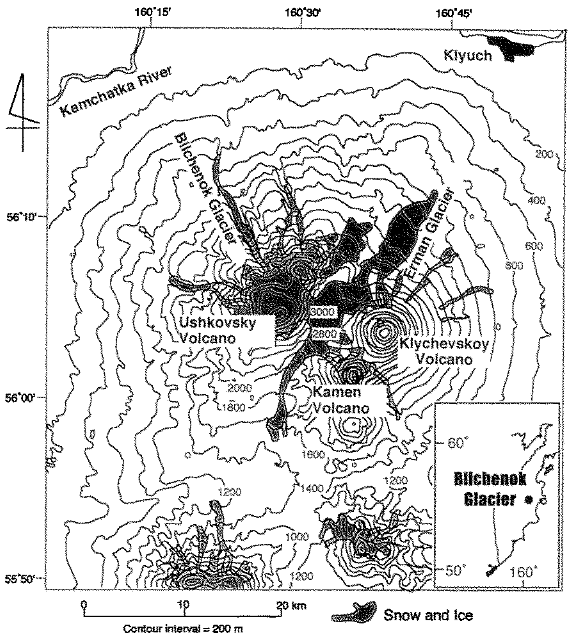

Fig. 1 Location of study area. Hatched areas indicate glaciers.

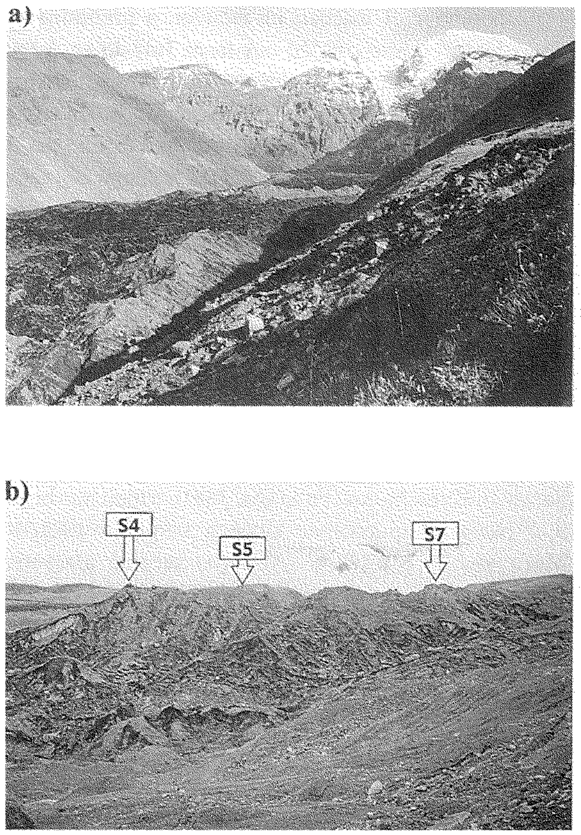

Fig.2 Bilchenock Glacier in summer of 1998. a: Upper part of the ablation area and the ice fall of Bilchenock Glacier, viewed from the western bank at about 950 m a.s.l. (August 14, 1998). The glacier flows from the center toward the left side in the foreground. b: A transverse ridge of the glacier surface viewed from the western bank around 850 m a.s.l. (July 22, 1998). Locations S4, 5 and 7 are indicated in Fig. 4.

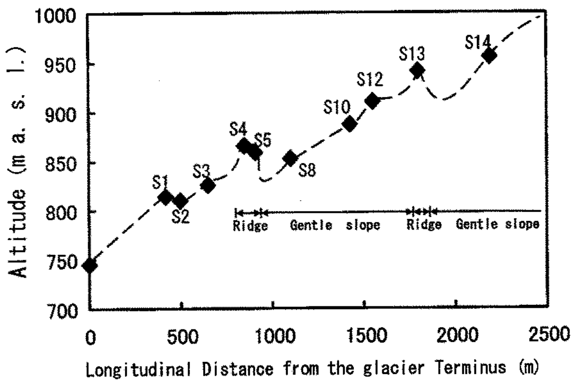

Fig.3 Longitudinal surface profile along the approximate centerline of Bilchenock Glacier. Surface profile between the GPS points(◆) was drawn by a broken line based on observation of the surface topography in 1998.

height of the ridge from the surrounding gentle slope surface was about 30 m and the distance between two ridges was from 500 to 800 m.

3. History of studies of Bilchenock Glacier

Table 1 shows documents of the glacier terminal altitude. The first information about Bilchenock Glacier was given in 1900 by Tyushov who tried to climb Ushkovsky volcano. He reported that Bilchenock Glacier terminus was located at approximately 900-920 m a. s. l. (Bogdanovich, 1904). Next information was obtained by an aerial survey in September 1949. The survey result showed that the terminus was at 800 m a. s. l. and the glacier surface near the terminus was heavily crevassed. In 1959/60, the occurrence of a surge was first reported. At that time, the altitude of the glacier terminus was 615-630 m a. s. l. (Vinogradov, 1965). In the 1970s, after the surge, the glacier active terminus rose to 930-950 m a. s. l., near the ice fall, having left a vast field of "stagnant ice" downstream(Muravyev *et al.*, 1987).

Table 1. The altitude of the glacier terminus and surge at Bilchenock Glacier

Year	Glacier terminus (altitude in m)	Memorandum
1900	900-920	
1949	800	
1959/60	615-630	Surge
1970's	930-950	
1982/84	400-500	Surge

In July 1980, it was reported by a field work that a bulge of dirty ice 15-20 m in height had been advancing over the stagnant ice zone. The glacier continued to advance with small speed (some tens of meters per year) for 1.5 years. At last, in February 1982, the glacier started to surge(Vinogradov *et al.*, 1982).

In spring 1982, the first full glaciological research was carried out at Bilchenock Glacier by Russian scientists (Vinogradov *et al.*, 1982). The research items were photographic survey near the terminus, measurement of surface velocities using an electric distance meter, snow survey and installation of seismometers. A meteorological station which recorded 6-hour-interval air temperature and atmospheric pressure was set up on the right bank at 850 m a. s. l. The second and the third researches were carried out in September 1982 and August 1983, respectively.

The results of these researches are summarized as follows.

- The surge continued for about two years and stopped in autumn 1984. The major advance happened in 1982-83 and the terminus reached 400-500 m a. s. l. (Muravyev *et al.*, 1987).
- A map of 1/25000 scale with vertical resolution of 10 m was compiled using photographic and surface surveys data by D. G. Tsvetkov and A. S. Tyuflin, Institute of Geography, Russian Academy of Science (Fig.4).
- The range of air temperature in April was from -30 °C in nighttime to -5 °C in daytime. That in September was from -3 °C in nighttime to 15 °C in daytime. The total surface lowering due to ablation near the terminus was 24 to 30 cm from September 5 to 17, 1982.
- Flow velocity at 4 km upglacier from the terminus was about 0.5 $\mathrm{m\,day^{-1}}$ in 1982, which was slower than 1980.

In general, surges recur at regular intervals (Paterson, 1994). At Bilchenock Glacier, the interval was calculated to be 23 years from 1959 to 1982. If we assume that the interval of surge is regular at Bilchenock Glacier, the glacier can be regarded to be approaching the next surge, which seems likely to start in the near future.

4. Outline of research in 1998

4.1. Survey of glacier dynamics

Survey of flow velocities was carried out at the lower reach of Bilchenock Glacier between July 18 and August 17, 1998.

4.1.1. Methods

A Global Positioning System (GPS) receiver used to measure the flow velocities of Bilchenock Glacier was GP-SX1 (TOPCON Co. Ltd.) and the method so-called "high-speed statics" was adopted. The largest problem to use a GPS in the field research was the power supply. The GPS receiver is able to work only eight hours even if its battery is full. Thus, in this research, we used a solar battery (H-1304:DAIDO) which can generate 13.2W under the clear-sky condition.

Two receivers were used, one was settled at a fixed point during the survey and a position on the glacier surface was measured for 30 minutes using the other one. Two fixed stations were established, one (α) on the left bank, which was used during surveys in the lower reach of the glacier, and the other (β) at the terminus, used during surveys near the terminus (Fig. 4). The altitudes of these fixed points were determined by the comparison with the Russian map, and the altitudes of the survey points were calculated as the relative height between the fixed points and the survey points. The survey point on the glacier was marked by a painted stone which was regarded as stable, since the glacier surface was covered with so thick debris that a stake could not be set up. Totally fifteen markers were established at three types of surface conditions. The first type is located near the glacier terminus, which is regarded as stagnant ice zone (S1, S2, S3), the second is on ridges (S4, S5, S7, S9, S13, S15) and the third is on gentle slopes (S6, S8, S10, S11, S12, S14), as shown in Fig. 4. Each position was measured at intervals from four to ten days.

4.1.2. Distribution of flow velocities

The GPS could always receive more than four satellites in this research. Under these conditions, the maximum horizontal error due to the GPS character is ± 8 mm and the vertical one is ± 16 mm, therefore it can be considered that the data in this survey have high quality enough to discuss the glacier dynamics.

Table 2 shows mean daily flow speeds and Fig. 4 shows the distribution of flow velocities. Velocities near the glacier terminus (S1, S2 and S3) were much

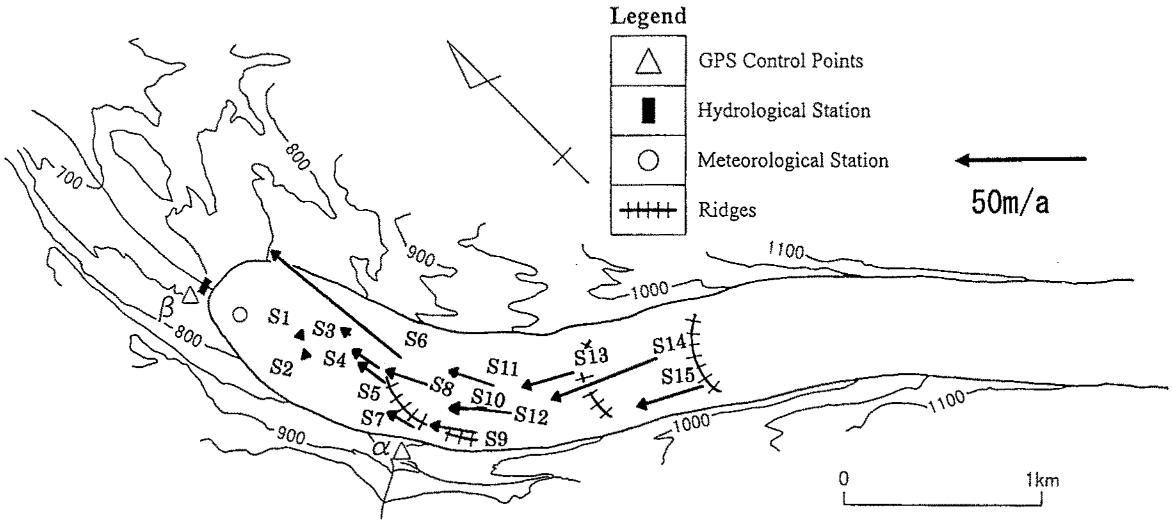

Fig. 4 Map of Bilchenock Glacier in 1983 (based on Tsvetkov and Tyuflin (unpublished)) with locations of observation points and distribution of flow velocities. The velocities are shown by arrows with annual values (m/a) by multiplying daily values with 365 days. Marks of ridges were drawn on the basis of field survey.

Table 2. Flow speeds at measurement points on Bilchenock Glacier (from July 18 to August 17, 1998)

Point	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15
Speed (cm day^{-1})	0.3	0.5	1.1	3.0	3.2	16.7	3.2	4.3	4.7	3.6	4.7	6.1	5.4	11.0	6.8

smaller than those at other positions and the rolling of the surface was much less than that of other place. For the reasons given above, we considered this area to be nearly stagnant ice caused by the rapid retreat after the surge in 1982/84 and the present active terminus of the glacier to be located upper than S3, at an altitude about 825 m a. s. l. Judging from the present altitude of glacier terminus with the stagnant ice was 750 m a. s. l., the glacier terminus should have risen by about 250-350 m from 1984 to 1998. Velocities varied considerably from place to place, particularly, velocities at S6 and S14 near the border between the ridge and the gentle slope, were significantly large though the reason is not clear.

In 1982/83, during the surge, velocities on the same ridges as S4 and S9 were measured by Russian scientists. Each annual velocity was reported to be 98 $\mathrm{m\,a^{-1}}$ (at S4) and 101 $\mathrm{m\,a^{-1}}$ (at S9), respectively. In our survey, velocities were obtained as 12 $\mathrm{m\,a^{-1}}$ (at S4) and 17 $\mathrm{m\,a^{-1}}$ (at S9) by multiplying mean daily velocities by 365 days. Since the present values are about one sixth of those in 1982/83, this glacier should be considered to be in the quiescent-phase now.

4.2. Meteorological observations

Meteorological research was carried out from July 22 to August 14, 1998 around the terminus of Bilchenock Glacier. We present methods of field observations and summary of preliminary results. Further studies including an analysis on surface heat balance are now going on and their results will be presented in the near future.

4.2.1. Methods

To evaluate the basic characteristics of ablation and heat balance of the debris-covered glacier, a meteorological station was established near the terminus. This station was located on the surface of the stagnant ice at an altitude of 778 m a. s. l. (Fig.4). The components measured at this station are net radiation, global radiation, air temperature, relative humidity, wind speed, and precipitation. All the meteorological data except precipitation were measured at 1.5 m above the ground and recorded automatically at 1-hour interval. Wind speed was obtained from the run-of-wind in 1 hour measured by a three-cup anemometer. Precipitation was measured several times a day using a "simple raingauge" composed of a funnel (diameter: 21 cm) and a bottle (Ushiyama and Matsuyama, 1995). Amount of ice ablation was also measured using a snow stake just beside the station.

4.2.2. Meteorological condition

Daily meteorological elements during the observation period are shown in Fig. 5. It was fine on the first day and during four days in the latter half of the period, but rainy days kept in the middle. There were four days with rainfall more than 10 $\mathrm{mm\,d^{-1}}$, and it was drizzle and foggy in the other five days (*i. e.* Aug. 1, 5, 6, 7 and 12). Daily mean relative humidity in these days was so high and close to 100 %. Air temperature was, corresponding with such condition, relatively low (around 8 °C) in this rainy and foggy period. Under fine weather conditions, the daily amount of global radiation exceeded 15 $\mathrm{MJm^{-2}d^{-1}}$, and daily mean air temperature rose higher than 12 °C. Hourly air temperature sometimes exceeded 20 °C in the daytime. Wind speed was largest in the event of rainstorm and maximum hourly speed in the whole period was 8.6 m/s. On fine days (*i.e.* Aug. 8, 9 and 10), wind speed was comparatively larger than preceding foggy days. Small-scale cold air drainage accompanied by fog was found on August 7, 8 and 12, flowing down inter-

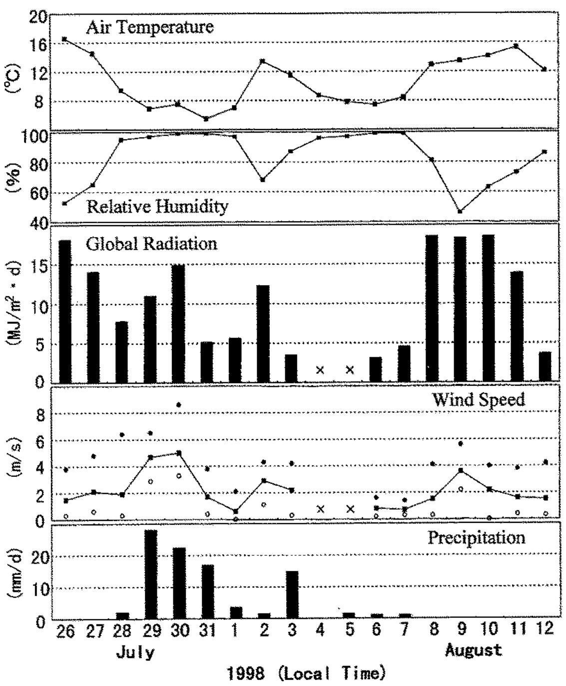

Fig. 5 Daily meteorological conditions near the terminus of Bilchenock Glacier. Solid circles, solid squares and open circles in the figure of wind speed indicate daily maximum, mean and minimum values, respectively.

mittently along a supraglacial stream on the stagnant ice.

Mean daily amount of icemelt around the meteorological station was 56 $mm d^{-1}$ (w.e.). Relationships between the sum of positive hourly air temperature, $\Sigma Th+$ (°Ch), and the cumulative amount of icemelt, Σm (mm), are shown in Fig. 6. A degree hour factor, which is expressed as a gradient of broken lines in Fig. 6, in the latter half of the period (Aug. 4–Aug. 13; including 2 missing data) was smaller than that in the former half (Jul. 30–Aug. 2). This may be attributed to differences in the weather condition, especially wind speed and in the thickness of surface debris between the two periods. Because surface form of the stagnant ice had been changing throughout the period due to melting, thickness of surface debris, mostly consisting of fine sand around the station, increased in the latter half of the period.

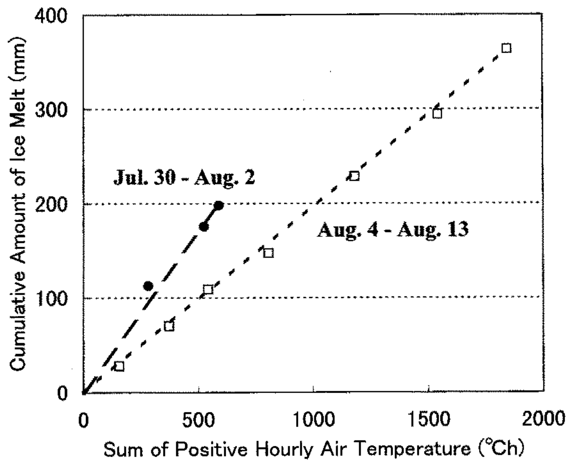

Fig. 6 Relationship between the cumulative amount of icemelt (mm w.e.) and the sum of positive hourly air temperature (°Ch).

5. Discussion

Some studies on surging glaciers at the ends of their quiescent state implied several kinds of abnormal surface profile to prepare for the next surges, for example, a bulge (Clarke and Blake, 1991), and a rapid thickening zone and a thinning zone (Raymond and Harrison, 1988).

At Bilchenock Glacier, we recognized characteristic repeated patterns of a transverse ridge followed by a gentle slope. But it seems reasonable to consider that these patterns do not indicate the abnormal surface profile for a premonition of a surge. One of the reasons for this supposition is that velocities on the ridges were as slow as those on the gentle slopes. The reports on the abnormal surface profile showed that the velocity in the thickening zone was faster than that at any other places, so that the thickening zone traveled from the upper reach to the lower reach of the glacier (*e.g.* Clarke and Blake, 1991). At Bilchenock Glacier, however, the ridges could not be propagated because of similar velocities with those at any other places. Another reason is that the widths of ridges at Bilchenock Glacier were some tens of meters at most, which were much smaller than of the thickening zones, whose widths were from some hundreds meters (Clarke and Blake, 1991) to some kilometers (Raymond and Harrison, 1988). Further, the pattern of a ridge and a following gentle slope was repeated.

One explanation for the cause of these repeated patterns may be the non-uniformity on distribution of surface debris. The debris thickness on ridges was more than 1 m, whereas the debris covering the gentle slope ice is thin or absent. Thus it is considered that the difference in debris thickness between ridges and gentle slopes caused the difference in ablation rate (*e.g.* Mattson *et al.*, 1993), and as the result ridges and gentle slopes were formed. It is a debatable point, however, that only the difference in ablation rate can really cause a 30 m high undulation which is the relative height between the ridge and the gentle slope.

The real causes of the non-uniformity of debris thickness are not clear. However, from the repetition of the patterns of a ridge and a gentle slope, it is probably that there is a relationship between the patterns and the surge cycles. At Bilchenock Glacier, it is considered that debris was supplied from the steep side-cliffs beneath the ice fall. During the surge period, the glacier should have gone so fast through the debris supplying zone that debris could not be deposited thick enough on the glacier surface. On the other hand, in the quiescent state, the glacier passed slowly through the zone with enough time to catch much debris on its surface. As mentioned in section 3, there were at least two surges. Thus, the comparison of the dates of these last two surges with the regular patterns of glacial morphology might give us clues to reveal the unrecorded surge cycles of this glacier. The flow velocity measured in this study will provide important data for the further examinations of this kind.

6. Concluding remarks

Bilchenock Glacier is reported as a surging glacier whose surge interval is estimated as about 23 years and the last surge broke out in 1982. Thus the glacier may be regarded to be in the last stage of the quiescence-phase. The velocities in 1998 were much slower than those in 1982, and the terminus had risen by about 250-350 m from 1984 to 1998.

The evaluated dynamical characteristics in the quiescent-phase at Bilchenock Glacier are that the surface shows repeated patterns of a ridge and a gentle slope, and speeds near the border between the ridge and the gentle slope were significantly larger than other places. But the causes of these spatial differences were left unknown.

Daily mean air temperature at the glacier terminus varied from 7 to 17 °C and relative humidity was often close to 100 %. Averaged daily amount of icemelt near the terminus was 56 mm d^{-1} w.e. (July 22 -August 14, 1998).

In order to make clear more detailed dynamical characteristics of quiescent-phase at Bilchenock Glacier, it is necessary to survey more precisely the distribution of flow velocity and short-term fluctuations of flow velocity. In addition to these, the surface heat balance and the distribution of debris thickness should give us effective clues.

Acknowledgments

We would like to express our sincere gratitude to Mr. Anton Y. Muravyev and Ms. Marina Vytkina of Kamchatka Institute of Ecology and Nature Management, Far East Branch of Russian Academy of Science, for their logistical supports in the field. We are also grateful to the following personnel for the supports and valuable suggestions given to us: Dr. Takayuki Shiraiwa and Dr. Toshio Sone of the Institute of Low Temperature Science, Hokkaido University, and Dr. Kotaro Yamagata of Joetsu University of Education, Division of Social Studies. We are also indebted to the cooperation between Institute of Volcanology and Institute of Ecology of Russian Academy of Sciences, and Institute of Low Temperature Science, Hokkaido University.

This research was supported in large part by the Inoue Fund of Field Science, Japanese Society of Snow and Ice (awarded to S. Yamaguchi and T. Matsumoto).

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