Proc. NIPR Symp. Antarct. Geosci., **8**, 239-249, 1995

GROUND TEMPERATURE REGIMES AND FROST HEAVE ACTIVITY IN THE VICINITY OF SYOWA STATION, EAST ANTARCTICA

Takanobu SAWAGAKI

Graduate School of Environmental Earth Science, Hokkaido University, Kita-10, Nishi-5, Kita-ku, Sapporo 060

Abstract: Ground temperature and frost heave activity were continuously measured during 1992-1994 at two sites on East Ongul Island (Site EO), Lützow-Holm Bay and Cape Hinode (Site CH), Prince Olav Coast. The maximum thickness of the active layer was 60-80 cm at Site CH and was more than 80 cm at Site EO. Diurnal freeze-thaw layers occurred above 10 cm depth at both sites in summer. In addition, a "zero-curtain" zone appeared below 10 cm depth. Isotherm lines of 0°C suggest that seasonal freezing in late summer at both sites was two-sided, occurring both downward from the ground surface and upward from the permafrost table. Diurnal frost heaves which frequently occurred at Site EO were caused by the diurnal freeze-thaw cycles above 10 cm depth. The maximum heave originated from the growth of the surficial needle ice. Seasonal frost heave amounting to 3 mm was observed at Site EO. This heave seems to have resulted from ice segregation near the permafrost table.

1. Introduction

The coastal ice-free areas along Lützow-Holm Bay and the Prince Olav Coast belong to a periglacial environment. Permafrost with active layer thinner than 60 cm has been reported in East Ongul Island, Lützow-Holm Bay and on Cape Hinode, Prince Olav Coast (FUJIWARA, 1973; MORIWAKI, 1976) (Fig. 1). Patterned ground is well developed on Cape Hinode (MORIWAKI, 1976) compared with East Ongul Island (YOSHIKAWA and TOYA, 1957; KOAZE, 1963; FUJIWARA, 1973; MORIWAKI, 1976). Ground surface temperature is one of the important factors affecting the patterned ground formation. In this connection, a number of measurements of ground temperature have been carried out at Syowa Station on East Ongul Island (*e.g*., FUJIWARA, 1973; MORIWAKI, 1976). MORIWAKI (1976) indicates that the diurnal freeze-thaw cycles occurred only a few times in summer near the ground surface at Syowa Station. Frost heave activity has not been measured on the Prince Olav Coast or in the Lützow-Holm Bay area.

Measurements of ground temperature and frost heave activity were carried out at two sites, East Ongul Island and Cape Hinode (Fig. 1), during the 34th Japanese Antarctic Research Expedition (JARE-34). This article provides basic data on temperature regimes and frost heave activity in an attempt to describe periglacial conditions at the two sites.

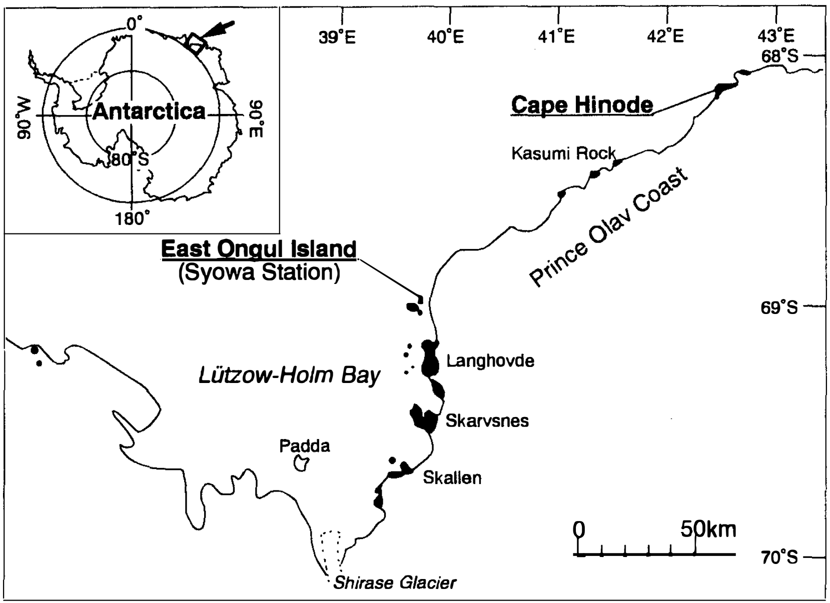

Fig. 1. Map of Lützow-Holm Bay and Prince Olav Coast, East Antarctica, indicating the location of the observation sites.

2. Study Area

2.1. *Cape Hinode*

Cape Hinode is an ice-free area located on the Prince Olav Coast (Fig. 1). Patterned ground or felsenmeer is widely developed in this area (MORIWAKI, 1976). In particular, stone circles composed of a mud core and a boulder rim surrounding the core are formed around a lake west of Mt. Hinode (157.7 m). They are formed on debris in various sizes with sandy matrix. MORIWAKI (1976) supposed that the debris was originated from till.

A measurement site (Site CH) was established on a mud core of the stone circle at the western margin of the lake, where MORIWAKI (1976) had once conducted the observation (Fig. 2). The mud core is about 2 m in diameter. The boulder rim was inundated in the summer of 1993. MORIWAKI (1976) also observed inundation onto a boulder circle on 3 January 1974. Inundation thus should be common feature at this site. MORIWAKI (1976) estimated that the thickness of the active layer of the mud core, in which sorting of materials occurs, was 13–30 cm. In the few centimeters below the surface of the mud core, fine materials less than 2 mm in diameter contain 5 to 10% of the clay and silt (Fig. 3). In addition, water content of this soil was 14.4% on 1 January 1993.

2.2. *East Ongul Island*

East Ongul Island is a small ice-free island separated from the Antarctic Continent by the 4 km-wide Ongul Strait (Fig. 1). The island topography is low-relief with the highest point at about 40 m a.s.l. Syowa Station lies on the northern part of the island. Since air temperature has been measured at the station, these records are available to represent the air temperature of the coastal ice-free areas.

There have been some ground temperature measurements on East Ongul Island (*e.g.*, FUJIWARA, 1973; MORIWAKI, 1976). The measurement sites of these studies were estab-

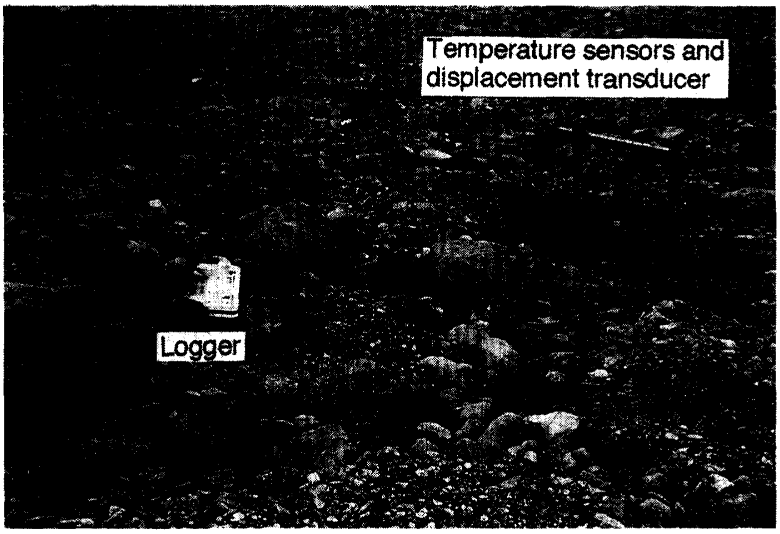

Fig. 2. The observation site (Site CH) on Cape Hinode. The instruments were established on a stone circle.

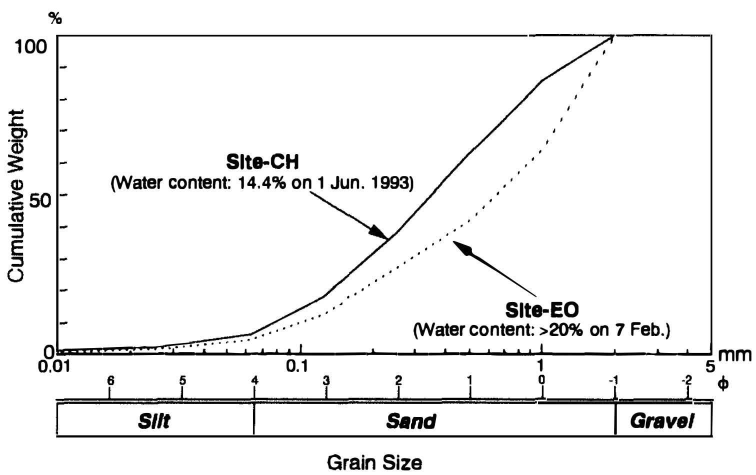

Fig. 3. Grain-size distribution curves for the less than 2 mm (in diameter) portion of the ground materials at the observation sites. The materials were collected from a few centimeters below the surface.

lished near Syowa Station. The site (Site EO) of this study, on the other hand, was established at the southern margin of Lake Midori located on the central part of the island, where the water condition of the ground surface is similar to that at Site CH.

Snow drifts thinner than 1 m had accumulated around Site EO from June to the beginning of December in 1993. In summer, the southern part of the lake was free from snow and became open water. In contrast, the northern part of the lake was covered with snow drift thicker than 5 m through the year. The summer insolation melt snow to produce lake water; then the ground surface was kept moist. Water content of the surface material was higher than 20% on 7 February 1993. The upper 100 cm of the sediment at Site EO was composed of sub-rounded gravels in various sizes with a sandy matrix. No significant vertical sedimentary structure was recognized. In the fine matter a few centimeters below the surface, matrix less than 2 mm in diameter contains *ca.* 5% silt and clay (Fig. 3).

3. Instrumentation

Both ground temperature and frost heave were automatically measured and recorded using the instruments illustrated in Fig. 4. This monitoring system is similar to that in MATSUOKA (1993). Platinum thermistor sensors were used for the measurement of ground temperature. Four sensors were inserted parallel to the ground surface at several soil depths to evaluate subsurface temperature profiles. The depths of the sensors were 0, 10, 40 and 80 cm at Site EO and 0, 10, 30 and 70 cm at Site CH. Frost heave was monitored using the displacement transducer DT-100A (Kyowa Electronic Instruments, Japan). Two legs of angle aluminum supporting the transducer were buried to the depth of 100 cm to be anchored in the permafrost. Both ground temperature and frost heave were recorded by a Datamark LS-3000-PtV logger (Hakusan Corporation, Japan) with recording interval of 2 hours.

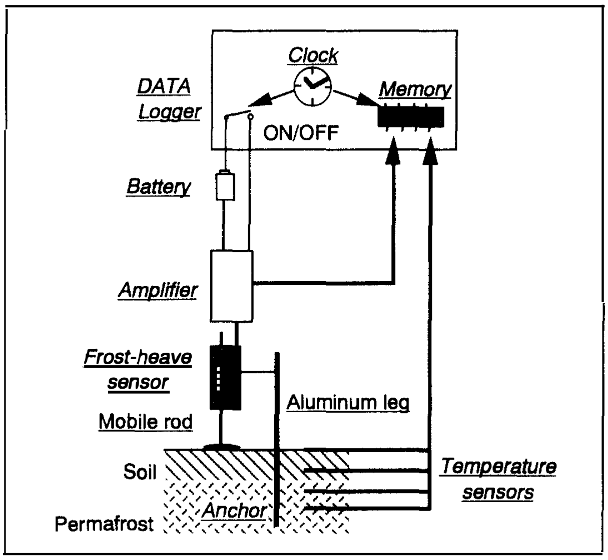

Fig. 4. Schematic sketch of the instruments.

4. Results

4.1. Data collection

The recording began on 7 February 1993 at Site EO. As the temperature sensor inserted at 80 cm depth at Site EO was broken in mid-March, data at this depth after that date are not available. Site EO was found to be flooded on 24 January, probably caused by melting of snow, hence the measurement was stopped manually on that day. Although the exact date of the flooding is uncertain, it is inferred to be 26 December because abnormal values were recorded starting on that date. The records until 25 December 1993 thus will be presented in this paper. The records in midsummer, from late December to

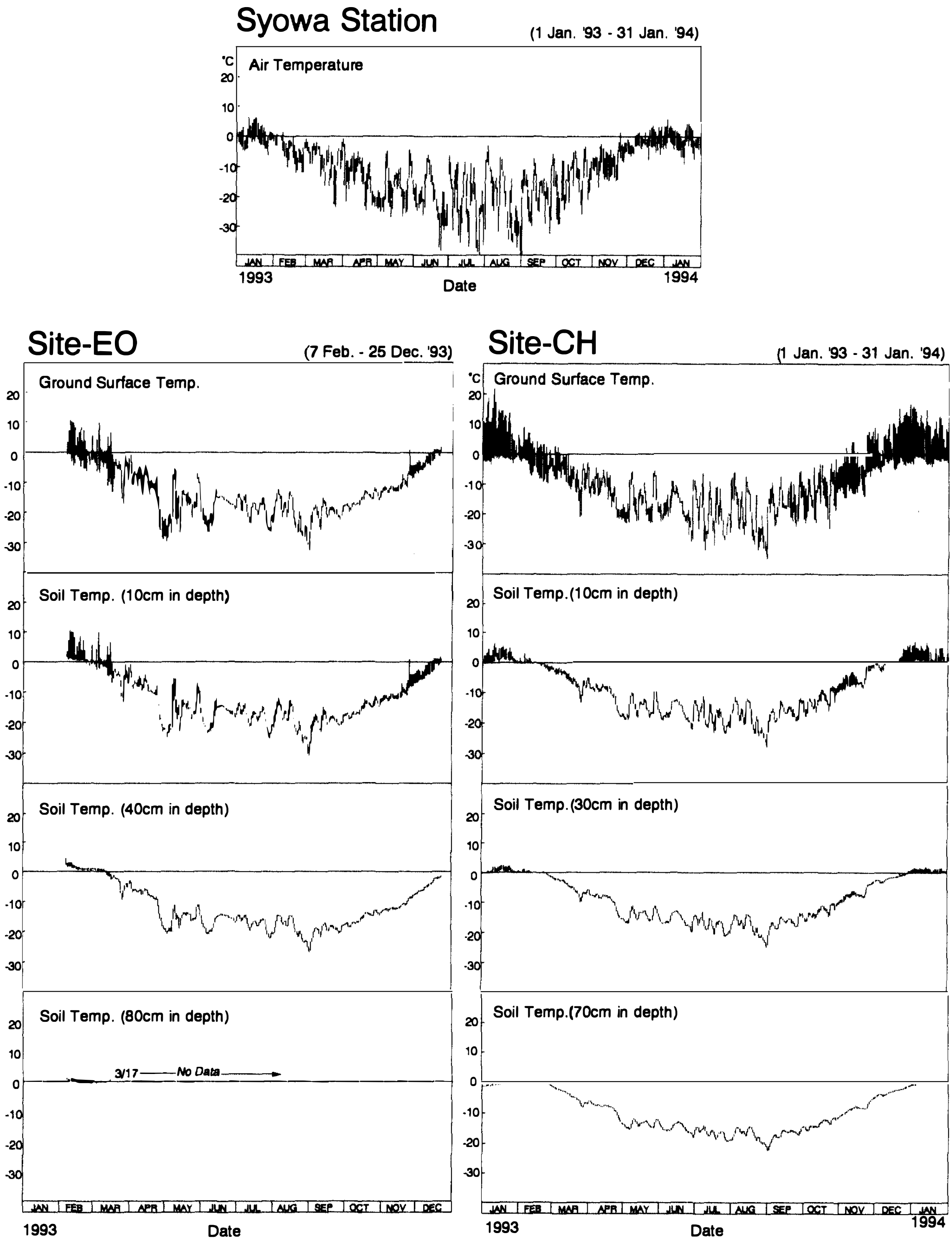

Fig. 5. Annual fluctuations in ground temperature including air temperature records at Syowa Station. Daily ranges are shown with solid lines.

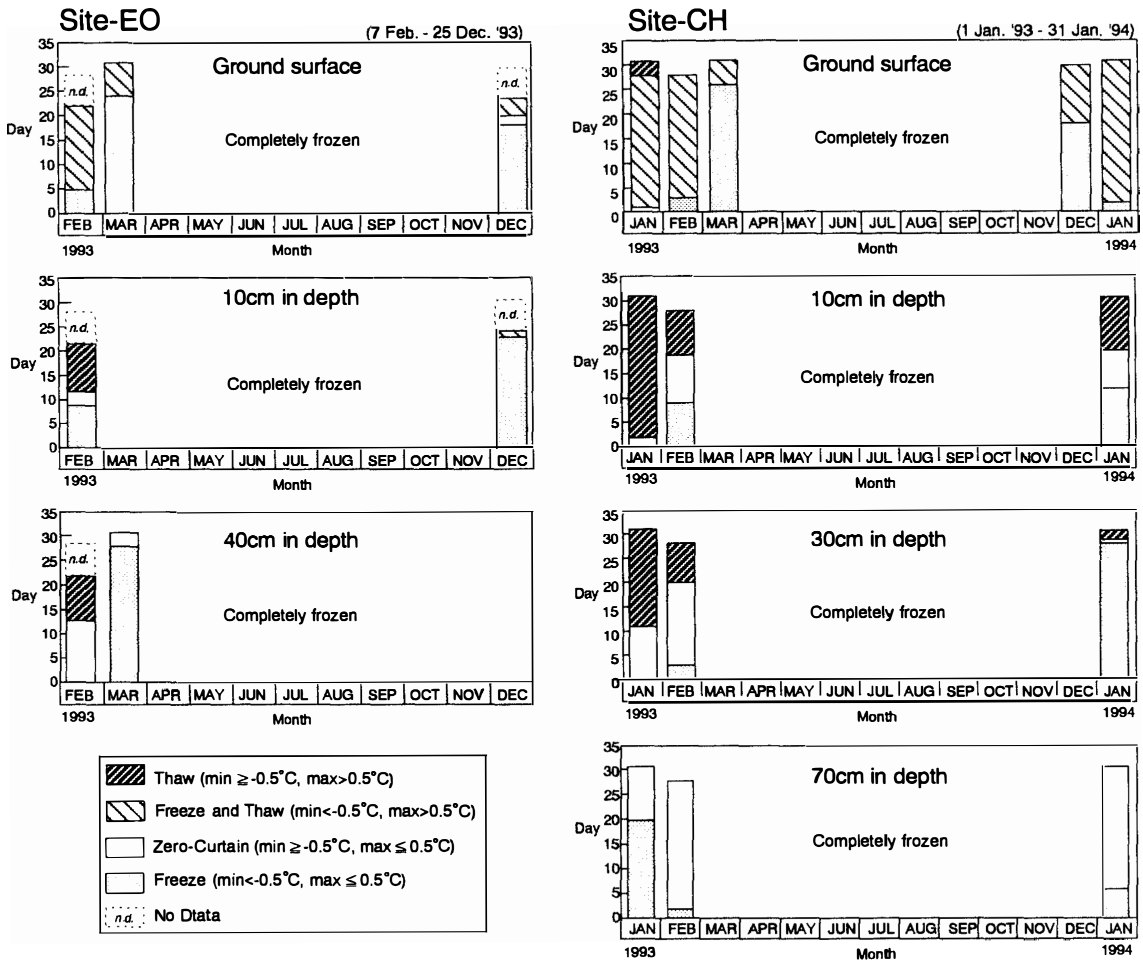

Fig. 6. Monthly ground temperature conditions at various depths. The conditions are classified according to the features of daily fluctuation of the ground temperature.

January, are unavailable at Site EO.

Measurements were conducted from 30 December 1992 to 11 February 1994 at Site CH. This record was completely obtained.

4.2. Ground temperature

Concerning latent heat of freezing, MÜLLER (1945) recognized a transitional zone of soil temperature for freezing, and called it the "zero-curtain". CHAMBERS (1966) introduced a transitional zone ranging between −0.5°C and +0.5°C. In the present paper, the zero-curtain is defined as the zone ranging between −0.5°C and +0.5°C. The freeze-thaw cycle is accordingly defined as the temperature oscillation across the zero-curtain. According to the definitions, the daily fluctuations in the soil temperature (Fig. 5) are classified into the four categories of thaw, freeze-and-thaw, zero-curtain and freeze (Fig. 6).

The ground was completely frozen from April to November at both sites (Figs. 5, 6). However, the daily ranges in the ground surface temperature through the winter were larger at Site CH than at Site EO (Fig. 5). The large daily temperature ranges indicate that

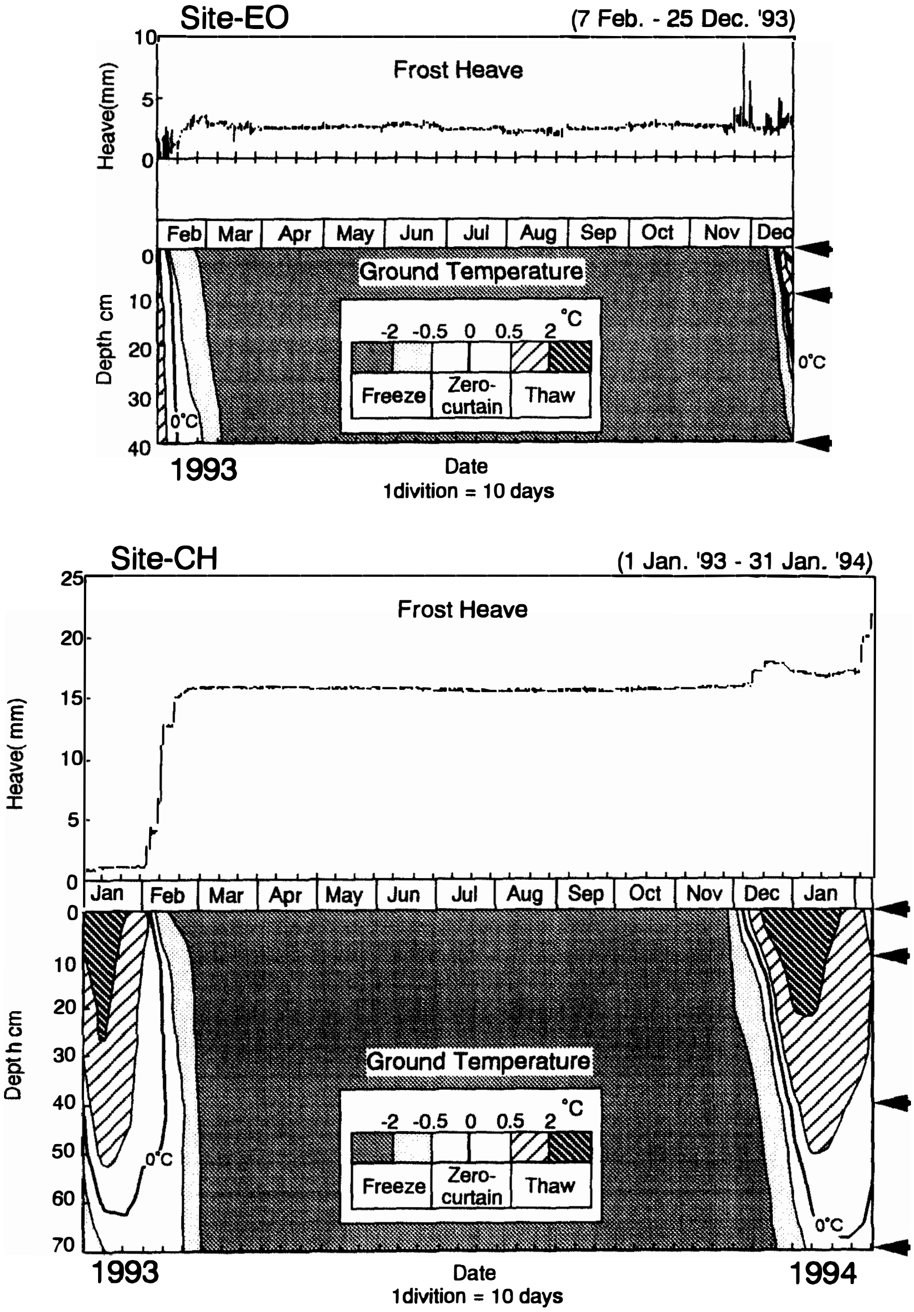

Fig. 7. Relationship between subsurface isotherms and frost heave activity. Subsurface isotherms are drawn on the basis of the mean ground temperatures for ten days. The arrows indicate the positions of temperature sensors.

relatively thin snow covered the ground at Site CH through the winter. In addition, seasonal thawing started in early November at Site CH and in late November at Site EO (Fig. 5). These facts indicate that the snow should have disappeared at Site CH earlier than at Site EO.

A 40–60 cm thick active layer has been observed at Syowa Station (FUJIWARA, 1973; MORIWAKI, 1976). An active layer thicker than 80 cm was recognized at Site EO (Figs. 7,

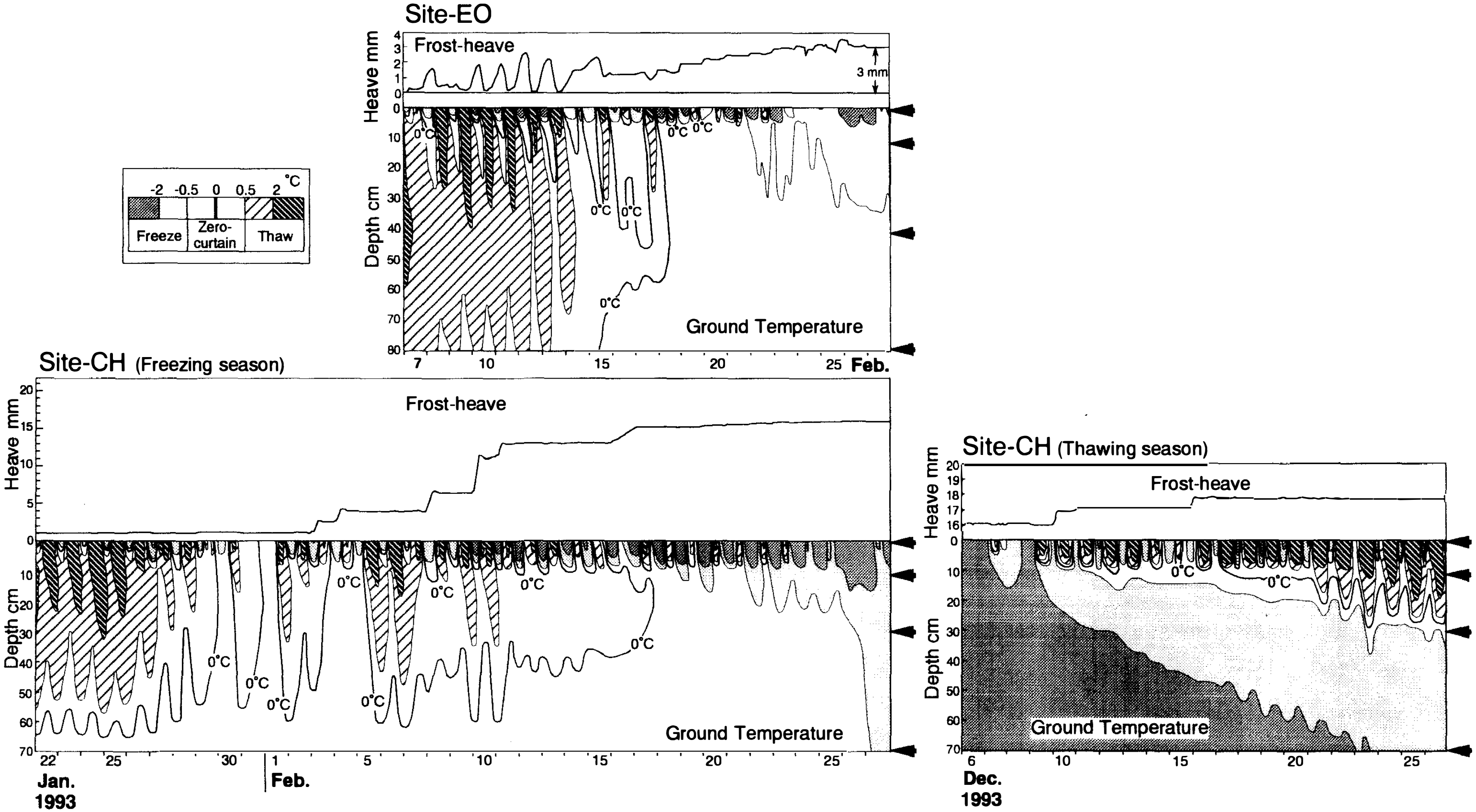

Fig. 8. Detailed subsurface isotherms and frost heave activity during summer. The arrows indicate the positions of temperature sensors.

8). The maximum thaw depth is uncertain at Site EO because of the lack of data in midsummer. Since Site EO was situated near a lake, the lake water would penetrate into the ground and promote thawing of the frozen ground. MORIWAKI (1976) observed a 13–30 cm thick active layer at Site CH. Figure 7 shows that the maximum thickness of the active layer at Site CH was 50–60 cm (or more than 70 cm including the zero-curtain) in late summer.

Despite these differences between the two sites, the following features are commonly recognized at both sites. Ground surface temperatures were well synchronized with the air temperature at Syowa Station (Fig. 5). However, the daily ranges of the ground surface temperature were greater than that in the air temperature, especially in summer (Fig. 5), due to solar insolation heating the ground surface. Moreover, diurnal freeze-thaw cycles occurred mainly near the ground surface from December to March (Fig. 6). On the other hand, no diurnal freeze-thaw cycles were recorded below 10 cm depth during summer, except for a few days in December at Site EO (Fig. 6). Similar features have been recognized near Syowa Station by FUJIWARA (1973) and MORIWAKI (1976). Accordingly, the active layers at both sites are divided into two parts on the basis of their thermal conditions. One is the "upper part" above 10 cm depth, where the diurnal freeze-thaw cycles dominate. The other is the "lower part" below 10 cm depth, where the thawed condition or the zero-curtain dominates from January to February.

The upper parts were completely frozen at both sites after the end of February (Fig. 8). In contrast, the thawed condition at 40–60 cm depth persisted until 12 February at Site EO. On the other hand, at Site CH, the thawed condition at 30–40 cm depth was continuously maintained until 26 January, and was intermittently maintained until 10 February. After that, the lower parts at both sites were dominated by the zero-curtain.

Because of the well-developed zero-curtain zone (Fig. 8), the border between frozen and thawed grounds is out of focus, and hence the border is not appropriately indicated by 0°C isotherm lines. However, the 0°C isotherm lines in Fig. 8 suggest that freezing in late summer was two-sided at both sites, occurring both downward from the ground surface and upward from the permafrost table. For example, at Site CH, the 0°C isotherm line extended from the surface to 10 cm depth, and also upward from 40–50 cm depth, in the period from 10 to 18 February (Fig. 8). Similar features were recognized at Site EO from 14 to 18 February (Fig. 8).

4.3. Frost heave

Diurnal frost heaves occurred frequently at Site EO from the middle of November to the middle of February. Although the maximum diurnal heave was 7.4 mm/day on 28 November, the ordinary heaves were less than 4 mm (Figs. 7, 8). On 1 December, needle ices about 3 mm high were observed on the ground surface at Site EO, when the recorded heave was 4 mm. These facts indicate that most of the heave on 1 December was due to growth of the surficial needle ice. Consequently, the maximum diurnal heave on 28 November at Site EO should be caused by the surficial needle ice. After 15 February, the ground gradually heaved from 1 to 3 mm at Site EO, and never returned to the original level (Figs. 7, 8). This heave is thus regarded as the seasonal frost heave.

No significant subsiding of the ground was recorded at Site CH through the year. In particular, it is expected that seasonal frost heaves will return to the original level in the next summer. Nevertheless, such a phenomenon was not observed (Fig. 7). The significant heaves were recorded in limited periods, at the beginning of summer and at the end of summer (Figs. 7, 8). In other periods, when most of the active layer was frozen or thawed, the values remained constant (Fig. 7). An instrumental problem which must be considered is that the aluminum legs supporting the displacement transducer might not be anchored in the permafrost and moved vertically with the ground movement. When the ground was frozen, the legs would be fixed to the ground to record the heaves. However, as the recorded heaves did not always correspond with the freeze-thaw cycle (Fig. 8), other instrumental problems remain. It is consequently risky to adopt the heaving records at Site CH.

5. Discussion

Because of the instrumental problem described above, the records of frost heave at Site CH cannot indicate the exact frost heave activity. In addition, summer data are lacking at Site EO. Accordingly, ground thermal condition and frost heave activity at the two sites can be briefly discussed on the basis of the available records, as follows.

Diurnal frost heaves less than 4 mm occurred frequently at Site EO from late November to the middle of February. Seasonal frost heave amounting to 3 mm was observed at Site EO at the end of summer (Figs. 7, 8). The matrixes of soil in which the diurnal freeze-thaw occurred contain 5–10% of clay and silt at both sites (Fig. 3). KAPLAR's (1974) criterion predicts that the frost heave rates of these soils are "low (1.0–2.0 mm/day)" or "medium (2.0–4.0 mm/day)". Thus the surficial sediments at both sites are not considered to be highly susceptible to frost heave mechanisms.

Water content is an important factor influencing frost heave. The water contents of the soils are sufficient to cause frost heave at both sites. In summer, diurnal freeze-thaw layers are observed above 10 cm depth at both sites (Figs. 6, 8). These layers were underlain by the layer of "thaw" or "zero-curtain" from January to February (Figs. 6, 8). In addition, this condition persisted for several days (Fig. 8). In these conditions, the diurnal freeze-thaw layer should contain sufficient water for ice segregation. Consequently, diurnal frost heaves should occur owing to ice segregation near the ground surface up to 10 cm depth at Site EO. However, it is still difficult to determine whether it is ice lensing or the growth of needle ice that contributes to the heaves, because the profile of the soil at this time was not observed to confirm the ice layer.

Seasonal frost heaves occurred at Site EO after 15 February, when the zero-curtain dominated below 10 cm depth. In this period, the diurnal freeze-thaw cycles still occurred in the layer above 10 cm depth (Fig. 8). The seasonal frost heaves are therefore regarded as mainly response to the ice segregation in the lower part. No trench survey was carried out in the freezing season. It is necessary to confirm the existence and the depth of seasonal ice segregation in this season.

As was described at the beginning of this paper, patterned ground is well formed on Cape Hinode compared with East Ongul Island. However, no significant differences between the two sites are recognized as far as environmental factors such as the soil and water environment, and ground temperature regimes below 10 cm depth are concerned. This study failed to record frost heaves at Site CH, and either frost heaves or ground temperatures in midsummer at Site EO. The diurnal frost heave in summer, as a result, still remains to be measured, including its frequency, height and relation to the ground temperature regimes.

6. Conclusions

Frost heave and ground temperature were observed on East Ongul Island (Site EO) and Cape Hinode (Site CH). The results of these observations are summarized as follows:

1) The active layers are thicker than 70 cm at both sites. They are thicker than the formerly revealed ones at Syowa Station and Cape Hinode.

2) The seasonal freezing at both sites was two-sided.

3) Diurnal frost heaves and a seasonal frost heave are recognized in summer and in late summer respectively at Site EO.

4) The results of this study cannot explain the difference of development of patterned ground between the two sites, because no significant differences are observed in the soil, water environment, or ground temperature regime below 10 cm depth.

Acknowledgments

This study was performed as a part of the 34th Japanese Antarctic Research Expedition. A part of this study was also supported by the JARE-33 wintering party and the JARE-35 summer party. I would like to express my gratitude to the members of the JARE for their kind collaboration in Antarctica. Thanks are also due to Drs. M. HAYASHI of Shimane University, K. HIRAKAWA of Hokkaido University, N. MATSUOKA of University of Tsukuba and K. MORIWAKI of the National Institute of Polar Research, for their advice, encouragement and support to this study.

References

CHAMBERS, M.J.G. (1966): Investigations of patterned ground at Signy Island, South Orkney Islands: I. Interpretation of mechanical analyses. Br. Antarct. Surv. Bull., **9**, 21-40.

FUJIWARA, K. (1973): Higashi Onguru Tô Mizukumi Zawa no ryûki teisen no chikei to shûhyôga chikei (The landforms of the Mizukumi Zawa near Syowa Station, East Antarctica). Nankyoku Shiryô (Antarct. Rec.), **46**, 44-66.

KAPLAR, C.W. (1974): Freezing test for evaluation relative frost susceptibility of various soils. CRREL Tech. Rep., **250**, 37 p.

KOAZE, T. (1963): Syowa Kiti fukin rogan chiiki no chikei (The landform of the northern part of Prince Harald Coast, East Antarctica). Nankyoku Shiryô (Antarct. Rec.), **20**, 61-74.

MATSUOKA, N. (1993): Monitoring system for some periglacial processes. Ann. Rep. Inst. Geosci., Univ. Tsukuba, **19**, 11-17.

MORIWAKI, K. (1976): Syowa Kiti fukin no rogan no chikei to tairikuhyô enpenbu no chigakuteki kansatu (Glacio-geomorphological observations in and around ice-free areas in the vicinity of Syowa Station, Antarctica). Nankyoku Shiryô (Antarct. Rec.), **57**, 24-55.

MÜLLER, S.W. (1945): Permafrost or perennially frozen ground and related engineering problems. USGS Spec. Rep., Strateg. Engineer. Study, **62**, 2nd ed., 231 p.

YOSHIKAWA, T. and TOYA, H. (1957): Dai-1-ji Nankyoku Chiiki Kansokutai chiri bumon hôkoku (Report on geomorphological results of Japanese Antarctic Research Expedition, 1956-57). Nankyoku Shiryô (Antarct. Rec.), **1**, 1-13.

(Received January 26, 1995; Revised manuscript received June 5, 1995)