Thermal regime of sporadic permafrost in a block slope on Mt. Nishi-Nupukaushinupuri, Hokkaido Island, Northern Japan

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Abstract

In this study, we discuss the predominant factors that determine the ground temperature regime of an active layer in a block slope. The distribution of the bottom temperature of snow measurements, warm funnels at the top of the slope, and ground temperature changes on the block slope indicate continuous air circulation during the winter. In the spring, snowmelt water flows to the valley bottom, and refreezes adding superimposed ice onto the perennial ice that fills the voids between coarse blocks. At the study site, the ground temperatures showed a simultaneous, abrupt increase at all depths in the active layer. These results strongly suggest that air circulation in winter, as well as the ice formation processes in the spring control the thermal regime of the active layer of the block slope with mean annual air temperature (MAAT) above 0°C.

Key words: permafrost, block slope, air circulation, superimposed ice, Hokkaido

1. Introduction

Block slopes composed of large blocky materials have the unique thermal characteristics for the preservation of permafrost on mountain slopes. Mean annual ground temperature is colder than in fine materials (Harris and Pedersen, 1998), and these thermal characteristics may affect the distribution of permafrost. In the European Alps, permafrost is sporadically found far below the regional limit of mountain permafrost (e.g. Schaeftlein, 1962; Von Wakkonig, 1996; Kneisel, 2000). Air circulation between the atmosphere and block slope, as well as ground ice formation have been proposed as the predominant factors controlling local permafrost occurrence in warmer climates (e.g. Von Wakkonig, 1996).

On Hokkaido Island, Northern Japan, mountain permafrost was first reported on a wind-blown plateau at 2175 m ASL in the Daisetsu Mountains (Fukuda and Kinoshita, 1974). Sone (1992) predicted permafrost distribution on the Daisetsu Mountains on the basis of mean annual air temperature (MAAT), freezing-thawing indices and periglacial landscapes. He estimated a regional limit of discontinuous permafrost at 1600 m ASL in Daisetsu Mountains, if snow cover is less than 50 cm in winter. In recent years, Ishikawa and Hirakawa (2000) confirmed this estimation using geophysical methods. They applied the bottom temperature of snow cover (BTS) measurements and DC

resistivity soundings to predict mountain permafrost distribution in the Daisetsu Mountains. They concluded that the lower limit of discontinuous permafrost is at approximately 1650 m ASL with MAAT at -2.0°C.

Unexpectedly low ground temperatures and ground ice during the summer also occur in taluses at lower altitudes (200 - 1000 m ASL) throughout the Daisetsu Mountains (e.g. Shiboi, 1974). Existence of permafrost is confirmed at some of these talus slopes. In these slopes, cold air blows out from voids between blocks. This micro-climatic phenomenon is called a “wind hole” in Japan (Sasaki, 1986). Air circulation created by the difference in air temperature between the open space of the block slope and the atmosphere is thought to be the predominant factor maintaining the wind hole system. A numerical simulation was conducted to explain the mechanism of this air circulation in block slopes (Tanaka et al., 2000).

However, the mechanism for preserving such localized permafrost is still unclear, since the previous studies were based primarily on indirect evidence. This evidence, such as cold airflow from blocks, and the presence of ground ice in late summer, suggested the presence of permafrost in the block slope.

This study discusses the predominant factors affecting the ground temperature regime of the active layer in a block slope. To reveal the distribution of air flow channels in a

blocky layer beneath the snow cover, BTS was measured at a number of sites in and around a block slope, where MAAT was above 0°C. Ground temperatures were also continuously monitored at two sites. The first site was located at the top of the block slope, where warmer air was blowing out from funnels in winter. The other site was at the valley bottom, where permafrost was found by pit survey. In addition, the level of ground ice was monitored at the valley bottom during the winter and the snowmelt period to reveal the effect that latent heat release due to ground ice formation has on the thermal regime of the active layer.

2. Site description

The study area is located on the summit slope of Mt. Nishi-Nupukaushinupuri (1254 m ASL), one of the lava domes of the Shikaribetsu volcano group that erupted during the last glacial period (Fig.1). The Mountain slope is widely covered with coarse blocks, 0.3-3 m in diameter, formed by collapses of the lava dome. Mean annual air temperature in the study area was 1.7°C in 1999 and 1.3°C in 2000. The annual range of air temperature exceeds 50ºC (Table 1), which are thermal conditions proper to continental climate. However, the Asian monsoon effect results in high annual precipitation of

1175.8 mm. This average is based on 12 years of data (1979 - 1990) obtained from the nearest meteorological station (Nukabira, 10 km NW).

The study area is divided into a block slope where coarse blocks form the ground surface, and a non-block slope (Figure 2). The northeast-facing non-block slope is dominated by broad-leaved trees (*Betula ermanii*) and spruce (*Picea jezoensis*), with a ground cover of bamboo grass bush (*Sasa senanensis*). The southwest-facing block slope spreads to the valley bottom. A large segment of the block slope is covered by spruce (*Picea glehnii)* dominated forest. The lower and the upper parts of the block slope, however, lack forest (shadowed area in Figure 2). Lichen, dwarf pine (*pinus pumila*), and alpine shrubs cover the exposed block surface on the slope. The valley bottom is dominated by spruce and dwarf pine and the forest floor is mostly covered by *Sphagnum* sp., and alpine shrubs. During the summer and fall, cold air blows from the wind holes along the valley bottom.

Sato (1995) described these funnels in the Shikaribetsu volcano group as the "cool spots" which maintain the alpine vegetation and moss ground cover through cool and humid air flow in summer and fall. The wind holes of the study area had an ice mass and icicles were visible in the voids between block deposits during the summer and fall.

Ground water ran beside the ice masses. The ground water levels decreased

throughout summer and fall. The water temperature remained at 0°C during this period because of melting ground ice. In October 1999, we found clear ice filling the open space between blocks using a pit survey. The depth of the ice table was -1.5 m along the valley bottom (specifically, at the ground temperature monitoring site indicated in Figure 2). This finding strongly suggests permafrost existence below the ground ice surface at the valley bottom.

3. Field measurements

3-1. BTS measurements

BTS is an empirical indicator of the occurrence or absence of permafrost (Haeberli, 1973; Hoelzle et al., 1993). Snow cover has a very low heat transfer capacity, thus a thick snow cover insulates the ground surface from short-term variations in air temperature. As a result, the BTS value is strongly influenced by the presence or absence of permafrost (Haeberli, 1985). Further, BTS distribution reflects a complex energy exchange in the blocky active layer (Hoelzle et al., 1999). In the present study, BTS can be influenced by cold airflow within the block fields where snow is thin or absent (Fig. 4). In such a case, BTS distribution reveals the complex heat exchange

from air circulation in the block slope. BTS measurements were conducted on 13 and 14 March 1999, when snow depth reached the annual maximum in the study area. A steel rod with thermistor sensor (resolution of 0.1°C and error less than 0.5°C) was used.

3-2. Shallow ground temperature monitoring

Shallow ground temperature was monitored at two sites from October 1999 to October 2000. One site is located at the valley bottom, connected to the foot of block slope (Fig 2), where permafrost existence was confirmed by pit survey in October 1999. Thermistor sensors were installed at depths of -50, -100, and -150 cm in the block layer. The other site is at the top of the block slope where warm funnels were discovered in the snow cover during the March 1999 BTS measurements. At this site, the thermistor sensors were installed at depths of -50 and -100 cm in the block layer. The ground surface temperatures were also monitored to determine the snow-cover periods at the two sites. All sensors were calibrated at 0°C, by using the apparent 'zero curtain' that occurs in spring, indicating the state change of ice into water. Air temperature was monitored at the block field (Fig. 2).

3-3. Observation of ground ice surface depth

At the valley bottom, ground ice formation was checked from November 2000 to May 2001. A plastic pipe with strainers was buried to the depth of ground ice (-157 cm, as shown in Fig. 3). Additionally, thermistor sensors were installed just beside the pipe at depths of 0, -20, -50, -100 and -157 cm. All sensors were calibrated at 0°C by the apparent 'zero curtain' that occurs in spring. The strainers allowed ground water penetration into the pipe. The depth of the ice surface was checked through the pipe. Intensive observations were carried out from 7 to 14 April 2001. Snow profiles at the pipe site were also checked during this intensive observations period.

4. Results

4-1. BTS and snow characteristics

BTS measurements showed a distinct distribution, with lower values (from -6.4 to -11.7°C) concentrated in the block field and valley bottom, while higher BTS values (near 0°C) occurred in the upper part of the block field and on the northeast-facing non-block slope (Fig. 2). Snow was removed from the rugged surface by the prevailing westerly wind during the winter, creating a thin and uneven snow cover on the block field (Fig. 4). Such snow cover characteristics allow cold air penetration into the block

field, lowering BTS values.

Funnels, which often open up beside larger blocks, conduct the cold air to the valley bottom through the unfilled space in the block layer. In contrast, while snow cover thickness exceeded 2-3 m at the valley bottom, BTS was also low. This fact suggests that low BTS values do not necessarily occur as a result of heat transfer from air above the snow cover. Surprisingly, higher BTS values occurred close to the low BTS sites at the valley bottom (Fig. 2). This indicates that the thermal conditions producing low BTS vary locally on the valley bottom.

Funnels expelling warm air (+2°C) were also found at the top of the block slope during the BTS measurements. Hoarfrost crystals grew around the funnel edge (Fig. 5), indicating the sublimation of vapor from warm funnels. Granular snow, generally formed under wet and warm conditions, developed in the snow pack around the warm funnels. These facts strongly suggest the occurrence of warm air emission at the uppermost part of the block slope. Similar funnels are reported at the Murtèl rock glacier in Switzerland, where the blocky active layer allows air circulation between the vacant areas of the large blocks and the atmosphere (Keller and Gubler, 1993; Bernhard, et al. 1998).

4-2. Ground temperature changes in 1999 - 2000

Fig. 6 compares measurements taken over a year: air temperature (a); ground temperatures at the top of the block slope (b), and at the valley bottom (c). Ground temperatures at the top of the slope remained positive throughout the snow-covered period (Fig. 6b), while those at the valley bottom dropped far below the freezing point (Fig. 6c). At the top of the block slope, the ground temperature during the snow period was higher at a depth of -100 cm (max. 7.3°C, min. 1.7°C) than at the -50 cm depth (max. 6.2°C, min. 1.1°C). The mean temperature gradient from January to March was 0.5°C/m between -50 and -100 cm depths. This positive temperature gradient suggests an upward thermal flux in the block slope. A spike in the temperature recorded at the -100 cm depth in early March (marked by the arrow in Fig. 6b) coincided with a sudden rise in air temperature (marked by the arrow in Fig. 6a). This coincidence suggests a connection between air temperature and thermal flux in the block slope. After the melting of the snow cover, a fluctuation in ground temperature followed the change in air temperature.

In contrast, ground temperatures at the valley bottom continuously decreased during the snow cover period from mid-December to mid-May (Fig. 6c). This indicates that the ground temperatures at the valley bottom are independent of air temperature. However,

a sudden increase in ground temperature (marked by the arrow in Fig. 6c) appears to have followed the trend of air temperature (marked by the arrow in Fig. 6a). This apparent synchronism suggests a connection between the atmosphere and the airflow in the vacancy of the block slope beneath the drifted thick snow cover on the valley bottom.

On April 11, a sudden temperature increase occurred at all depths (Fig. 6c). The second abrupt warming took place on April 22, and temperatures at all depths approached 0°C. These warming events suggest a sudden change of ice and water states. After the second event, ground temperature became constant. The temperature at -150 cm remained at 0°C (zero curtain) until the end of fall, while the temperatures at -50 cm and -100 cm began to increase after the snowmelt period. These temperature regimes also suggest permafrost existence near the depth of -150 cm.

4-3. Ground ice formation and snow profiles at the snowmelt period in 2001

Fig. 7 shows the measurements of air and ground temperatures, and ground ice levels for the April 2001 monitoring. The ground temperature at the valley bottom shows a remarkably similar regime to that observed in April 2000 (Fig. 6). Air temperature first rose above the freezing point on April 7. On the same day, ground temperatures at 0 and

-20 cm depths at the valley bottom site increased slightly, and then decreased again (see white triangles in Fig. 7). On April 8, air temperature rose again, and remained at a positive value until April 12. During this monitoring period, ground temperatures suddenly increased at all depths on April 9 (see black triangles in Fig. 7). The -157 cm temperature increase from -6.0°C to -0.2°C occurred within 4 hours. Simultaneously, ice began to grow at the depth of -157 cm, and continuously increased its depth after April 9 (Fig. 7g). The ice formation continued until April 23. During this period, ground temperatures fluctuated significantly at all depths, and the magnitude of fluctuations was largest at -157 cm, where ice formation took place.

Fig. 8 illustrates the snow profiles and temperatures on April 9, 10, 14 and 18 for the ground ice monitoring site at the valley bottom. On April 9, snow melting started only in the upper part of the snow cover and the lower part was still frozen, while the ground ice already began to grow (Figure 7g). The melting front reached the bottom of the snow layer on April 14. However, snowmelt water could not penetrate underground, because the ground was still frozen, as shown in Fig. 7b-f. An ice layer formed in the bottom part of the snow cover and reached 2 cm on April 18. This confirms that the snowmelt water could not penetrate vertically during the ice formation.

5. Discussion

5-1. Air circulation between the block slope and the atmosphere

Several theories have been presented to explain unexpectedly low ground temperatures in a block slope (Harris and Pedersen, 1998). The balch effect (Balch, 1900 in Harris and Pedersen, 1998) is gravitational drainage resulting from colder air, which is denser and heavier, easily penetrating into the vacancy of blocky deposits and pushing out the warmer air above. The chimney effect is also driven by a density difference, but occurs on a larger scale, with numerous entrances and exits of air (Ohata et al, 1994). This theory has been applied to an ice cave system (Wigley and Brown, 1976) and has been suggested as the predominant mechanism for air circulation in an unexpectedly cold block slope, where island permafrost is preserved (Von Wakkonig, 1996).

The winter condition of the present block slope seems to be explained by the chimney effect, because the warmer air in the block slope rises through the voids, and then flows out from the funnels (Fig. 5) in the upper part of slope. The positive temperature gradient at the top of the block slope (Fig. 6b) supports this idea. On the other hand, the cold air penetrates the block field (Fig. 4) where the snow is thin or absent, and moves to the lower part of the block slope through the voids, replacing the warmer air that

escaped upwardly. An apparently synchronous change between air and ground temperatures (indicated by arrows in Fig. 6a, c) suggests the existence of an airflow channel connecting the block field and the valley bottom. The air circulation, driven by a density difference between the cold and warm air, is the predominant effect cooling the block slope in winter.

5-2. Ground ice formation

The ground temperatures at the foot slope show an abrupt rise at all depths on April 9 2001, when the ground ice began to grow at the -157 cm depth. This coincidence between ground temperature rising and ground ice formation clearly indicates a latent heat release from the ice formation at -157 cm on April 9. This induced a rapid increase in temperature at -157 cm. The period of ground temperature fluctuations recorded at all depths (Fig. 7b-f), which coincides with the interval of ice formation (Fig. 7g), suggests that the ground temperature is strongly affected by refreezing of the snowmelt water in the block slope.

The ground water could not be supplied from the snow at the monitoring site, because the melting had not reached the bottom of the snow cover at the foot slope. When the melting front reached the bottom of the snow cover, melt water came in contact with the

frozen surface, and refroze at the bottom of the snow cover (Fig. 8). Therefore, the water refreezing at -157 cm depth was definitely supplied laterally from the surrounding slope (NE facing non-block slope and SW facing block slope), to the valley bottom. This fact suggests that the flow channel system of snow-melt-water is essential for forming the ground ice at the valley bottom.

6. Conclusion

BTS distribution, warm funnels at the top slope, and ground temperature changes on the block slope indicate a continuous air circulation in winter. Warmer air in the voids of block slope escapes upward and finally exits from warm funnels at the top of the slope. Meanwhile, cold air enters into the block slope from the block field where snow cover is thin or absent, and moves downward to the foot of the block slope, filling the voids where warmer air escaped. In spring, snowmelt water flows to the valley bottom, and refreezes, adding a superimposed ice layer on the perennial ice that fills the voids between coarse blocks. Ground ice may also play an important role in preserving the perennial ice beneath the seasonal ice layer. These results strongly suggest that not only the air circulation in winter, but also the ice formation processes in spring control the

thermal regime of permafrost in the block slope at a lower altitude with MAAT above 0°C.

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Table 1 Annual mean, maximum and minimum temperature (°C) in the block slope in Mt. Nishi-Nupukaushinupuri (see Fig. 2 for the monitoring site).

year	mean	max.	min.
1999	1.7	30.6	-21.2
2000	1.3	28.3	-23.9

Figure captions

Figure 1

Study area

Figure 2

Vegetation, sites of ground temperature monitoring, and BTS distribution on 13 and 14 March 1999. Permafrost was found by pit survey at the monitoring site in valley bottom in October 1999. At the same site, depth of ground ice surface was monitored from November 2000.

Figure 3

Instruments for ground ice monitoring

Figure 4

Rough topography and thin snow cover on block slope. Photo was taken on 13 March 1999.

Figure 5

A warm snow funnel at the top of block slope. Photo was taken on 14 March 1999.

Figure 6

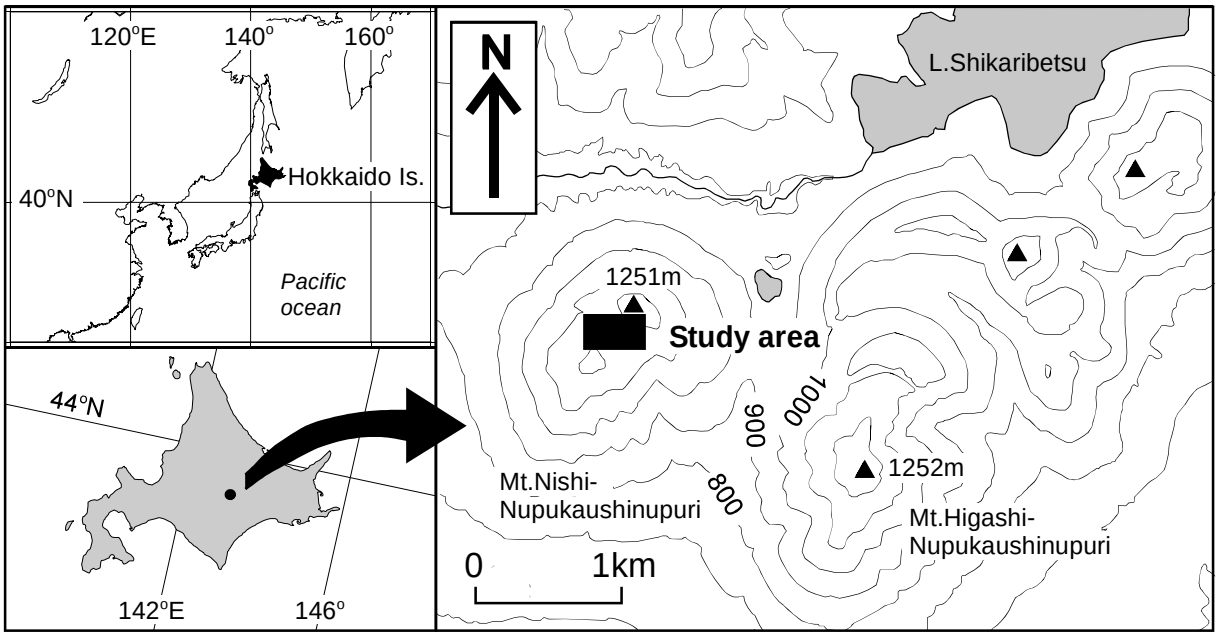
Air temperature (a), ground temperatures at the top of block slope (b), and ground temperatures in the valley bottom (c) from 15 October 1999 to 14 October 2000. The period of snow cover was inferred from the ground surface temperature.

Figure 7

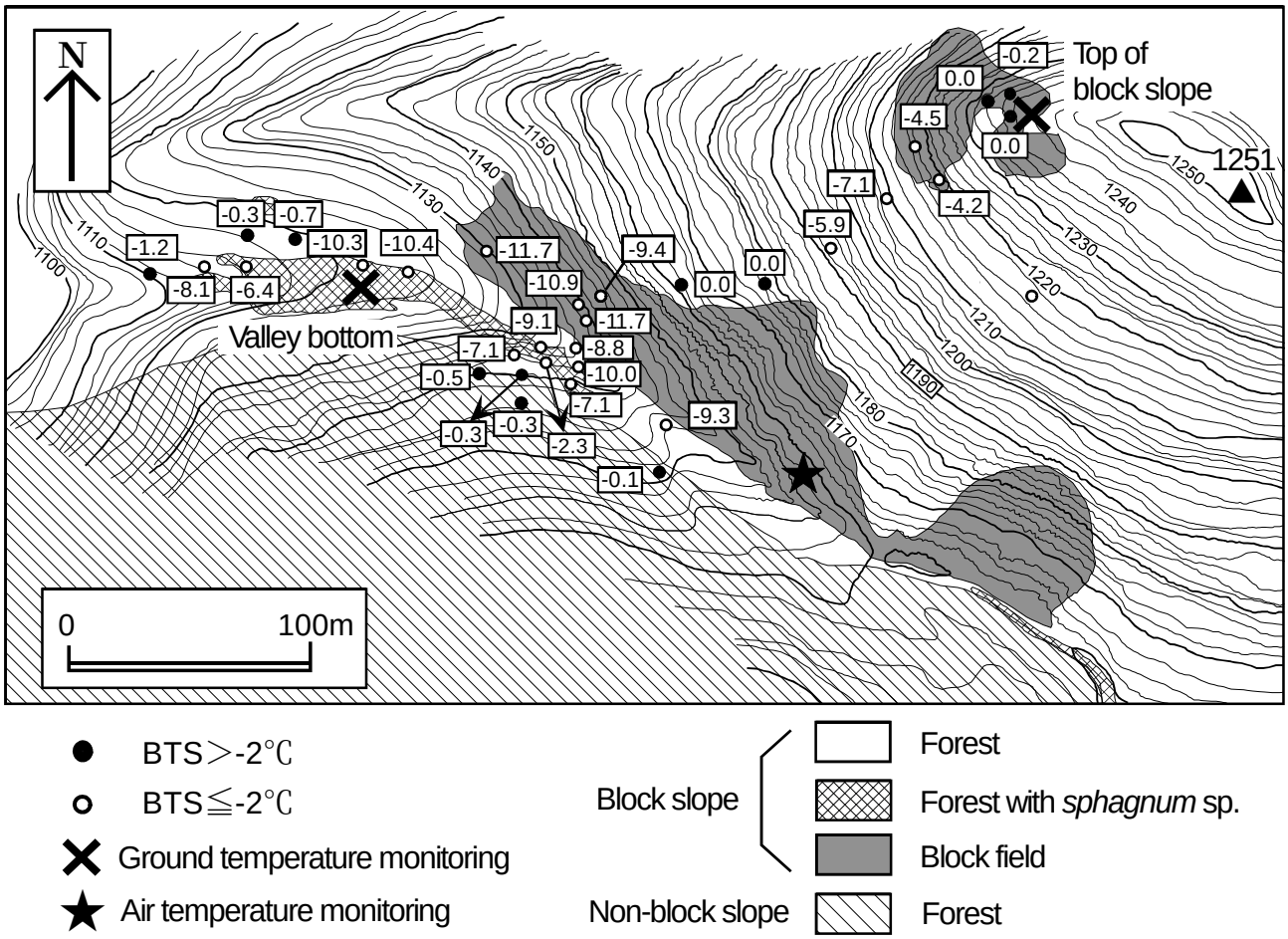
Air temperature in block field (a), ground temperatures at the valley bottom (b-f), and depth of ground ice surface at the valley bottom (g) in April 2001.

Figure 8

Snow temperature and profile in the period of ground ice accumulation.



Sawada Yuki, Figure 1



● BTS＞-2℃

○ BTS≦-2℃

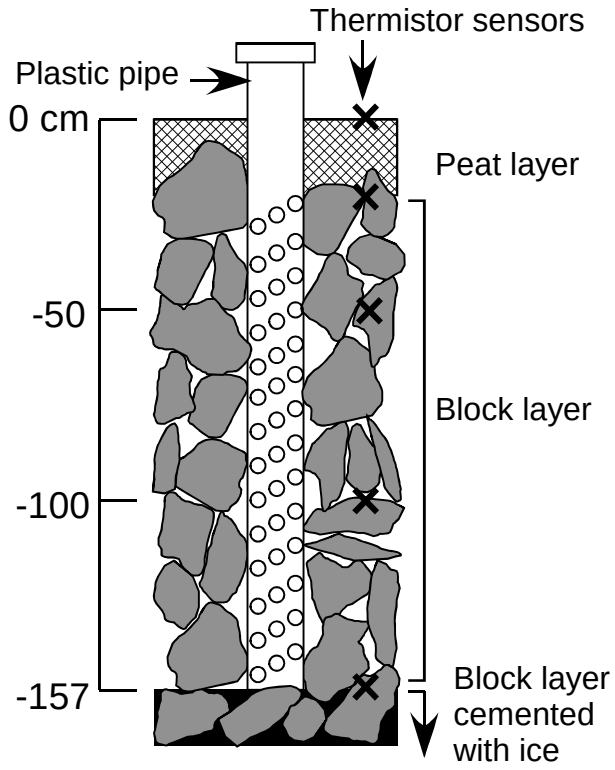
✕ Ground temperature monitoring

★ Air temperature monitoring

Block slope: Forest; Forest with *sphagnum* sp.; Block field

Non-block slope: Forest

Sawada Yuki, Figure 2



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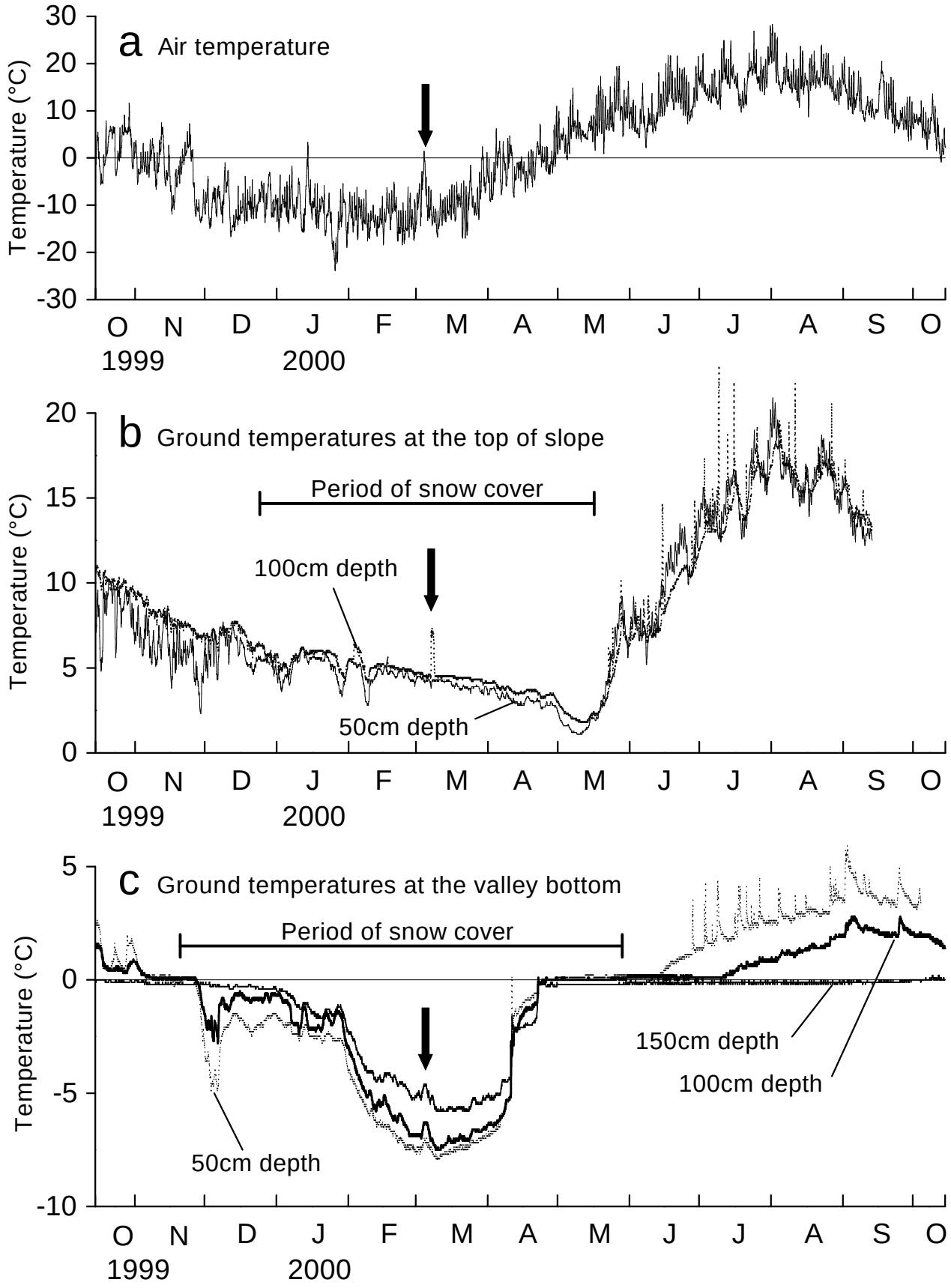
Sawada Yuki,　Figure 4

Sawada Yuki, Figure 5



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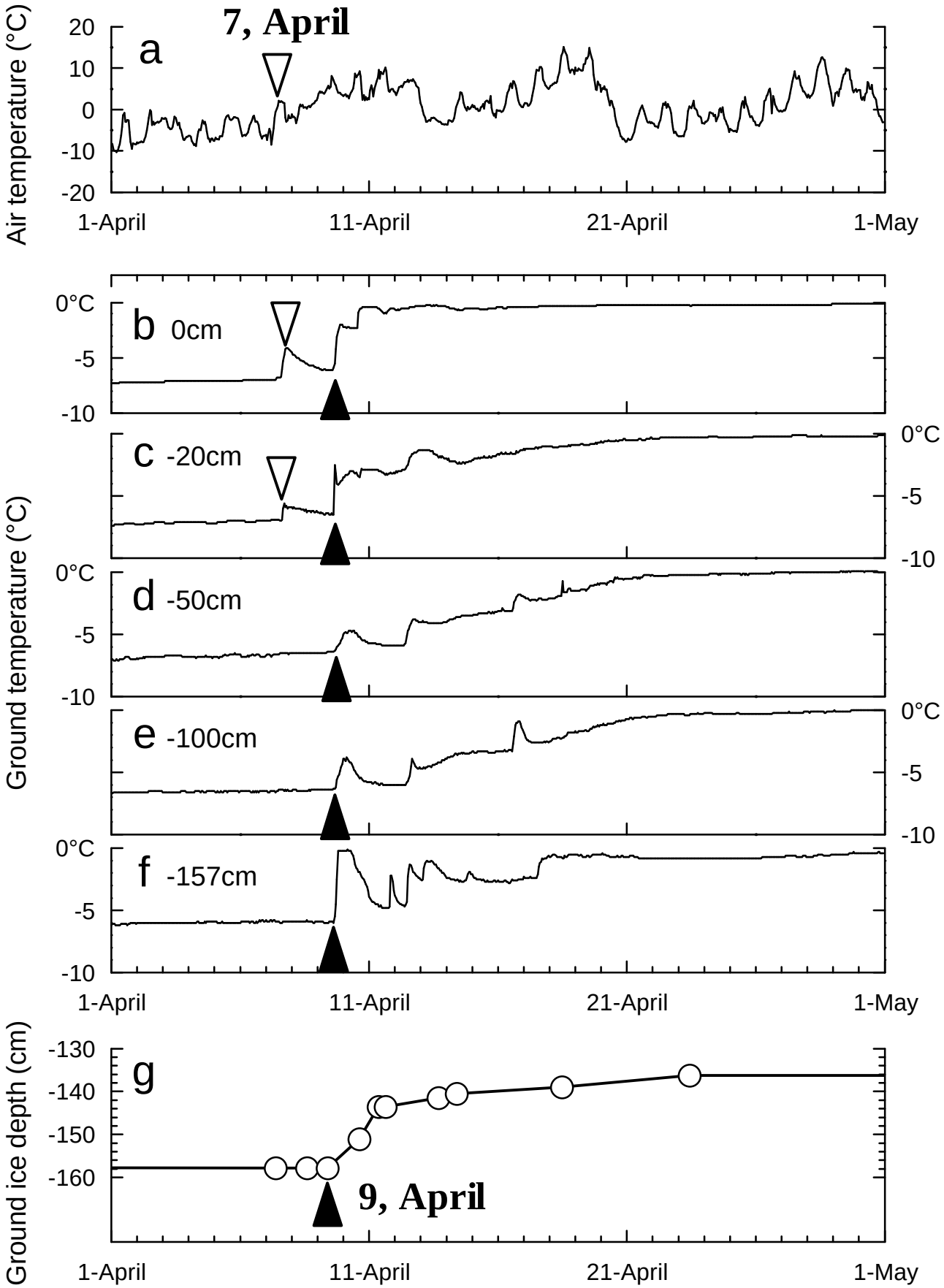

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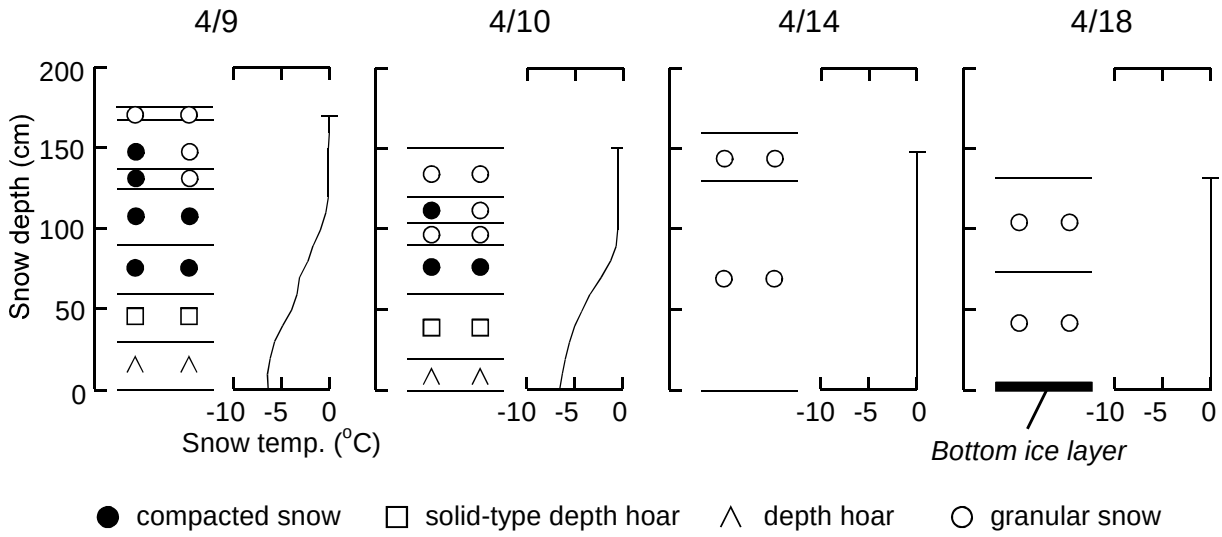

Sawada Yuki, Figure 8