

Meteorological and glaciological observations at Suntar-Khayata Glacier No. 31, east Siberia, from 2012–2014

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Abstract

This paper outlines meteorological and glaciological observations of Glacier No. 31 in the Suntar-Khayata Range, east Siberia, obtained from 2012 to 2014. We set up meteorological instruments and seven stakes on the glacier for the purpose of measuring surface mass balance and flow velocity. The mean air temperature between July 8, 2012 and August 7, 2013 was -13.9°C at site 31–2 (2446 m a.s.l.) and the minimum temperature was -46.0°C . The air temperature on the glacier from November to April was approximately 10°C higher than that at Oymyakon village, suggesting a temperature inversion phenomenon, which typically occurs during winter in this region. The snow depth records show that snow increased at the beginning and end of winter, and that there was almost no change from the beginning of October until the end of April. The maximum snow depth from the previous summer was 158 cm at site 31–2 on May 28, 2013. The average annual surface mass balance for the 6 sites was -1256 mm water equivalent (w.e.) during the period from August 24, 2012 to August 16, 2013, indicating that ablation proceeded rapidly in all areas of the glacier. Surface flow velocity in 2013/2014 was 1.57 m a^{-1} at the approximate midpoint of the glacier, and was much slower than that measured during the IGY (International Geophysical Year) period (4.5 m a^{-1}) in 1957/1958. The length and areal extent of the glacier were 3.85 km and 3.2 km^2 in 1958/1959 and 3.38 km and 2.27 km^2 in 2012/2013, respectively, showing a decrease over the last 54 years.

Key words: GRENE Arctic, Suntar-Khayata Glacier No. 31, surface mass balance, surface flow velocity, DEM

1. Introduction

Mountain glaciers and small ice caps are overwhelmingly small in volume compared to the Antarctic and Greenland ice sheets. Therefore, they show a fast response to climate change compared to ice sheets, and are known as sensitive indicators of climate change. The glacial and mountainous environments of the Arctic are changing drastically due to recent intense warming in this region; yet the Siberian glaciated region is one of the least studied areas in the whole Arctic (Yamada *et al.*, 2002). The Suntar-Khayata region, located between 62° to 63°N and 140° to 142°E , forms a watershed between the Arctic Ocean and the Sea of Okhotsk. Oymyakon (677 m a.s.l.), which recorded the lowest

temperature in the northern hemisphere of -72°C in January 1926, is located in the northeast of the region. Three glacial areas are recognized in the Suntar-Khayata, namely the northern massif, central massif, and southern massif.

In the IGY (International Geophysical Year, 1957–58) period, Russia (then the Soviet Union) set up a weather station in the Suntar-Khayata mountains, where observations continued for several winters. Moreover, they made detailed investigations of the distribution of mountain glaciers (Koreisha, 1963). However, except for partial observations carried out in 1970 (Vinogradov *et al.*, 1972), no further studies were performed in this region for many years. Yamada *et al.* (2002) resumed observation of the Suntar-Khayata glaciers in 2001 and determined the location of Glacier No. 31, in the first

short-term study of mass balance and meteorological data. Furthermore, Takahashi *et al.* (2011) carried out meteorological, snow, and ice observations in the vicinity of the Suntar-Khayata mountains and Oymyakon in 2004 and 2005, and analyzed the response of the glaciers to regional climate change. Furthermore, Ananicheva *et al.* (2005) examined the distribution, areal extent, and length of the Suntar-Khayata glaciers from satellite observations, and described the recent trend of glacier retreat from the terminal moraine.

After the IGY, only short-term studies have been carried out during the summer in this region, and there have been no long-term investigations of the glaciers that span multiple years. In particular, there has been no information obtained on mass balance, glacier flow, glacier surface topography, or basement topography in recent years. These observations are important in order to model long-term glacier flow and variability.

This study was conducted under the framework of the 2011–2016 GRENE Arctic Climate Change Research Project. In this paper, we present data on the meteorology, surface mass balance, surface flow velocity, and glacier mapping of Glacier No. 31. Glacier No. 31 was chosen as the study area because it has been described in detail with observational data from IGY (1957–58), reported by Koreisha (1963).

Some of the findings from the GRENE Arctic research project have previously been published. Galanin *et al.* (2014) reported the age and extent of the last glacial maximum in the Suntar-Khayata Range based on lichenometry and the Schmidt Hammer Test. Nakazawa *et al.* (2015) showed radiocarbon ages of insects and plants frozen in Glacier No. 31. Takeuchi *et al.* (2015) discussed the dynamics of three processes that may affect glacier ablation, and Tanaka *et al.* (2016) described the snow and ice algal communities on four separate glaciers.

In this study, we present observation methods and data on the meteorology, surface mass balance, surface flow velocity, and glacier mapping of Glacier No. 31. The aims of this study are as follows:

- To clarify the change in glacier morphology since the mid-20th century (Koreisha, 1963);
- To analyze the relationship between climate and glacier mass balance in the study period (2012–2014);
- To develop an observation network for future monitoring of the glacier and mountain environment.

2. Observation periods

In-situ observations were made 4 times between 2011 and 2014 as part of a Russia-Japan collaboration. During each visit, automatic instruments were set up to obtain year-round meteorological and glaciological measurements. After 2015, the Melnikov Permafrost Institute of the Russian Academy of Sciences (MPI) continued to visit the area as part of their own research program.

The timings of the four visits from 2011 to 2014 and the research team members involved are listed below, with dates of arrival and departure in the study area indicated. Transportation to the study area for each visit is also cited.

- 1) 2011
 Period: from 30 September to 1 October
 Russian Members: Alexander Fedorov, Pavel Konstantinov (MPI)
 Japanese Members: Tsutomu Kadota, Keiko Konya (JAMSTEC)
 Access: (To) helicopter, (From) helicopter
- 2) 2012
 Period: from 2 July to 5 September
 Russian Members: Fedorov Alexander, Konstantinov Pavel, Galanin Alexey, Fedorov Kolya, Dmitry Suzudalov, Peter Efremov, Radik Arugnov (MPI), Fedorov Pavel (IBPC: Institute for Biological Problems of Cryolithozone, Yakutsk), Vasily Shishkov (IGRAS: Institute of Geography Russian Academy of Sciences, Moscow)
 Japanese Members: Tsutomu Kadota (JAMSTEC), Tatsuo Shirakawa, Ryo Kusaka (KIT: Kitami Institute of Technology), Sota Tanaka, Masaya Miyairi (CU: Chiba University)
 Access: (To) helicopter, (From) helicopter (some members returned by land route)
- 3) 2013
 Period: from 29 July to 24 August
 Russian Members: Konstantinov Pavel, Sasha Vasiliev, Lytkin Vasily, Torgovkin Nikolay (MPI), Bulat Mavlyudov (IGRAS)
 Japanese Members: Tsutomu Kadota (JAMSTEC), Fumio Nakazawa (NIPR), Tatsuo Shirakawa, Ryo Kusaka (KIT), Masaya Miyairi, Yuta Fujisawa (CU)
 Access: (To) helicopter, (From) helicopter
- 4) 2014
 Period: from 20 July to 14 August
 Russian Members: Pavel Konstantinov, Vasylii Lutkin (MPI)
 Japanese Members: Tsutomu Kadota (JAMSTEC), Yuta Fujisawa (CU)
 Access: (To) land route, (From) land route

The Japanese leader of the field campaign was Dr. Tsutomu Kadota of JAMSTEC, and the Russian leader was Dr. Alexander Fedorov of MPI.

3. Description of Glacier No. 31

Glacier No. 31 is located in the central massif of Suntar-Khayata Mountains, which divides the Indigirka river drainage towards the Arctic Ocean and the south-oriented drainage towards the Sea of Okhotsk. The terminus of Glacier No. 31 is located at 62°36'15.8"N, 140°51'23.4"E and 2075 m a.s.l., approximately 510 km west from Yakutsk (the capital city of the Sakha Republic).

Figure 1 shows Glacier No. 31 and adjacent Glaciers

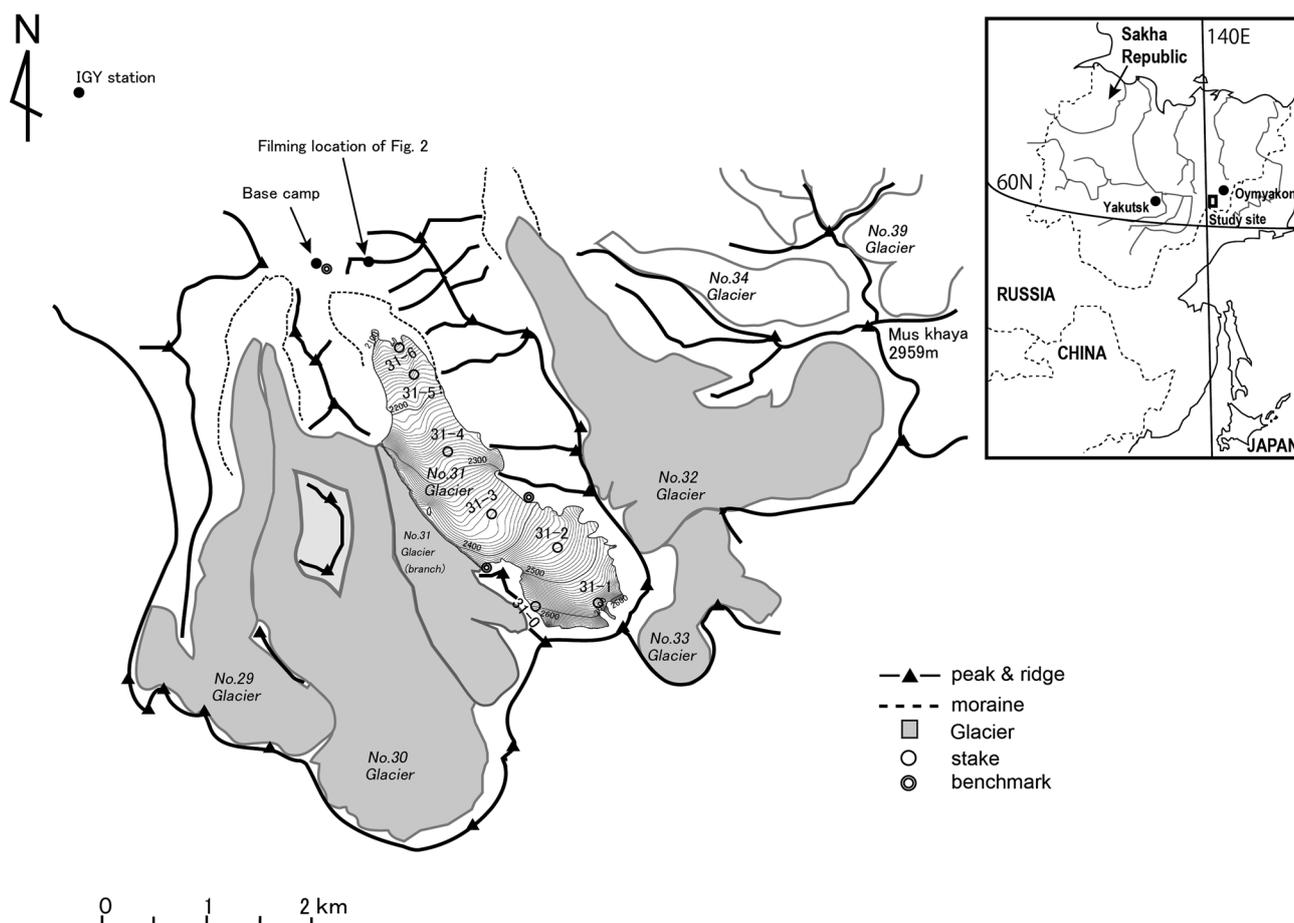


Fig. 1. Map showing the locations of observation sites of the GRENE Project in the Suntar-Khayata Range. On Glacier No. 31, the contour interval is 5 m. Open circles indicate glaciological observation sites in 2012, 2013, and 2014.

No. 29 and No. 30, which are located within the same glacial basin and therefore have a complex relationship. Furthermore, Glacier No. 31 has tributary glaciers, which are joined down the center. The neighboring Glacier No. 32 is located at the foot of Mus Khaya mountain (2959 m a.s.l.), which is the highest peak in the Suntar-Khayata region.

The weather station used during the IGY period was located at $62^{\circ}37'28''\text{N}$, $140^{\circ}48'21''\text{E}$ and 2020 m a.s.l. This is approximately 3 km downstream from the terminus of Glacier No. 31 (August 2013), which is the most thoroughly studied glacier. Photographs of the glacier taken during IGY observations, belonging to the Melnikov Permafrost Institute (Russian Academy of Science) in Yakutsk, were used to compare to present glacier conditions. A panoramic view of Glacier No. 31, which was taken in August 2013, is shown in Fig. 2.

4. Observations

Table 1 shows the study sites and observational equipment installed on the glacier. At site 31-2, air temperature, humidity, air pressure, precipitation, wind direction, wind speed, and downward shortwave radiation were automatically measured every hour with a HOBO automatic weather station (AWS), shown in Table 2. At



Fig. 2. A photograph of Glacier No. 31, taken on 11 August, 2013. View is from north to south.

all study sites except 31-0, air temperature was measured every hour with a thermometer (TR-52i, T&D, Table 3). Ice temperatures at depths of 1 m, 2 m, 5 m, and 10 m from the glacier surface were measured every 2 hours with thermometers (HOBO data logger, Table 4). In order to monitor the change in height of the snow surface, photographs of the surface were taken automatically every hour with an interval camera (Garden

Table 1. Position, altitude, and installed equipment at observation sites.

Site name	Position	Altitude (a.s.l.)	Installed equipment
31-0	62°34'57"N, 140°52'59"E	2584	Stake
31-1	62°34'57"N, 140°53'31"E	2541	Stake, thermometer
31-2	62°35'14"N, 140°53'10"E	2446	Stake, AWS, interval camera, thermometer, thermometer for ice temperature
31-3	62°35'27"N, 140°52'30"E	2354	Stake, thermometer, interval camera
31-4	62°35'46"N, 140°52'06"E	2258	Stake, thermometer
31-5	62°36'10"N, 140°51'45"E	2158	Stake, thermometer
31-6	62°36'17"N, 140°51'40"E	2120	Stake, thermometer
Base camp	62°36'45"N, 140°50'42"E	2003	Thermometer

Table 2. Specification of AWS at site 31-2 on Glacier No.31.

Parameter	Range	Accuracy	Resolution	Installation height from the glacier surface
Air temperature	-40°C to 75°C	±0.2°C (0°C to 50°C)	0.02°C (25°C)	1.7 m
Humidity	0% to 100%RH	±2.5%RH (10% to 90%RH)	0.1% (25%)	1.7 m
Air pressure	660 hPa to 1070 hPa	±3 hPa	0.1 hPa	1.7 m
Precipitation	127 mm/h	±1%(20 mm/h)	0.2 mm	2.0 m
Wind direction	0° to 355°	±5°	1.4°	2.5 m
Wind speed	0 m/s to 76 m/s	±1.1 m/s	0.5 m/s	2.5 m
Downward shortwave radiation	0 W/m ² to 1280 W/m ²	±10 W/m ²	1.25 W/m ²	1.2 m

Table 3. Specification of thermometers used for air temperature at site 31-1, 31-2, 31-3, 31-4 and 31-5 on Glacier No.31.

Item	Specification
Range	-60°C to 155°C
Accuracy	±0.3°C
Resolution	0.1°C
Installation height	1.5 m

Table 4. Specification of thermometers used for ice temperature measurement at site 31-2 on Glacier No.31.

Item	Specification
Range	-40°C to 100°C
Accuracy	±0.2°C (0°C to 50°C)
Resolution	0.03°C
Installation depth from the glacier surface	1 m, 2 m, 5 m, 10 m

Watch Cam, Brinno) at sites 31-2, 31-3, and 31-4.

In order to determine the surface mass balance, stakes (length: 3.0 or 3.5 m) were installed at each study site. Then, the length from the glacier surface to the top of the stake was measured (accuracy: 1 cm). The change in surface level was converted into a water equivalent using the densities of snow and ice, assumed to be 400 kg m^{-3} and 900 kg m^{-3} respectively.

A kinematic GPS survey was used to measure the installation position of the stake relative to the observation site. The GPS equipment used was Leica Viva Uno. The GPS survey was conducted using a differential GPS (DGPS), comprising two receivers (base station and rover). The data obtained were post-processed using Leica Geo Office software. The nominal precision is 5 to 10 mm for horizontal position and 10 to 20 mm for vertical position (Table 2). Coordinates of a total of 613 points on the glacier surface were collected using a GPS receiver in order to create a glacier digital elevation model (DEMs) covering the entire area of the glacier. Based on the GPS data, we created DEMs using geographical information system software (ArcGIS), using the spline function to interpolate the GPS data. The mesh size of the DEMs was 1 m and the accuracy of the elevation data was dependent on the GPS survey data (Table 2).

Radio-echo soundings were conducted in order to measure the ice thickness covering the total area of the glacier. The instrument was composed of a transmitter (built at Ohio State University) and a receiver (Tektronix Digital Storage Oscilloscope). The transmitter was powered by a battery, and produced a short pulse signal of a few hundred volts in amplitude. The oscilloscope recorded the transmitted and reflected signals. For ice thickness calculations, the velocity of electromagnetic waves in ice was used.

5. Results and discussion

5.1 Meteorology

The thermometers installed at each site on the glacier, except for site 31-2, were unable to recover data for the full year. In addition, the data logger of the AWS installed at site 31-2 failed on August 8, 2013, and then was not able to recover the data. Therefore, in this paper we describe the meteorological data obtained at site 31-2 from July 8, 2012 to August 7, 2013. Figure 3 shows the meteorological data from site 31-2 (2446 m a.s.l.), obtained between 16:00 July 8, 2012 and 12:00 August 7, 2013. Furthermore, Fig. 3 includes the ice temperature data measured by thermometer, and the snow height converted from images captured by the interval camera.

The mean annual air temperature from July 9, 2012 to July 9, 2013 was -13.9°C and the accumulated freezing index was 5361°C-days (the freezing index is given by the sum of degree-days for a freezing season with a daily mean temperature below zero). Daily average

temperatures from August 20, 2012 to May 21, 2013 were continuously below the freezing point; the lowest temperature was -46.0°C at 18:00 December 23, 2012 and the maximum temperature was $+11.7^\circ\text{C}$ at 16:00 July 19, 2013. Accumulated precipitation from July 9, 2012 for one year was 342 mm . Snowfall was highest in September and May. The height of the snow cover showed almost no change from the beginning of October to the end of April. Snow height then reached 158 cm on May 28, 2013 before decreasing. The IGY period (Koreisha, 1963) and 2004/2005 (Takahashi *et al.*, 2011) both showed similar patterns. Based on the description of Takahashi *et al.* (2011), this is a common pattern in inland areas with a strong Siberian High (SH). The high stability in mid-winter prevents atmospheric disturbances, and water vapor required for snowfall is limited to the beginning and end of winter. The average wind speed over the year from July 9, 2012 was 2.1 ms^{-1} , and the maximum wind speed was 26.4 ms^{-1} on August 19, 2012.

Here, the data from site 31-2 are compared with meteorological data (NOAA GSOD published data) from Oymyakon (677 m a.s.l.), which is located 135 km northeast of the glacier terminus. At Oymyakon, the annual average temperature (starting from July 9, 2012) was -14.2°C and the accumulated freezing index was 6634°C-days . The average daily temperature from October 2, 2012 to April 26, 2013 was continually below freezing. The lowest temperature was -58.6°C on December 24, 2012 and the highest was 32.0°C on July 14, 2012. At Oymyakon, the temperature variation was larger than at site 31-2. Accumulated precipitation over a year from July 9, 2012 was 169 mm , which is about half that of site 31-2. At Oymyakon, the snow cover period lasted 213 days from October 6, 2012 to May 7, 2013. The snow depth did not change significantly from mid-November and the highest value was 38.1 cm, which was recorded between March 11 and March 21, 2013. The average wind speed over the year, from July 9, 2012, was 1.3 ms^{-1} , and the maximum was 9.0 ms^{-1} on October 1, 2012, which was low compared to site 31-2. These results suggest a temperature inversion phenomenon, which is typical during winter in this region.

5.2 Surface Mass balance

Figure 4 shows the surface mass balance measured at each site on Glacier No. 31 during the period from August 24, 2012 to August 16, 2013, approximately one full year. Results show that all sites have negative values and there are no accumulation areas on the glacier, only areas of ablation. The values of mass balance for each site in Glacier No. 31 are as follows; 31-0: -495 mm water equivalent (w.e.), 31-1: -774 mm w.e., 31-2: -1170 mm w.e., 31-3: -1197 mm w.e., 31-4: -1566 mm w.e., 31-5: -1755 mm w.e., 31-6: -1836 mm w.e. The average value of the 6 sites is -1256 mm w.e.

In the IGY period, there was an area of ice accumulation and an equilibrium-line altitude (ELA) in the

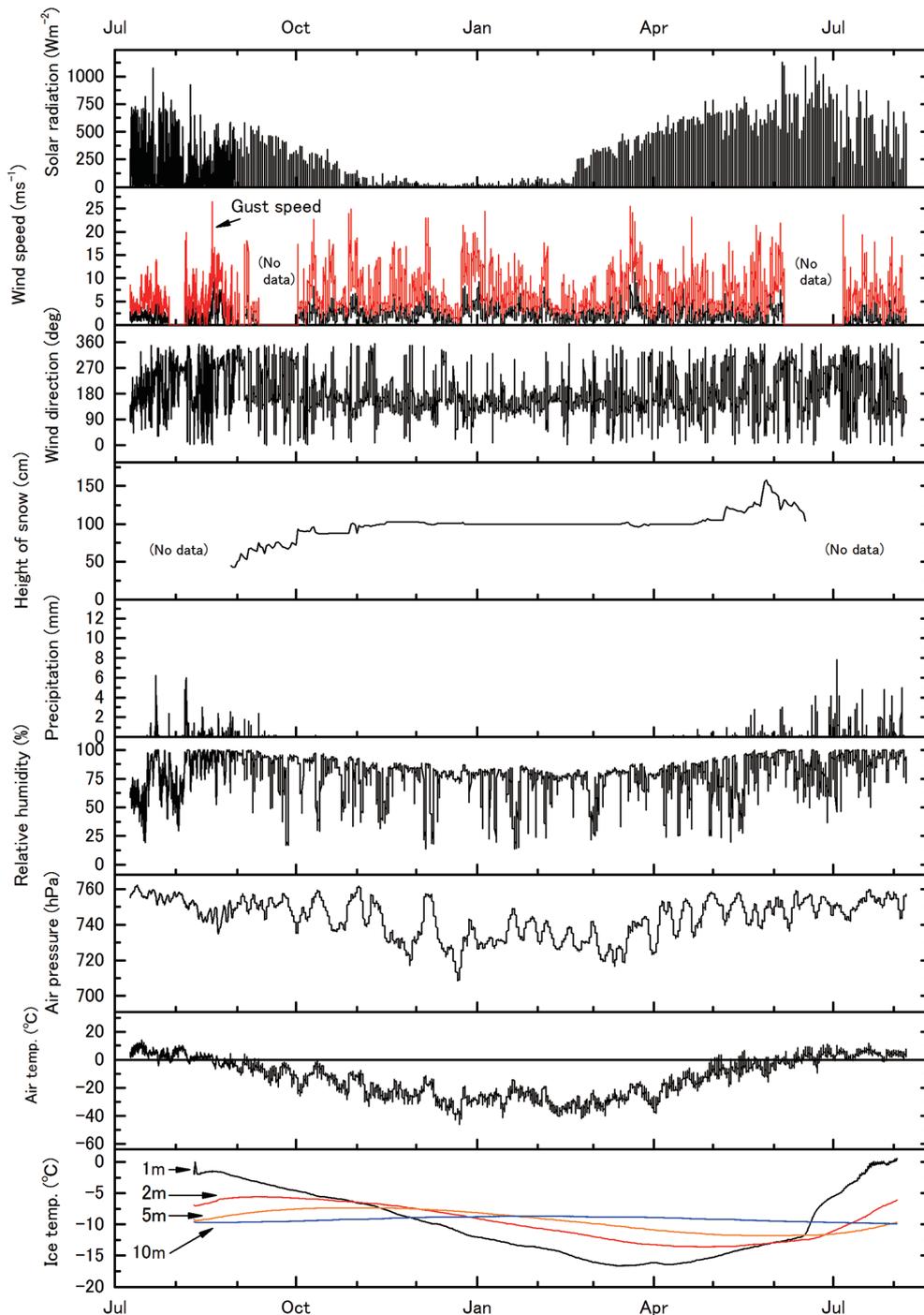


Fig. 3. Meteorological data at site 31-2 (2446 m a.s.l.) from 16:00 on July 8, 2012 to 12:00 on August 7, 2013.

vicinity of 2350 m a.s.l. (Koreisha, 1963). However, in this study, all areas of the glacier were ablation areas. As shown in Fig. 4, there is a high correlation between the elevation and the mass balance of each site ($r=0.98$). From the obtained regression equation, the ELA of this glacier is estimated to 2799 m, significantly higher than in the IGY period (2350 m). This result indicates that ablation is proceeding in all areas of the glacier.

5.3 Surface flow velocity

Figure 5 shows the surface flow velocity of the glacier, measured at all sites from August 16, 2013 until

July 29, 2014, approximately one full year. Some benchmarks were located on the rock surrounding the glacier (Fig. 1). For five sites, 31-1, 31-2, 31-3, 31-4, and 31-5, it was possible to acquire an accurate position (fix solution), yet for site 31-6, only a float solution was obtained and the unreliable data were excluded from Fig. 5.

Surface flow velocity at each site on Glacier No. 31 were as follows; 31-1: 1.35 ma^{-1} , 31-2: 2.32 ma^{-1} , 31-3: 1.70 ma^{-1} , 31-4: 1.85 ma^{-1} , 31-5: 0.63 ma^{-1} . The average surface flow velocity was 1.57 ma^{-1} , much slower than that measured in the IGY period (4.5 ma^{-1}) of

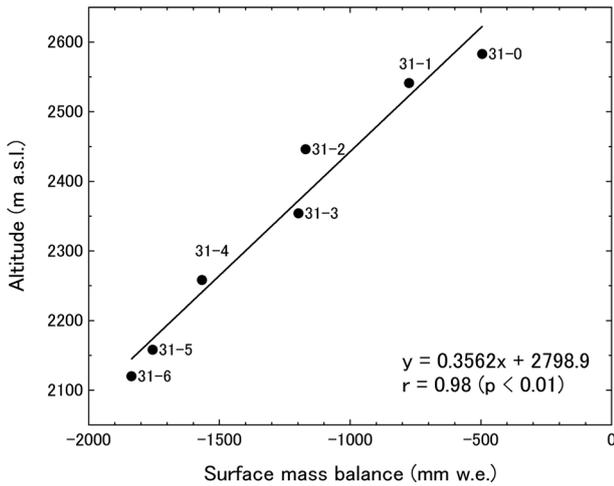


Fig. 4. Change with altitude of the surface mass balance of Glacier No. 31 from August 24, 2012 to August 16, 2013.

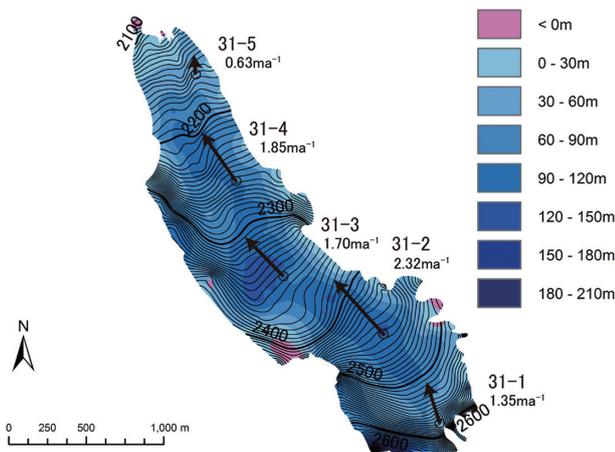


Fig. 5. Contour map of Glacier No. 31 derived from DEM data from August 2013. The arrow indicates the surface flow velocity of Glacier No. 31 from August 24, 2012 to August 16, 2013. The spatial distribution of ice thickness of Glacier No. 31 is also shown, measured by ice radar in August, 2013.

1957/1958 (Koreisha, 1963). Surface flow velocity was compared at different depths in the glacier and found to be greater in the middle than in the upper and lower areas.

5.4 Glacier mapping

In this study, a contour map of Glacier No. 31 was produced using digital elevation models (Fig. 5). In the summer of 2013, Glacier 31 was 3.38 km long (longitudinal central stream) with an aerial extent of 2.27 km². The length and areal extent of the glacier were 3.85 km and 3.2 km² in the IGY period, showing a decrease over the last 54 years.

Figure 5 shows the ice thickness distribution measured by ice radar. In the summer of 2013, the ice thickness of Glacier 31 was 68.5 m on average, with a standard deviation of 32.1 m. The maximum thickness

was 201 m (most upstream part). Ice thicknesses of each site were as follows; 31-1: 61 m, 31-2: 109 m, 31-3: 67 m, 31-4: 80 m, 31-5: 39 m, 31-6: 32 m. The middle part in particular showed the greatest thickness of ice, with more than 120 m of ice distributed on the left side of site 31-3 site. In Koreisha (1963), the ice thickness at 2300 m a.s.l. was recorded as 95 m (IGY), which is similar to our results. However, the ice thickness at 2260 m a.s.l. was 140–148 m (IGY), therefore ice thickness in this area has decreased. It should be noted that, since the method of measurement between this study and the IGY period is different, a simple comparison is difficult.

6. Concluding remarks

Intensive and comprehensive in-situ observations of glaciers at Suntar Khayata Mountain Range were taken during the three summers of 2012 to 2014, for the first time since the IGY (1957–59), to clarify the present conditions and changes. The conclusions of this study are as follows:

- The mean air temperature in the 2012/2013 season was -13.9°C at site 31-2 (2446 m a.s.l.) on the glacier and the minimum temperature was -46.0°C . A comparison to Oymyakon village, located near Glacier No. 31, showed a temperature inversion phenomenon, which is typical during winter in this region.
- The height of the snow surface increased at the beginning and end of winter, and almost no change was observed from the beginning of October until the end of April. The maximum snow depth from the previous summer was 158 cm at site 31-2 on May 28, 2013.
- The average annual surface mass balance for the 6 sites was -1256 mm w.e. during the period from August 24, 2012 to August 16, 2013.
- Surface flow velocity in 2013/2014 was 1.57 ma⁻¹ at the approximate midpoint of the glacier, and was slower than that measured during the IGY period (4.5 ma⁻¹) in 1957/1958.
- The length and areal extent of the glacier were 3.85 km and 3.2 km² in 1958/1959 and 3.38 km and 2.27 km² in 2012/2013, respectively, showing a decrease over the last 54 years. The ice thickness of Glacier 31 was 68.5 m on average, with a standard deviation of 32.1 m. The maximum thickness was 201 m in the most upstream part of the glacier.

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