Bulletin of Glacier Research 16 (1998) *51–56*

Distribution and short-term variations of flow velocities at Koryto Glacier in the Kronotsky Peninsula, Kamchatka, Russia, in 1997.

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(Received April 1, 1998 ; Revised manuscript received May 7, 1998)

Abstract

Ice flow velocities were measured at the Koryto Glacier in the Kronotsky Peninsula, eastern Kamchatka, in September 1997. The maximum velocity along a flow line was obtained as 0.16 m d^{-1} around 700 m a.s.l., and the minimum was 0.06 m d^{-1} around 1000 m a.s.l.. The velocity at 700 m a.s.l., near the equilibrium line in normal years, has decreased by an amount of about 30 m a^{-1} from 1960 to 1997. Hourly variations in surface flow velocity and daily variations in basal ice movement measured at the terminal part of the glacier showed that the glacier was sliding at the base and there was a good relation between the variations in the flow velocity and the water discharge from the glacier.

1. Introduction

In Kamchatka Peninsula, there are numerous glaciers which are the nearest ones to Japan. However, characteristics of the glacier dynamics in Kamchatka have been unknown to Japanese glaciologist. Studying the characteristics of glacier dynamics in Kamchatka may give us a plenty of information about glaciers which existed in the Last Ice Age in Japan. In addition, it is very important to understand the response of those glaciers to possible environmental changes such as the global warming.

Based on these points, a joint Russo-Japanese glaciological research on Kamchatka glaciers has been done since 1996 (Kobayashi *et al.*, 1997). In summers of 1996 and 1997, observations were carried out at the Koryto Glacier in the Kronotsky Peninsula, eastern Kamchatka. In this report, results of flow surveys at the Koryto Glacier in 1997 are presented.

2. Regional settings

The Kronotsky Peninsula is located at the eastern coastal region of Kamchatka as a prominent massif intruding into the Pacific Ocean. According to Vinogradov (1968), there are 32 glaciers in this region (Fig. 1). They lie at the lowest altitude in Kamchatka, some of which flowing down to an altitude of 250 m.

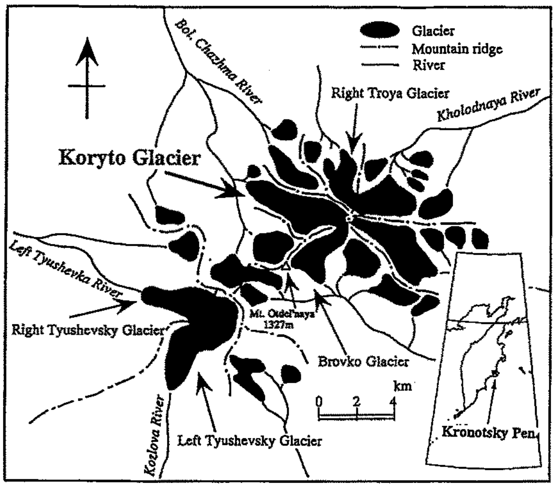

Fig. 1. Distribution of glaciers in the Kronotsky Peninsula. Data source : Vinogradov (1968).

The Koryto Glacier, which has an area of 8.9 km^2 and extends northwestward from 1200 m to 250 m a.s.l., is the third largest glacier among 32 glaciers (Vinogradov, 1968). The glacier surface is not covered with debris and lacks any icefalls or intensive crevasses (Fig. 2). The equilibrium line altitude (ELA) was reported to be 780 m in the balance year of 1981 / 82 (IAHS (ICSI) - UNEP - UNESCO, 1988).

Observations to know glaciological features of the Koryto Glacier were carried out in July 1996, and the results show that the Koryto Glacier is a temperate glacier with basal sliding and has more than 6 m (in water-equivalent) snow accumulation at the ELA (Yamaguchi *et al.*, 1997 ; Shiraiwa *et al.*, 1997).

In September 1997, observations which surveyed distribution of flow velocity along a flow line and variations of basal sliding were carried out to obtain more detailed characteristics of the dynamics for the Koryto Glacier.

3. Methods of measurements

3.1. Surveys along a flow line

Surveys of flow velocity along a flow line at the Koryto Glacier were carried out between 8th and 14th September, 1997. Thirteen snow stakes of 2 m-long metallic pipe were established along the center line of the glacier (Fig. 2). The highest altitude of the stakes was approximately 1020 m a.s.l. at S_{17}, and the lowest was 540 m a.s.l. at S_5. Horizontal and vertical angles, and distances to the stakes were measured from control points on the left bank (A, B) and the nunatak (C) in the glacier by using an electronic distance meter (Topcon EDM-theodolite Guppy GTS-2R : the minimum angle and distance readings : 10 seconds and 1 mm). In the distance survey, a mirror was attached to each stake. The error of the survey became larger with the distance between the control point and the snow stake. The largest error in distance was estimated as 0.06 m for a case of S_7 which was about 1400 m away from the control point B.

3.2. Surveys in the terminal area

Surveys of short-term variations in flow velocity were carried out at the terminal area with two methods. One was a use of stakes which were set up on the glacier (stake method), and the other was to measure basal sliding speed directly at the glacier bed (direct method).

3.2.1 Stake method

A control point D was established on a huge boulder approximately 400 m down from the glacier terminus, and two stakes α and β, each with a reflection mirror, were set up near the glacier terminus (Fig. 2). The direction from α (or β) to D was considered to coincide well with the ice-flow direction. Distances from the control point to α (or β) were measured at

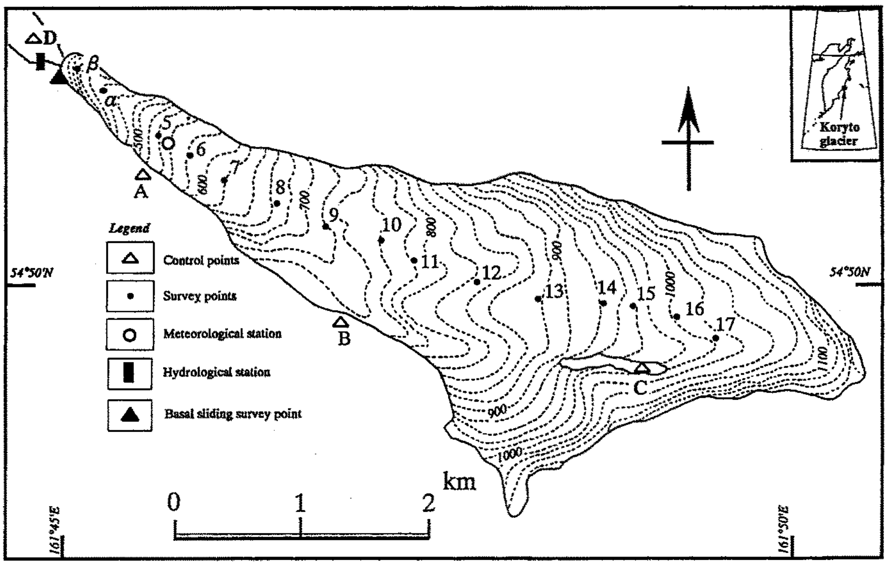

Fig. 2. Contour map of the koryto glacier. Locations of several observation points are plotted by symbols.

intervals of several hours with the EDM from 19 : 00 on 11th to 9 : 00 on 14th September, 1997.

The previous observation at this glacier in 1996 showed that the short-term flow variations in night time were not so much as that in day time (Yamaguchi *et al.*, 1997). So detailed surveys in night time were carried out for one night, from 19 : 00 on 11th to 7 : 00 on 12th September, with an interval of two or three hours. During the other nights, the interval was ten hours between 22 : 00 and 8 : 00. Whereas, in day time from 8 : 00 to 22 : 00, aiming to obtain more detailed changes in flow velocity, the survey was made every hour.

During the survey period, the theodolite was fixed firmly on the control point and leaning of the survey stakes on the ice was checked three times by using a tape measure. The errors in calculated velocity at α, which were caused by the leaning (max. 10 mm) and the atmospheric condition (1~2 mm), were estimated to be less than 12 mm for each measurement. On the other hand, the leaning of stake β was such large that the errors due to them were almost comparable to the flow velocities. Therefore, the result for α is only shown in the next chapter.

3.2.2 Direct method

Near the glacier terminus, the basal ice contacted to the base could be seen at the left lateral margin (Fig. 2). To measure basal sliding speed, a hole, which diameter was approximately 10 mm, was drilled at the side of the basal ice by using a hand drill. Distances between the hole and the fixed point on the bedrock (Fig. 3) were measured with a tape measure every day from 15 : 00 on 11th to 11 : 00 on 15th September.

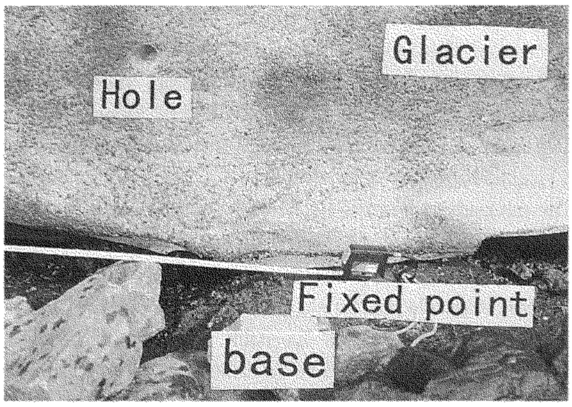

Fig. 3. Illustration of the direct method of basal sliding measurement.

4. Results and discussions

4.1. Distribution of flow velocities along the flow line

Flow velocities obtained at 11 points along the flow line are compiled in Table 1. Stakes S_6 and S_8 could not be measured, because they lay down during the survey period. Figure 4 shows the distribution of flow velocities over the glacier, which was given as daily mean values during the survey period. The maximum velocity along the flow line was 0.16 m day^{-1} at S_9 near 700 m a.s.l., and the minimum was 0.06 m day^{-1} at S_{17} and S_{16} near 1000 m a.s.l. in the accumulation area.

Table 1. Result of surveys along the flow line

Stake No.	Flow velocity (m/day)	Change of distance between S_n and S_{n-1} (m)	Longitudinal strain rate (day^{-1})
S_{17}	0.06	−0.10	-5.1×10^{-5}
S_{16}	0.06	+0.26	$+1.2\times10^{-4}$
S_{15}	0.10	+0.01	$+7.0\times10^{-6}$
S_{14}	0.10	+0.01	$+4.1\times10^{-6}$
S_{13}	0.10	+0.01	$+7.9\times10^{-6}$
S_{12}	0.12	−0.00	-2.9×10^{-7}
S_{11}	0.14	−0.09	-2.3×10^{-5}
S_{10}	0.13	−0.12	-4.5×10^{-5}
S_9	0.16	−0.19	-3.9×10^{-5}
S_7	0.12	−0.16	-8.8×10^{-6}
S_5	0.15		

Change of distance from September 8th to 14th (S_9-S_{17}) or from 9th to 14th (S_5, S_7)
+ : stetched
− : compressed
*Changes of distance at S_9 and S_7 show the changes of distance between S_9 and S_7 and between S_7 and S_5.

Changes in distance between neighboring stakes during the survey period, and calculated longitudinal strain-rates are also shown in Table 1. It was found that the ice body in the upper reach from S_{12} to S_{16} stretched longitudinally, with a maximum strain-rate of 1.2×10^{-4} day^{-1} at S_{16}-S_{15}. On the other hand, the ice body in the lower reach from S_5 to S_{12} was compressed, with a minimum strain-rate of -4.5×10^{-5} day^{-1} at S_{10}-S_9. The absolute values of longitudinal strain-rate at the Koryto Glacier were one or two orders of magnitude smaller than those at Glacier Soler, Patagonia (Naruse *et al.*, 1992).

In late September 1960, the flow velocities of the Koryto Glacier were surveyed by a Russian group. An annual flow velocity, which was simply calculated from multiplying the data obtained in September by

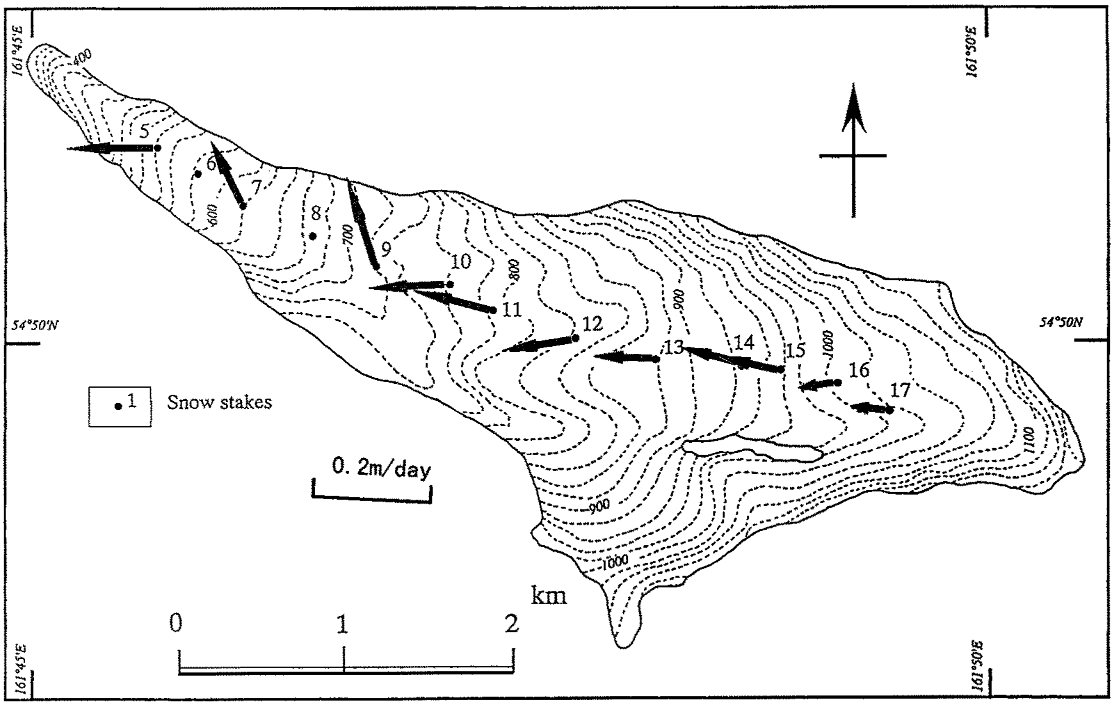

Fig. 4. Horizontal vectors of surface velocities along a flow line.

365 days, was reported as 90 m a^{-1} at about 700 m a.s.l. near S_9 (Y. Muravyev, unpublished). The observation period in 1997 was almost the same as in 1960, then an annual flow velocity of present study at S_9 was also simply estimated to be about 60 m a^{-1}. A comparison of these values indicates that the annual flow velocity near S_9 has probably decreased by an amount of about 30 m a^{-1} from 1960 to 1997. The terminus of the Koryto Glacier retreated 80 m between 1971 and 1982 (IAHS (ICSI) - UNEP - UNESCO, 1988). If this terminus recession may have been caused by thinning of the ice, it can be possible to consider that the decrease in the flow velocity was also caused by the shrinkage of the glacier.

4.2. Short-term variations in ice-flow

4.2.1 Stake method

Fluctuations in flow velocity obtained at the point α from 11th to 14th September are shown by thick lines in Fig. 5-a, together with air temperature at the ablation area (b : 545 m a.s.l.) and discharge of a stream from the glacier terminus (c). The variations in flow velocity had two clear peaks on 12th and 13th September, and they were larger around 15 : 00 and smaller at night. This tendency is similar to the result obtained in July 1996 (Yamaguchi *et al.*, 1997). The maximum velocity at 15 : 00 on September 12th was about ten times larger than the minimum velocity at night.

In general, surface flow velocity of a glacier is a sum of plastic internal deformation of ice and basal sliding. It is difficult to consider that plastic deformation rate can change within this short time. This short -term variation in flow velocity is, therefore, regarded as the influence of basal sliding variation.

Assuming that there was no basal sliding in night time and the velocity at night was caused only by deformation of ice, the basal sliding speeds were estimated as about 89 % on 12th and 67 % on September 13th of maximum flow at the surface, by dividing ($V_{max.}$ - V_{night}) by $V_{max.}$, where $V_{max.}$ and V_{night} denote the maximum and the night velocity. These ratios and the maximum velocity were larger than those in 1996 (Yamaguchi *et al.*, 1997). In general, the value of basal sliding depends on the stage of growth of water channels or cavities at the ice-rock interface (Paterson, 1994). Because the survey in 1996 was carried out in the early summer, the cavities filled with water may not grow so big. On the other hand, because the survey in 1997 was conducted at the end of summer, it can be

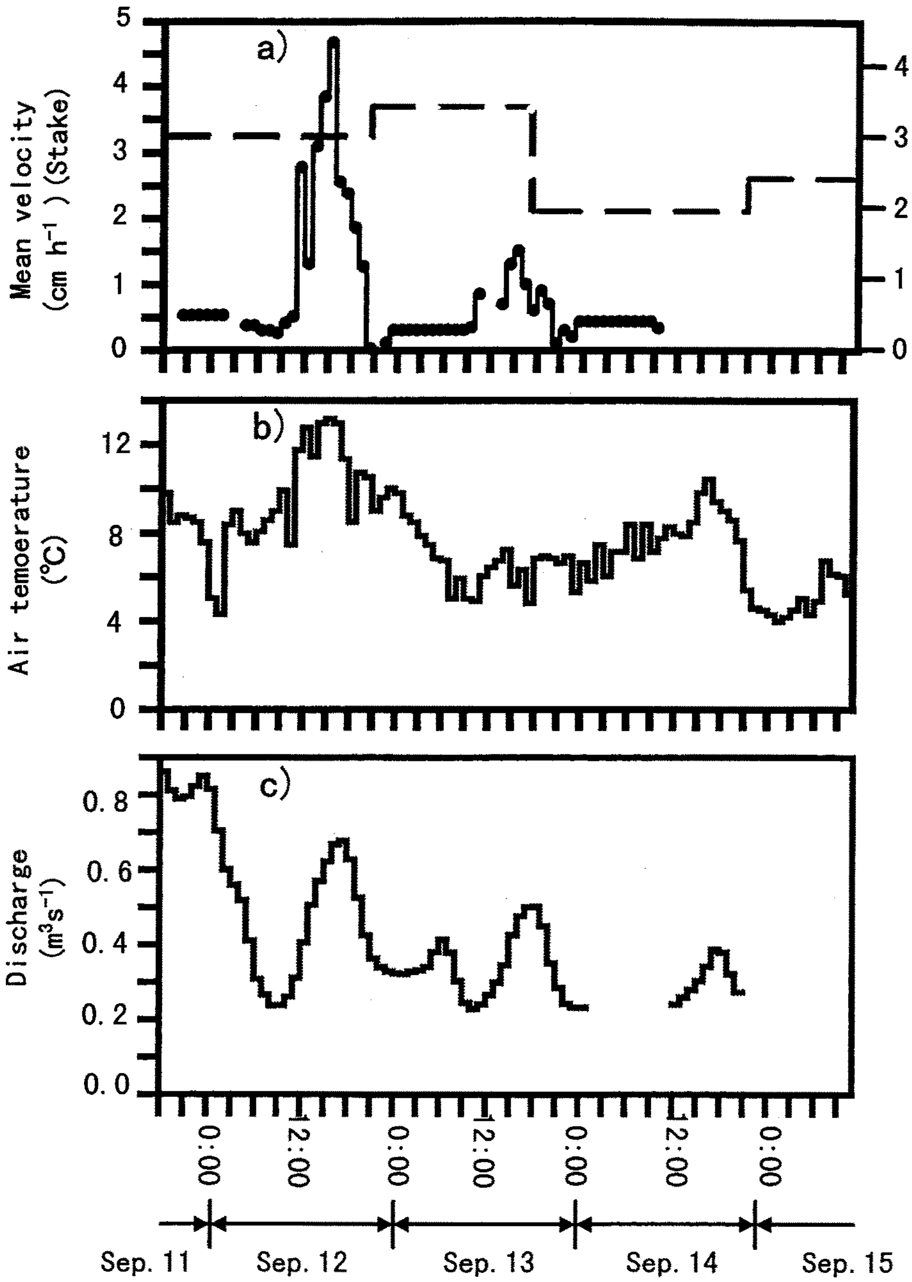

Fig. 5. a) Variation in surface flow velocity obtained at point α (stake method : thick lines) and variation in basal sliding speed (direct method : broken lines).
b) Air temperature (1 houe average) in the ablation area (545 m a.s.l.).
c) Discharge of stream (1 hour average) from the glacier terminus.

considered that the cavities have grown bigger than those in the survey period in 1996.

Though it is often pointed out that basal sliding is closely connected with water discharge from the glacier terminus (*e.g.* Iken *et al.*, 1983), the result of the survey in 1996 does not show such a relation (Yamaguchi *et al.*, 1997). However, in this observation, a good correlation between variations in flow velocity and discharge was found (Fig. 5). Peaks of flow velocity were found around 15 : 00 and peaks of discharge, except the first peak in the night of 11th, were found around 18 : 00 after three hours from the peak of flow velocity. This time lag may be explained by the situation that the hydrological station was located at a few hundreds meter down stream of the point of flow measurement. The peak of flow velocity was larger, when the peak of the discharge was larger.

A reason why the good correlation between the flow velocity and the discharge could not be found in 1996 may be that, because the survey period in July 1996 was early summer, there was much seasonal snow around the glacier and melt water of the snow flowed directly into the stream along the cliff. On the other hand, the changes in discharge in September 1997 were mostly caused by the changes in the subglacial water, since there was little seasonal snow around the glacier.

4.4.2 Direct method

Fluctuations in basal sliding speed from 11th to 14th September measured by the direct method are also shown by broken lines in Fig. 5-a. The value of basal sliding speed is shown as a mean value between measurements. The maximum mean velocity was 3.7 mm h^{-1} from 21 : 00 on 12th to 16 : 00 on 13th September, and the minimum was 2.1 mm h^{-1} from 16 : 00 on 13th to 10 : 00 on 15th September. These values were one order of magnitude smaller than those by the stake method. A reasonable cause of this difference should be a difference in topographical conditions of the survey points, namely one was close to the lateral margin and the other was on the center line of the glacier. Although there is no information about conditions of the base and subglacial water pressure, a major cause may be a difference in ice thickness between the survey points.

5. Concluding remarks

Flow velocities at the Koryto Glacier in the Kronotsky Peninsula, Kamchatka, were measured from 8th to 14th September, 1997. The survey along the flow line showed that the largest velocity was 0.16 m d^{-1} at S_9 (700 m a.s.l.) and the smallest was 0.06 m d^{-1} at S_{17} and S_{16} (around 1000 m a.s.l). Changes in distance between neighboring stakes revealed that the ice body in the upper area of the glacier stretched and that in the lower area was compressed longitudinally. The annual mean velocity at about 700 m a.s.l. has decreased by an amount of about 30 m a^{-1} from 1960 to 1997.

Two short-interval measurements of ice-flow velocity at the terminal area suggested that the Koryto Glacier was sliding at the base and the ratios of the basal sliding were considerably large. Flow velocities became the highest in the afternoon and the smallest at night. There was a good relation between the variations in flow velocity and water discharge from the glacier, and the peaks of discharge were found at three hours after the peaks of flow velocity.

Acknowledgments

We would like to express our sincere gratitude to Dr. Alexander A. Ovsyannikov and Mr. Igor Markov for their logistical support in the field. We are also indebted to the staff of the Workshop in Institute of Low Temperature Science for their effort in making or modifying equipments used in the field. This study was supported by a grant-in-aid for International Scientific Research (No. 08041090 : Principal Investigator, Dr. D. Kobayashi) of the Ministry of Education, Science, Sports and Culture of Japan.

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