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# Ground thermal regime on the Kaffiøyra Plain (NW Spitsbergen) in the period from 1 September 2012 to 31 August 2014

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**Abstract.** The article presents the results of ground temperature measurements taken at 1 cm to 100 cm below ground level on the Kaffiøyra Plain (NW Spitsbergen) from 1 September 2012 to 31 August 2014. Observations of thermal conditions were carried out at three sites located in characteristic polar ecotopes: on a beach, in tundra and on a moraine. The results of ground temperature measurements for the Kaffiøyra Plain were compared to the observations of weather conditions at the nearby meteorological station in Ny-Ålesund. The variability of ground temperature was analysed in annual, seasonal and diurnal courses. These reflected the prevailing meteorological conditions at the time. Substantial differences in ground thermal conditions were found between the ecotopes, which was due to the morphological diversity of the ground, its moisture content, vegetation and snow cover, as well as the depth of the permafrost.

**Key words:**
Arctic,
Spitsbergen,
Kaffiøyra,
ground temperature,
active layer,
climate

## Introduction

Ground temperature depends on the heat balance, and – in particular – on the amount of thermal energy generated by the sun and reaching the earth's surface. The influx of solar energy varies with the solar elevation angle and undergoes diurnal and annual changes. Ground temperature is also affected by advections of various air masses, changes in cloudiness, precipitation, evaporation, albedo, the degree of vegetation cover and the thickness of snow cover (Washburn 1979). It is also influenced by the exposure of the ground to the sun and inflowing air masses, and by the humidity conditions in the ground which determine its heat capacity and thermal conductivity. In Polar regions, the thermal conditions of the top layers of the ground are also affected by the depth of permafrost (cf. Baranowski 1968; Migała 1994; Araźny et al. 2016).

Since 1975, observations of the thermal conditions and the thickness of the active layer have been carried out in the area of Kaffiøyra in three selected ecotopes: on a beach, in tundra and on a moraine (Araźny et al. 2016) (Fig. 1). There are numerous literary references concerning the temperature of the ground in Kaffiøyra; however, so far they have mainly focused on summer seasons. Results of the measurements can be found in articles describing general weather conditions during expeditions to Kaffiøyra (cf. Leszkiewicz 1977; Wójcik 1982; Marciniak and Przybylak 1983, 1991; Wójcik and Marciniak 1983; Araźny 1999, 2002). A few studies specifically concerning thermal conditions of the ground have also been published (Wójcik and Marciniak 1987; Wójcik et al. 1988, 1990; Kejna 1990, 1991; Kejna et al. 1993; Marciniak et al. 1991; Przybylak et al. 2010; Araźny 2001, 2012; Araźny et al. 2016). Results of observations conducted in all summer seasons of the years 1975–2014 and a detailed overview of literature for Spitsbergen can be found in Araźny et al. (2016), whereas the annual variability of ground temperature at a moraine site (in 2006–2012) has been described by Sobota and Nowak (2014). They carried out observations of the ground temperature on a moraine at 50 cm, 100 cm and 150 cm b.g.l. in the years 2006–2012.

The aim of this article is to provide an analysis of the variability of ground temperature on the Kaffiøyra Plain (Spitsbergen) in three typically Polar ecotopes: beach, moraine and tundra, on different timescales (annual, seasonal, monthly). We present the all-year-round results of comprehensive measurements carried out in the three ecotopes. The research is important in the context of climate changes occurring for the last few dozens of years in the Norwegian Arctic – especially as regards a substantial increase in air temperature (e.g. Hanssen-Bauer et al. 2002; Nordli 2010; Førland et al. 2011; Nordli et al. 2014; Przybylak 2016) – and in the area of Kaffiøyra in NW Spitsbergen (e.g. Przybylak and Araźny 2006; Przybylak et al. 2011; Araźny et al. 2016).

## Location, data and methods

The observations of thermal conditions of the ground were carried out at the Nicolaus Copernicus University Polar Station (latitude 78°41'N, longitude 11°51'E). The station is located in the northern part of the coastal plain of Kaffiøyra, in NW Spitsbergen, the largest island in the Arctic archipelago of Svalbard. The ground temperature was measured at three ecotope types: on a sandy beach, at the flat top of the terminal-lateral moraine of the Aavatsmark Glacier and in tundra (Figs 1 and 2).

- The beach site (B) was located on an accumulation plain, unaffected by major tidal motions of the Greenland Sea. Sand and gravel layers prevail to a depth of 1 m there. The surface is not covered with any vegetation.
- The tundra site (T) was located at an outwash fan extending from a terminal-lateral morainal arc of the Aavatsmark Glacier. The arc comprises mainly sand and gravel deposits with a large share of rock crumbs. The surface is approx. 70% covered with tundra vegetation (Gugnacka-Fiedor and Noryśkiewicz 1982).
- The moraine site (M) was located on the flat top of the Aavatsmark Glacier's terminal-lateral moraine, made from sandy, gravelly and silty loams


Fig. 1. Ground temperature measurement sites on the Kaffiøyra Plain: Beach (B), Tundra (T) and Moraine (M) (Photo by A. Araźny)

and sand. The moraine is approx. 20% covered with tundra vegetation (Fig. 2).

The analysed sites were included in the Circumpolar Active Layer Monitoring network (Brown et al. 2000) where they were designated as P2A (beach), P2B (tundra) and P2C (moraine).

The ground temperature data from the three sites, collected from 1 September 2012 to 31 August 2014, were used for this study. The thermal conditions of the ground were measured using HOBO automatic data loggers (accuracy of temperature sensor ± 0.2°C) at 6 depths: 1, 5, 10, 20, 50 and 100 cm. The recording was done at an hourly interval of UTC time. The thermal conditions of the ground were presented against the background of the meteorological conditions observed at a nearby station in Ny-Ålesund (approx. 30 km away). The meteorological data (total solar radiation, air temperature and relative humidity and the depth of the snow cover) were sourced from the Norwegian Meteorological Institute and the Alfred Wegener Institute for Polar and Marine Research. The above-mentioned meteorological data from Ny-Ålesund were used because continuous meteorological measurements have not been performed on the Kaffiøyra Plain.

## Weather conditions

The temperature of the ground depends on its heat balance, of which radiation balance is the key component. The amount of incoming solar radiation depends on latitude. At the 79$^{th}$ parallel the polar day is about 129 days long (18 April – 24 August) and the polar night is nearly 2 weeks shorter (25 October – 17 February) than the polar day, because of refraction (Hisdal 1985). According to the data from Ny-Ålesund, which provides the weather background in the area of Kaffiøyra for this study, the mean annual amount of solar radiation which reached the ground in the analysed period was approx. 2,208 MJ·m$^2$ (or about 6 MJ·m$^{-2}$·day$^{-1}$) (Table 1). In an annual course, the highest mean diurnal sums were recorded in May and June: approx. 17 and 15 MJ·m$^{-2}$·day$^{-1}$, respectively. The highest diurnal sums of solar radiation in May and June exceeded 25–30 MJ·m$^{-2}$; for example, on 1 June 2014 it was 34.1 MJ·m$^{-2}$ (Fig. 3).

In the analysed period, the mean annual air temperature at Ny-Ålesund was -3.5°C, which was 2.3°C higher than the long-term mean (Araźny 2008). The warmest months were July and August with 5.6°C (2013) and 5.3°C (2014), and 5.2°C (2013) and 4.2°C (2014), respectively. The coldest months of 2013 were March and February (-13.2°C

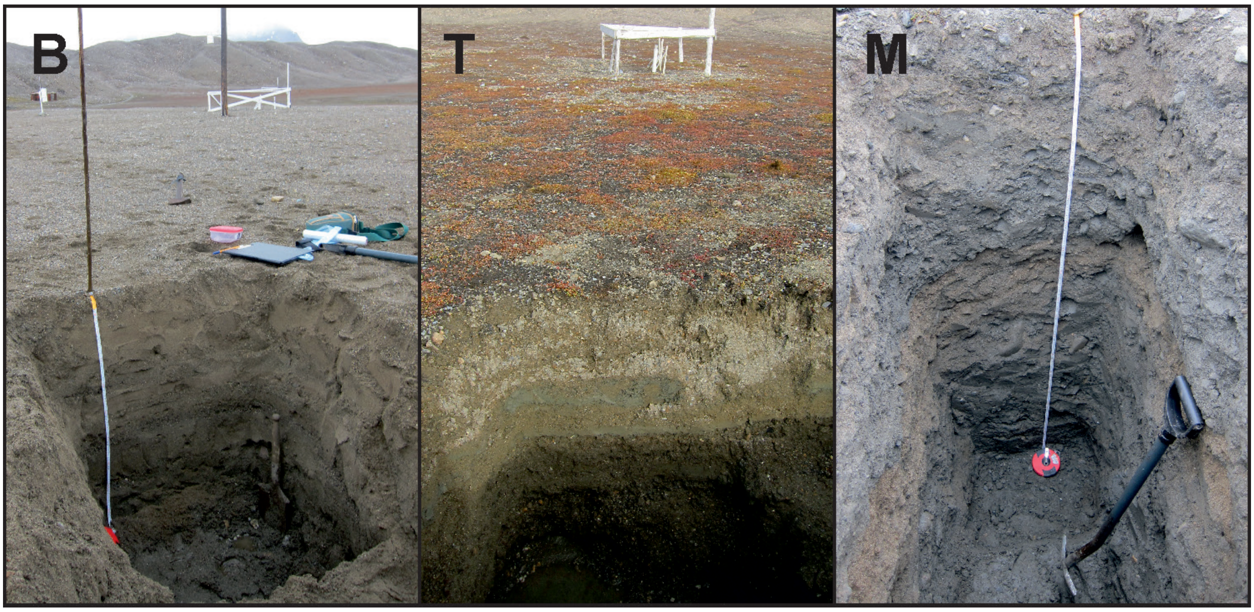


Fig. 2. Lithological profile of the measurement sites on the Kaffiøyra Plain: Beach (B), Tundra (T) and Moraine (M) (Photo by M. Kejna)

Table 1. Monthly values of meteorological elements at Ny-Ålesund in the period from 1 September 2012 to 31 August 2014

| Year | Month | SR | Ti | Tmin | Tmax | f | SCmax |
|---|---|---|---|---|---|---|---|
| | | (MJ·m$^{-2}$) | (°C) | (°C) | (°C) | (%) | (cm) |
| 2012 | Sep | 42.0 | 2.1 | 0.2 | 3.9 | 84 | 10 |
| | Oct | 1.7 | -3.3 | -6.3 | -0.9 | 77 | 9 |
| | Nov | . | -7.4 | -10.1 | -5.1 | 68 | 28 |
| | Dec | . | -8.0 | -11.9 | -5.1 | 74 | 45 |
| 2013 | Jan | . | -7.9 | -11.5 | -5.1 | 71 | 22 |
| | Feb | 16.8 | -10.8 | -14.0 | -7.8 | 66 | 34 |
| | Mar | 197.5 | -13.2 | -16.4 | -10.3 | 62 | 29 |
| | Apr | 414.9 | -9.2 | -12.4 | -6.5 | 68 | 30 |
| | May | 566.9 | -1.8 | -3.8 | 0.9 | 79 | 28 |
| | Jun | 408.3 | 3.2 | 1.3 | 5.4 | 81 | 8 |
| | Jul | 324.2 | 5.6 | 3.8 | 7.8 | 88 | . |
| | Aug | 162.2 | 5.2 | 3.4 | 7.6 | 84 | . |
| | Sep | 55.0 | 3.3 | 1.3 | 5.3 | 79 | . |
| | Oct | 2.0 | -6.0 | -9.2 | -3.2 | 72 | 47 |
| | Nov | . | -9.1 | -12.0 | -6.4 | 67 | 39 |
| | Dec | . | -8.7 | -11.9 | -6.0 | 65 | 32 |
| 2014 | Jan | . | -4.7 | -8.7 | -1.9 | 74 | 64 |
| | Feb | 15.8 | -2.7 | -5.5 | -0.3 | 72 | 65 |
| | Mar | 166.6 | -9.2 | -12.7 | -6.3 | 67 | 131 |
| | Apr | 469.6 | -10.4 | -14.0 | -7.4 | 68 | 107 |
| | May | 485.2 | -3.4 | -5.7 | -0.5 | 75 | 99 |
| | Jun | 495.7 | 2.0 | 0.1 | 4.6 | 78 | 79 |
| | Jul | 408.0 | 5.3 | 3.3 | 7.7 | 85 | . |
| | Aug | 183.5 | 4.2 | 2.2 | 6.4 | 81 | . |
| Jan 2013 – Dec 2013 | | 2147.8 | -4.1 | -6.8 | -1.5 | 74 | 47 |
| Sep 2012 – Aug 2014 | | 4415.9 | -3.5 | -6.3 | -1.0 | 74 | 131 |

Explanations: SR – global solar radiation, T – air temperature (Ti – mean, Tmax – maximum, Tmin – minimum), f – relative air humidity; SCmax – maximum depth of snow cover; Ti, Tmin, Tmax, f and SCmax are taken from the Norwegian Meteorological Institute, and SR from Alfred Wegener Institute

and -10.8°C), and in 2014 the coldest months were April and March (-10.4°C and -9.2°C). The mean maximum annual air temperature for the whole analysed period was -1.0°C, whereas the mean minimum temperature reached -6.3°C (Table 1).

Most of the year, Spitsbergen is exposed to humid maritime air masses carried from the Atlantic, which is caused by cyclonic activity (Araźny 2008). In an annual course, the highest values of relative humidity (>80%) at Ny-Ålesund occurred in July and August (Table 1, Fig. 3). This is connected with the inflow of warm and humid air masses from the sea in the southwest to the cooler land. The lowest values, on the other hand, were recorded in the cold part of the year, when the waters surrounding Spitsbergen were covered with ice to a much larger extent than in the summer, particularly from the east and north, which provides favourable conditions for the inflow of dry air masses (Araźny 2008; Przybylak et al. 2014).

Snow cover, persisting for the most of the year (Table 1, Fig. 3), plays a significant role in the insulation of the ground in the Polar regions. At Ny-Ålesund, snow or sleet can occasionally fall even in such summer months as July or August. In the years 2012–2013, the snow cover formed in early October and, in the analysed period, its maximum thickness (131 cm) was observed on 3 March 2014. The speed and direction of wind at Ny-Ålesund and on Kaffiøyra are largely modified by the local topography (Beine et al. 2001; Araźny and Przybylak 2012); therefore, the two elements were considerably different at the sites, and greater speeds of wind were observed on the Kaffiøyra Plain (Przybylak and Araźny 2006). The snow is substantially driven and redeployed by high winds in the area of Kaffiøyra. The exposed measurement site at the top of the moraine was not covered with snow for the most part of the year (Araźny and Grześ 2000; Sobota 2003; Sobota and Nowak 2014). On Spitsbergen, when the snow lies thin on the ground and the wind is strong, an intensive turbulent exchange of heat with the ground occurs, and the ground is considerably wind-chilled in tundra (Migała 1994).

## Annual course of ground temperature

This section contains the results of ground temperature measurements, taken for a few years (from September 2012 to August 2014) on the beach, on the moraine and in the tundra in all months and seasons of the year (Table 2). The seasons were identified according to Putnins et al. (1959) and Gavrilov and Sokolov (1969), who assigned November to March to winter, April and May to spring, June to August to summer, and September and October to autumn. In the area of Kaffiøyra, the ground temperature is considerably varied. The mean annual ground temperature in the analysed period at the beach site was stable and reached from -1.9°C at a

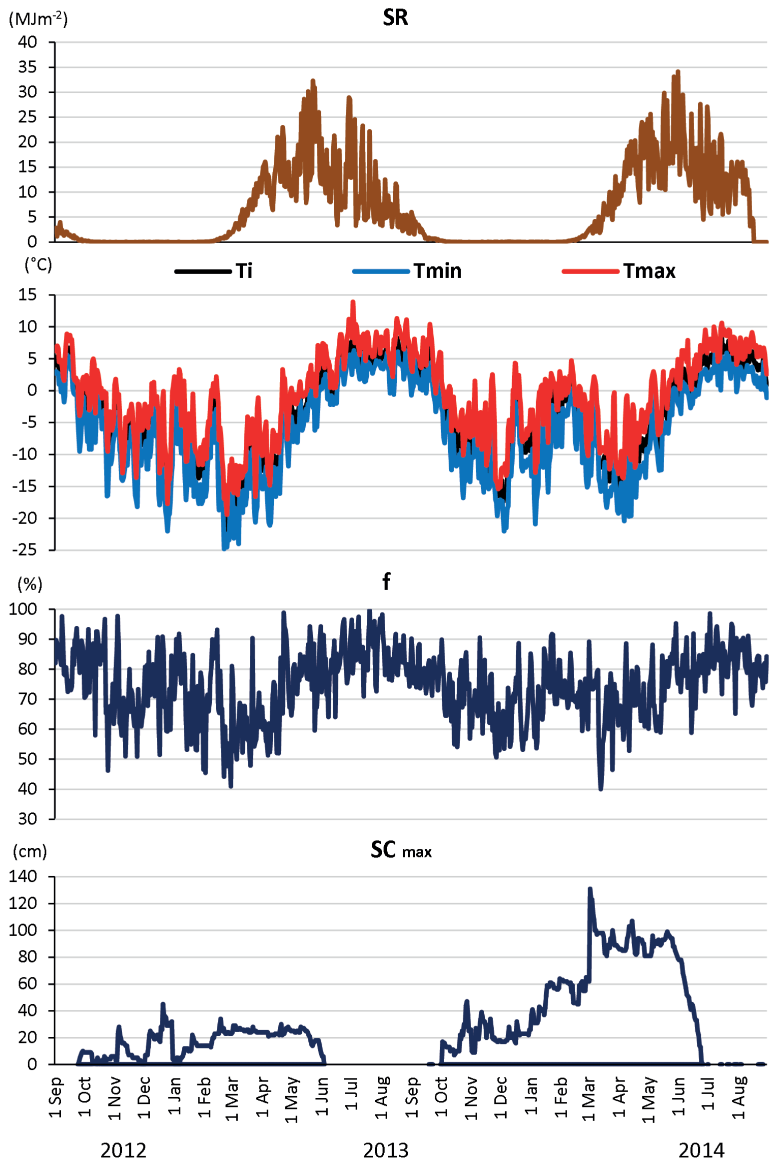


Fig. 3. Courses of selected meteorological elements at Ny-Ålesund in the period from 1 September 2012 to 31 August 2014 (abbreviations explained in Table 1)

depth of 1 cm to -1.8°C at 50 cm and 100 cm. In tundra, the values reached from -1.7°C to -1.9°C, whereas on the moraine these were from -3.0°C to -2.9°C (Table 2). Despite the substantial seasonal variability, the mean values determined for the whole range of analysed depths were comparable.

The mean monthly values of ground temperature at the analysed sites were positive across the tundra and moraine profiles from July to September, but only in August and September on the beach. At a depth of 1 cm b.g.l., the coldest month of the whole analysed period on the beach and in the tundra was December (-7.5°C and -6.7°C, respectively) and on the moraine it was March (-12.0°C). At greater depths, down to 20 cm b.g.l., similar correlations were observed in the annual course. At the depths of 50 cm and 100 cm b.g.l., the coldest month (on average) on the beach and in the tundra was April (-5.7°C and -4.8°C, and -5.6°C and -5.1°C, respectively). On the moraine, the coldest month was March (-11.1°C at 50 cm and -10.3°C at 100 cm b.g.l.). The warmest month at all the three sites (down to 20 cm b.g.l.) was July, when the mean monthly temperatures at 1 cm b.g.l. were 8.1°C (beach), 7.6°C (moraine) and 7.3°C (tundra).

By comparing the values of ground temperature in the analysed ecotopes, it was found that the highest mean temperature at 1 cm b.g.l. was on the beach and on the moraine (Table 1, Fig. 4), whereas the highest mean monthly values at 50 cm and 100 cm b.g.l. were determined for the beach and tundra in August (3.7°C and 0.5°C, and 4.2°C and 2.0°C, respectively). In the annual course, the highest temperature at the depth of 50 cm on the moraine was recorded in July (5.7°C), and at 100 cm b.g.l. in August (4.6°C). At intermediate depths, the above-described delay of occurrence of maximum and minimum values of ground temperature, proportional to depth, is consistent with the Fourier's third law.

The thermal stratification of the ground changes during the year (Table 2). All the sites in the winter season, when there is no solar radiation, have the lowest values of temperature at the surface layers. At that time, the greatest mean temperature difference (3.4°C) across the 100 cm profile was found for the beach site, and the smallest (2.1°C) for the moraine. In summer, an insolation pattern was observed in the analysed ecotopes. The greatest mean temperature difference between the depths of 1 cm and 100 cm across the profile occurred on the beach (6.4°C), whereas the smallest difference was found at the moraine site (3.6°C).

Table 2. Mean seasonal values of ground temperature (°C) in the Kaffiøyra region in autumn (Sep–Oct), winter (Nov–Mar), spring (Apr–May), and summer (Jun–Aug), and in the period from September 2012 to August 2014

| Sites | Depth | Autumn | Winter | Spring | Summer | Sep 2012 – Aug 2014 |
|---|---|---|---|---|---|---|
| Beach | 1cm | -0.9 | -6.1 | -4.6 | 6.2 | -1.9 |
| | 5cm | -0.7 | -6.0 | -4.6 | 5.8 | -1.9 |
| | 10cm | -0.5 | -5.8 | -4.6 | 5.4 | -1.9 |
| | 20cm | -0.1 | -5.4 | -4.6 | 4.5 | -1.9 |
| | 50cm | 0.4 | -4.2 | -4.4 | 2.2 | -1.8 |
| | 100cm | 0.1 | -2.7 | -4.1 | -0.2 | -1.8 |
| Tundra | 1cm | -0.5 | -5.8 | -4.6 | 5.5 | -1.9 |
| | 5cm | -0.4 | -5.6 | -4.6 | 5.2 | -1.9 |
| | 10cm | -0.2 | -5.5 | -4.6 | 4.8 | -1.9 |
| | 20cm | 0.1 | -5.1 | -4.5 | 4.3 | -1.8 |
| | 50cm | 0.6 | -4.3 | -4.5 | 2.7 | -1.7 |
| | 100cm | 0.5 | -3.3 | -4.4 | 0.6 | -1.9 |
| Moraine | 1cm | -0.5 | -9.3 | -3.8 | 6.4 | -3.0 |
| | 5cm | -0.2 | -9.1 | -3.8 | 6.2 | -2.9 |
| | 10cm | 0.1 | -8.9 | -4.0 | 6.0 | -2.9 |
| | 20cm | 0.3 | -8.8 | -4.2 | 5.5 | -2.9 |
| | 50cm | 1.0 | -8.2 | -4.6 | 4.3 | -2.9 |
| | 100cm | 1.2 | -7.2 | -5.0 | 2.8 | -2.9 |

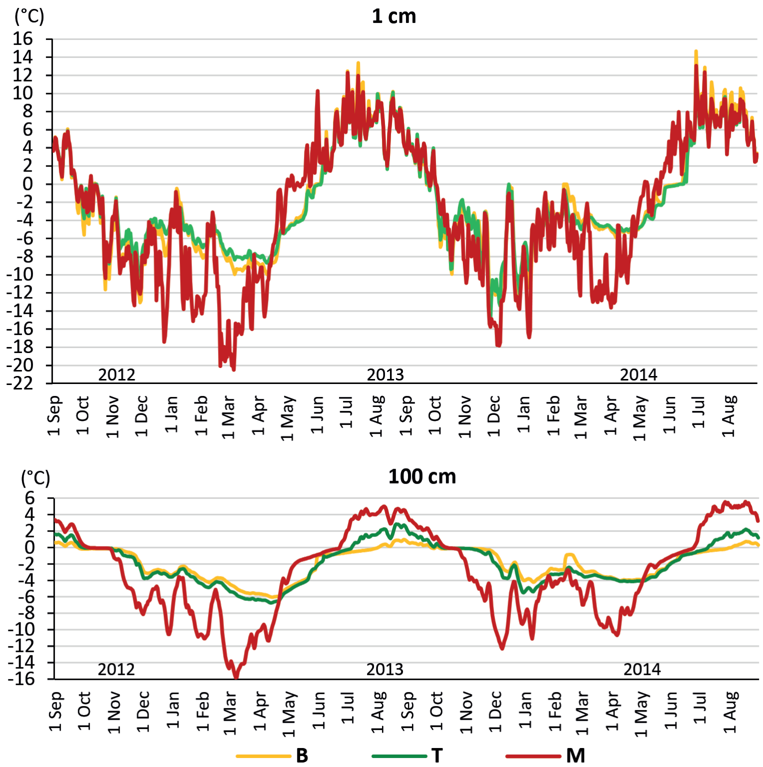


Fig. 4. The courses of ground temperature (°C) at 1 cm and 100 cm b.g.l. on the beach (B), in the tundra (T) and on the moraine (M) in the period from 1 September 2012 to 31 August 2014

In accordance to Fourier's second law, mean annual amplitudes of ground temperature decrease with depth (1 cm to 100 cm) at all the sites. The following decreases were observed: from 15.7°C to 5.3°C on the beach, from 14.0°C to 7.1°C in the tundra, and from 19.5°C to 14.9°C on the moraine.

Figure 4 shows the courses of ground temperature at two depths (1 cm and 100 cm) in the analysed period. The ground layer at 1 cm undergoes changes in temperature the most, both in the annual cycle and day-to-day variability. Substantial temperature fluctuations in this layer are due to a rapid exchange of heat between the ground and the air. On the other hand, the ground temperature at the deepest layers (e.g. 100 cm b.g.l.) is clearly affected by the depth of the permafrost table. Long-term observations show that at the end of the summer season the active layer is thickest on the moraine, reaching more than 2 m, whereas on the beach the ground thaws to only a little deeper than 1 m (Araźny and Grześ 2000; Sobota and Nowak 2014; Araźny et al. 2016). The measurements taken in the years 2012–2014 confirm these correlations. The mean maximum depths of thaw measured on the beach, on the moraine and in the tundra were 133 cm, 156 cm and 231 cm, respectively (Sobota, pers. comm.).

The annual courses of ground temperature at the three Kaffiøyra sites (for the 100 cm profile) are presented as thermo-isopleths in Figure 5. From May to September, on average, the insolation type of ground temperature distribution prevailed at all the sites (from April in the case of the moraine site), that is to say, the values decreased as the depth increased. On the other hand, from October to March the situation was quite the opposite and an inversion was observed at the time, with the deepest layers being the warmest. The heat flux changes its direction from winter to summer in April/May, and from summer to winter at the end of September and the beginning of October.

The mean diurnal ground temperature at 1 cm b.g.l. was found to be the most variable (Figs 4 and 5). In the analysed period, a standard deviation of

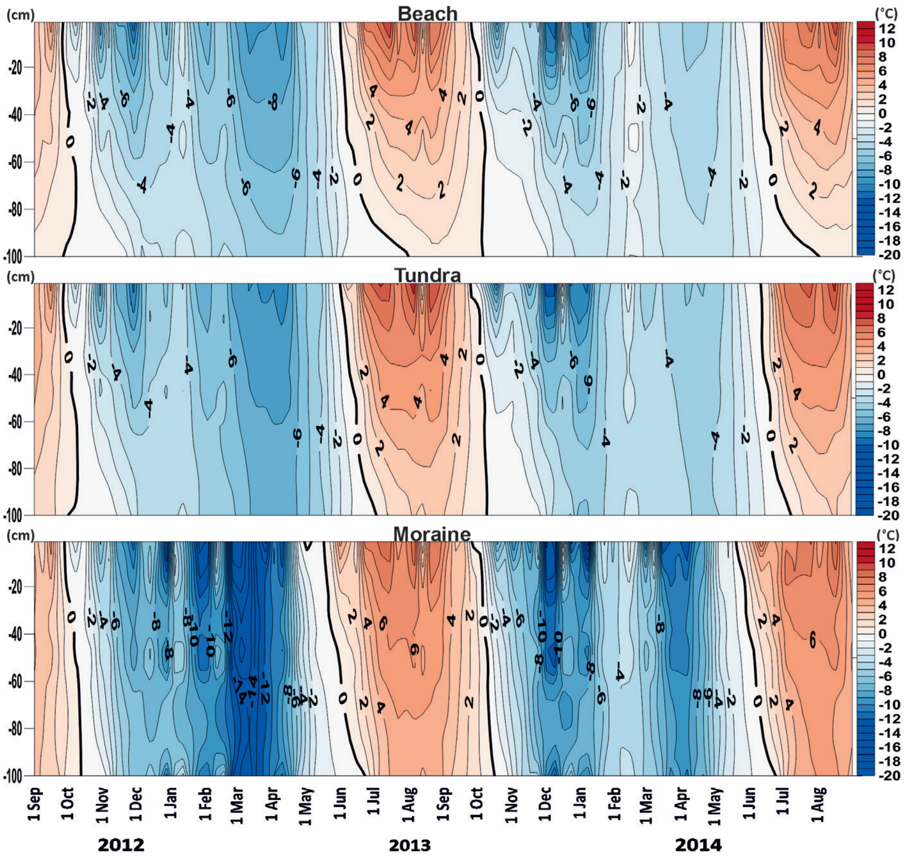


Fig. 5. Thermo-isopleths of the ground temperature (°C) on the beach, in the tundra and on the moraine in the period from 1 September 2012 to 31 August 2014

temperature was the greatest (7.6°C) on the moraine and the smallest (5.5°C) in the tundra. The values of standard deviation decreased with the depth of the measurement profile and, for example, on the beach they dropped from 6.0°C per 1 cm to 1.9°C per 100 cm. Comparing two extreme seasons – summer and winter – it was found that in the subsurface layer of the ground (to 20 cm b.g.l.) diurnal means tend to vary more at the beach and the tundra sites in summer. Considerable fluctuations of the mean diurnal ground temperature in summer are influenced by the radiation type of weather (strong warming of the surface during the day and subsequent cooling at 'night'). On the moraine, on the other hand, diurnal means are more variable across the profile in winter than in summer. This may be a result of the temporary presence or absence of snow cover (Araźny and Grześ 2000).

The direction and quantity of the heat flow in the three analysed profiles are presented using vertical gradients of mean monthly ground temperature (Fig. 6). The values of mean monthly vertical gradients change in an annual course. In summer, the biggest drops in temperature with depth were observed. For the three analysed sites, the greatest gradients were noted on the beach and in the tundra in July (-0.86/10 cm and -0.66/10 cm, respectively), and in June on the moraine (-0.53°C/10 cm). In July 2013 and 2014, the gradients were even greater in the top layer of the ground (1 cm – 50 cm) and exceeded -1°C/10 cm on the beach. This results from two things: the beach has the highest degree of dryness at that ground depth among the three sites (dry ground conducts heat less) and the shallowest permafrost table, which has a cooling effect (Araźny and Grześ 2000; Araźny et al. 2016). The opposite was observed in the winter season: the deeper layers were warmer. The greatest mean values of the gradient were noted in November on the beach, in the tundra and on the moraine (0.64°C/10 cm, 0.55°C/10 cm and 0.41°C/10 cm, respectively). In the transitional months and seasons, the gradients were the smallest (Fig. 6). For example, in April of 2013 and 2014 the gradient in the following layers: 1 cm – 50 cm, 50 cm – 100 cm and 1 cm – 100 cm was quite small at all the sites and the same across the profile: 0.2°C/10 cm, 0.1°C/10 cm and 0.0°C/10 cm on the beach, in the tundra and on the moraine, respectively. A homothermy develops in these seasons.

## Diurnal course of ground temperature

The diurnal courses of ground temperature at the three analysed sites for selected months (January and July) and for the whole year are shown in Figure 7. In the winter season, of which January is representative, a very stable diurnal course of temperature was observed at all six levels of measurement at the beach, moraine, and tundra sites.

In July, in polar day conditions, the mean diurnal course of ground temperature in all ecotopes analysed in the area of Kaffiøyra is correlated with the variability of the radiation balance, revealing its maximum in midday hours in the surface lay-

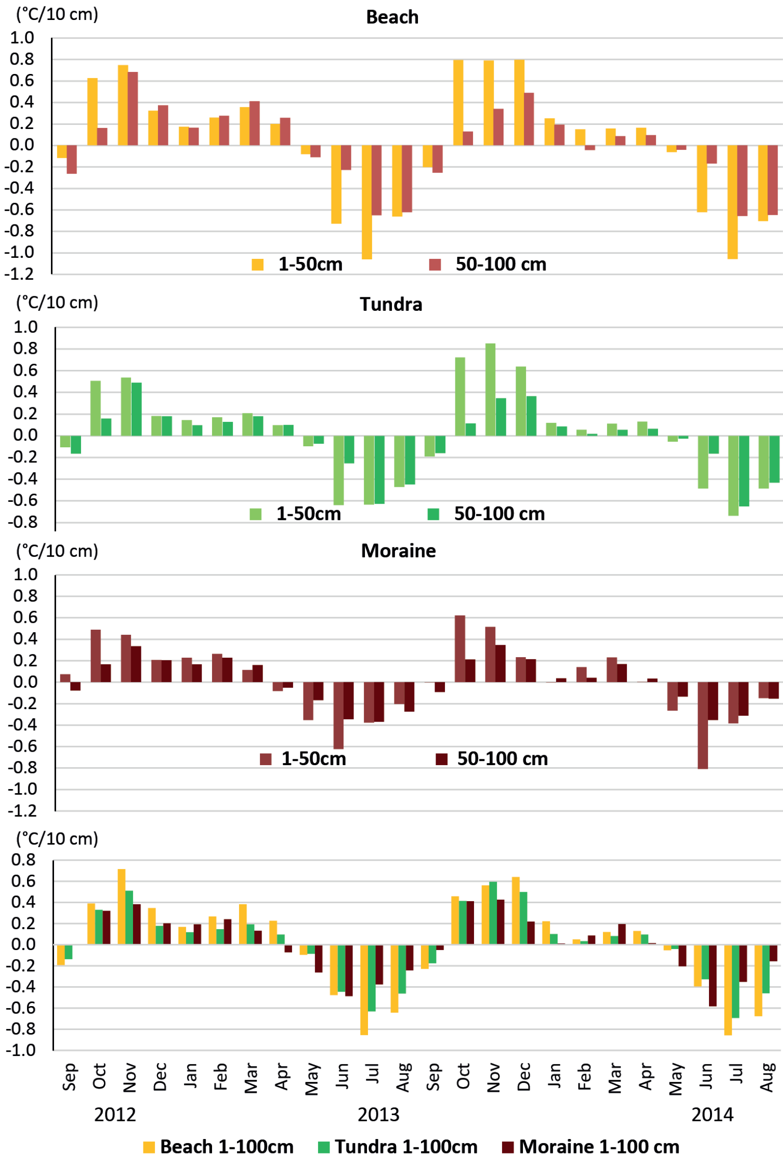


Fig. 6. Vertical gradients of ground temperature (°C/10 cm) on the beach, in the tundra and on the moraine in the period from 1 September 2012 to 31 August 2014

er of the ground. In the active layer, at a depth of 1 cm b.g.l., the mean diurnal amplitudes are greatest (4.1°C) on the beach and smallest (3.5°C) in the tundra and on the moraine. The maximum values occur at 12:00–13:00 UTC and the minimum values at 0:00–03:00 UTC (Fig. 7). As the solar elevation angle increased, the diurnal course became more regular. The mean diurnal amplitudes decreased in three of the analysed profiles. At the beach site, for example, at the depths from 1 cm to 100 cm b.g.l. they were: 4.1°C (at 1 cm), 3.2°C (at 5 cm), 2.3°C (at 10 cm), 1.2°C (at 20 cm), 0.2°C (at 50 cm) and 0.0°C (at 100 cm).

Throughout the whole period of measurement, the ground temperature at a depth of 1 cm had the greatest mean diurnal amplitude (1.9°C) on the moraine, but was nearly twice lower at the other two sites, the tundra and the beach (1.1°C and 1.2°C). At lower depths, the amplitudes decreased until a complete disappearance at 50 cm to 100 cm b.g.l. on the beach and in the tundra, and at 100 cm b.g.l. on the moraine (Fig. 7).

The highest ground temperature (21.5°C) was observed at 1 cm b.g.l. at the beach site at 13:00 UTC on 8 July 2014 when radiation weather prevailed. At that time the temperatures recorded on the moraine and in the tundra were 19.6°C and 17.8°C, respectively. In the another site in Spitsbergen (Petuniabukta) the ground surface temperature reached up to 26.5°C (Laska et al. 2012). Diurnal amplitudes in the active layer at all the three sites in Kaffiøyra were high on 8 July 2014 (13.5°C–13.1°C). For example, at 20 cm b.g.l. the time of occurrence of the maximum temperature values (11.4°C on the moraine, 10.2°C on the beach and 9.2°C in the tundra) was shifted by 4 hours. On that day, the temperature at 100 cm b.g.l. was stable and its amplitudes were small: from 0.0°C on the beach, through 0.1°C in the tundra, to 0.3°C on the moraine.

Figure 8 presents vertical ground temperature profiles for selected times of observation (0:00 UTC, 6:00 UTC, 12:00 UTC and 18:00 UTC) at the three sites for January, July and the whole year. In January, on average, at all the times the temperature increased with depth. The mean vertical gradient was the biggest (0.19°C/10 cm) on the beach, and at the other two sites it was smaller (0.11°C/10 cm). In July, an insolation-type temperature distribution was clearly observed in all three ecotopes at 6:00 UTC and 12:00 UTC. At midday, it was most evident on the beach (-1.06°C/10 cm) and least on the moraine (-0.55°C/10 cm). In July, the radiation-insolation type occurred at 0:00 UTC and 18:00 UTC. Throughout the year, the mean gradient at all three sites at the depths from 50 cm to 100 cm is close to zero. At 12:00 UTC, at the top part of the profiles the observed ground temperature distribution at all the sites is of the insolation type and, for example, on the moraine the gradient was -0.10°C/10 cm. At 6:00 UTC, the insolation-radiation type was recognised, at 0:00 UTC it was the radiation type and at 18:00 UTC the radiation-insolation type (Fig. 8).

## Dependence of ground temperature on meteorological factors

The dependence of ground temperature on meteorological factors was determined by calculating the values of the Pearson linear correlation coefficient (r) for the beach site. The ground temperature series at all depths were found to be strongly correlated. At the beach site, the Pearson correlation coefficients ranged from 1.00 to 0.64 at the different levels (Table 3) and all were statistically significant.

To a large extent, the thermal conditions of the ground depends on the amount of incoming solar radiation, particularly during the polar day, and on the amount of heat lost through outgoing long-wave radiation.

There were statistically significant values of correlation coefficients of ground temperature with the total solar radiation in the analysed period. The greatest influence of solar radiation (r=0.67–0.42) was observed in autumn at the depths of 1–20 cm b.g.l. (Table 4). Surprisingly, there was no correlation between the analysed summer series (Table 4), which must be due to the persistence of snow cover in June. Only after the snow melted did the ground temperature start to increase as more solar radiation reached the surface in July and August; then the respective correlation coefficients were quite high (r=0.35–0.31).

In the analysed period, the air temperature revealed the strongest connection with ground temperature (Table 4). For the temperature series

Table 3. Pearson linear correlation coefficients between the values of the mean daily ground temperature (GTi) at the beach at 1 cm, 5 cm, 10 cm, 20 cm, 50 cm and 100 cm b.g.l. in the period from 1 September 2012 to 31 August 2014

| Variable | GTi | GTi | GTi | GTi | GTi |
|---|---|---|---|---|---|
| | 5 cm | 10 cm | 20 cm | 50 cm | 100 cm |
| GTi 1 cm | 1.00 | 1.00 | 0.98 | 0.91 | 0.64 |
| GTi 5 cm | | 1.00 | 0.99 | 0.92 | 0.66 |
| GTi 10 cm | | | 1.00 | 0.94 | 0.68 |
| GTi 20 cm | | | | 0.96 | 0.72 |
| GTi 50 cm | | | | | 0.86 |

Note: All correlation coefficients are statistically significant at the 0.05 level

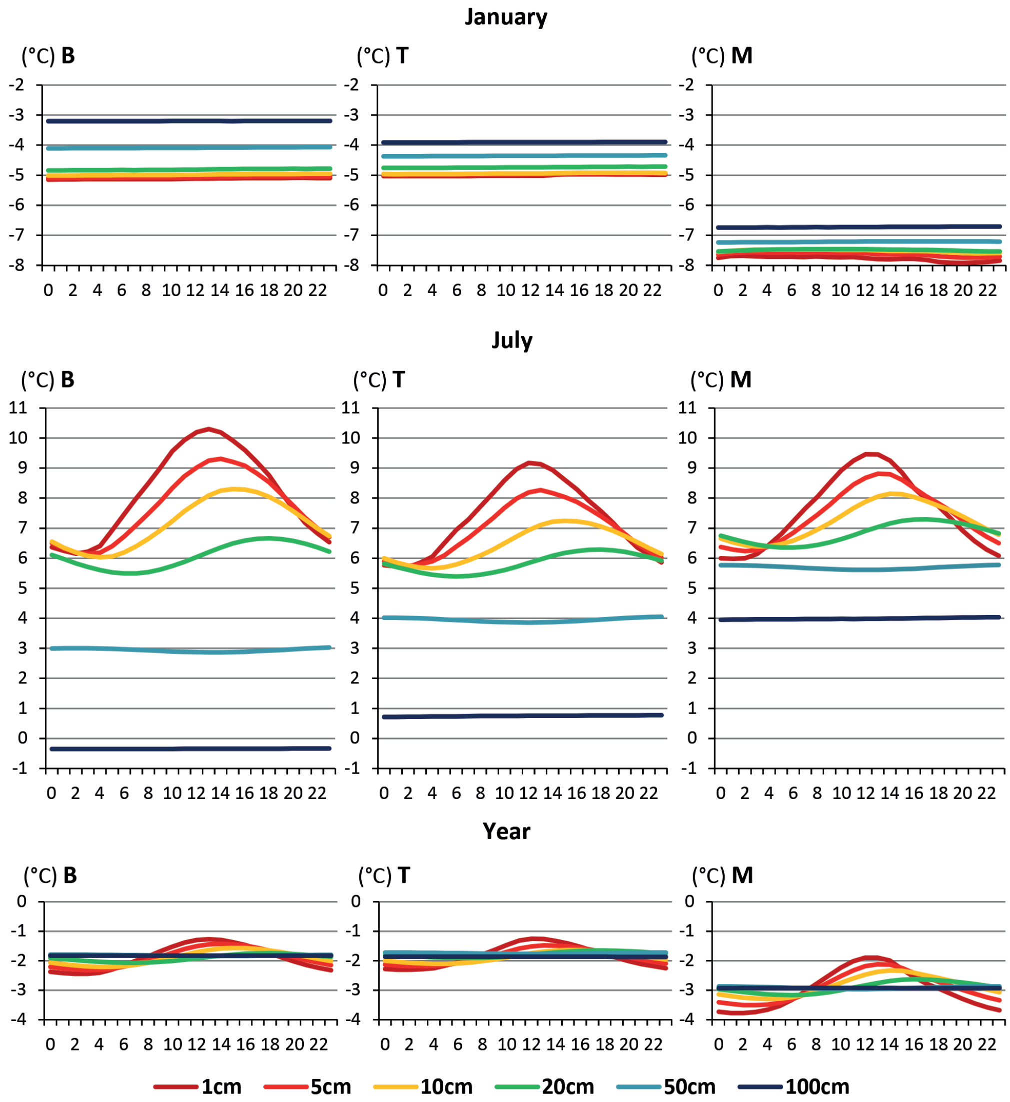


Fig. 7. Mean diurnal course of ground temperature (°C) on the beach (B), in the tundra (T) and on the moraine (M) in the period from 1 September 2012 to 31 August 2014 in selected months (January and July) and throughout the year (2012–2014)

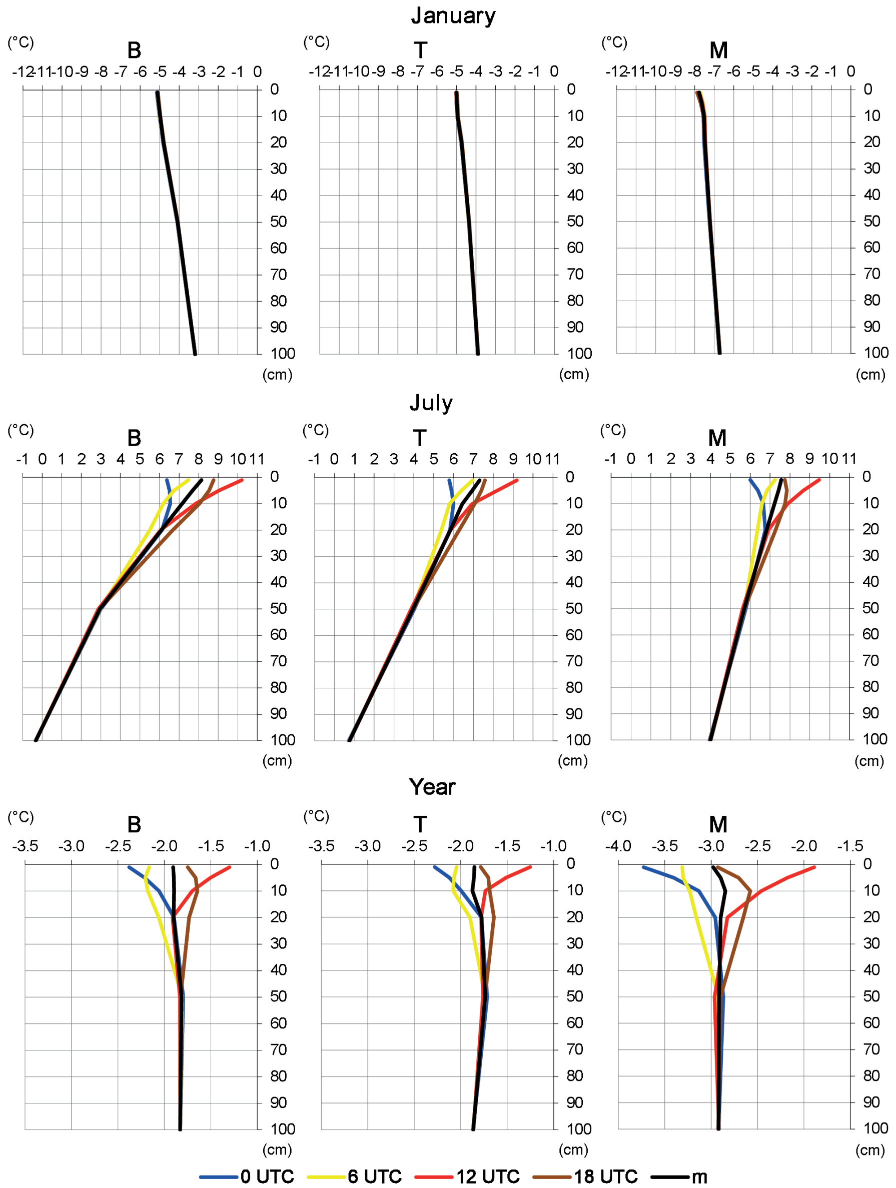


Fig. 8. Mean vertical gradients of ground temperature (°C/10 cm) on the beach (B), in the tundra (T) and on the moraine (M) at the main times of observation (0:00, 6:00, 12:00 and 18:00 UTC), and the diurnal means (m) for January, July and throughout the year (2012–2014)

at the subsurface layers of the ground (to 20 cm b.g.l.) and for the air temperature parameters (Ti, Tmin and Tmax), the Pearson linear correlation coefficients in all seasons exceeded 0.5. Their highest values were observed in summer and autumn (0.90–0.68), whereas the lowest correlations were found in winter (r=0.60–0.51). All the correlations between ground and air temperature were statistically significant at $p<0.05$.

Snow cover is an important factor which isolates the ground surface in polar regions from external influences. In the subsurface layers, the greatest correlations (r=0.40–0.26) between the snow cover thickness and the ground temperature were observed, as expected, in winter and spring – the seasons when snow persists on the ground. Thicker snow layers reduce the amount of heat lost by the ground.

The relative humidity of the air also revealed statistically significant correlations with the ground temperature at $p<0.05$ (Table 4). Their correlation coefficients were the highest in spring and

Table 4. Pearson correlation coefficients between the values of mean daily ground temperature (GTi) on the beach (at 1 cm, 5 cm, 10 cm, 20 cm, 50 cm and 100 cm b.g.l.) and mean daily values of selected meteorological elements at Ny-Ålesund in the period from 1 September 2012 to 31 August 2014

| Seaon | Variable | GTi | GTi | GTi | GTi | GTi | GT |
|---|---|---|---|---|---|---|---|
| | | 1 cm | 5 cm | 10 cm | 20 cm | 50 cm | 100 cm |
| Winter | SR | **-0.10** | -0.12 | -0.14 | -0.18 | -0.34 | -0.52 |
| | SC | 0.40 | 0.39 | 0.38 | 0.37 | 0.26 | -0.14 |
| | Ti | 0.57 | 0.55 | 0.54 | 0.51 | 0.40 | 0.19 |
| | Tmin | 0.56 | 0.55 | 0.54 | 0.52 | 0.42 | 0.22 |
| | Tmax | 0.60 | 0.59 | 0.57 | 0.54 | 0.41 | 0.17 |
| | f | 0.43 | 0.42 | 0.40 | 0.37 | 0.24 | **0.08** |
| Spring | SR | 0.43 | 0.43 | 0.43 | 0.42 | 0.38 | 0.33 |
| | SC | 0.26 | 0.26 | 0.27 | 0.29 | 0.36 | 0.53 |
| | Ti | 0.70 | 0.69 | 0.69 | 0.67 | 0.60 | 0.46 |
| | Tmin | 0.72 | 0.72 | 0.71 | 0.69 | 0.62 | 0.48 |
| | Tmax | 0.71 | 0.70 | 0.69 | 0.67 | 0.61 | 0.48 |
| | f | 0.52 | 0.51 | 0.50 | 0.49 | 0.44 | 0.34 |
| Summer | SR | -0.16 | -0.19 | -0.22 | -0.28 | -0.46 | -0.64 |
| | SC | -0.60 | -0.62 | -0.63 | -0.64 | -0.58 | -0.58 |
| | Ti | 0.75 | 0.76 | 0.77 | 0.77 | 0.60 | 0.39 |
| | Tmin | 0.71 | 0.73 | 0.75 | 0.76 | 0.61 | 0.40 |
| | Tmax | 0.66 | 0.68 | 0.68 | 0.68 | 0.52 | 0.33 |
| | f | 0.21 | 0.23 | 0.24 | 0.26 | 0.20 | **0.05** |
| Autumn | SR | 0.66 | 0.66 | 0.66 | 0.67 | 0.68 | 0.83 |
| | SC | -0.49 | -0.51 | -0.52 | -0.53 | -0.51 | -0.49 |
| | Ti | 0.90 | 0.89 | 0.89 | 0.87 | 0.81 | 0.70 |
| | Tmin | 0.90 | 0.89 | 0.89 | 0.88 | 0.81 | 0.71 |
| | Tmax | 0.89 | 0.89 | 0.88 | 0.87 | 0.82 | 0.70 |
| | f | 0.56 | 0.54 | 0.52 | 0.49 | 0.43 | 0.27 |

Keys: not statistically significant correlation coefficients on level $p < 0.05$ marked bold

autumn and, for example, ranged from 0.56 to 0.49 in the depth profile of 1 cm to 20 cm b.g.l.

## Summary and conclusions

This article presents the results of ground temperature measurements taken on a beach, on a moraine and in tundra in the area of Kaffiøyra (Spitsbergen) from 1 September 2012 to 31 August 2014.

The mean ground temperatures at all depths of measurement were higher than the air temperature (by approx. 0.6°C on the moraine, and 1.6°C on the beach and in the tundra). The differences are due in the first place to the thermal properties of the ground in the analysed ecotopes, and its heat capacity and conductivity. Snow cover also plays an important role, insulating the ground from the cold; therefore the lowest temperatures were observed on the moraine, which is not covered by snow for the most of the year as high winds drive the snow away (Araźny and Grześ 2000). On the other hand, the thermal regime of the lower sites on the beach and in the tundra was found to be similar throughout nearly the whole year.

The thermal conditions of the ground in the analysed profiles, especially in the deepest layers of the ground, are also affected by the depth of permafrost. At the end of summer, its active layer was thickest on the moraine (>2 m) and thinnest on the beach (just over 1 m) (Sobota and Nowak 2014; Araźny et al. 2016).

In an annual course, from May to September, the insolation type of ground temperature distribution was ascertained at all the sites (on the moraine it appeared even earlier – in April). From October to March the radiation type was observed. The heat flux changed its direction from winter to summer in April/May, and changed back at the end of September or the beginning of October.

The ground temperature at the analysed sites revealed a clear diurnal cyclicality, particularly in the summer months; for example, in July the mean diurnal amplitudes in the active layer were highest on the beach (4.1°C), and lower in the tundra and on the moraine (3.5°C in each case). In the winter months (e.g. January), mean diurnal temperature changes did not occur due to a lack of solar radiation (polar night) and the persistence of snow cover.

In the upper depths of the analysed profiles (1 cm to 50 cm b.g.l.), the insolation type of ground temperature distribution was observed at 12:00 UTC, then the insolation-radiation type at 6:00 UTC, the radiation type at 0:00 UTC and the radiation-insolation type at 18:00 UTC. On average, in the lower layers of the ground (50 cm to 100 cm b.g.l.), the mean gradient at all the three sites was close to zero.

The ground temperature series at the three sites and at all depths are very strongly correlated. Very strong and statistically significant correlations were also found between diurnal series of ground temperature at all measuring depths and air temperature characteristics (Ti, Tmin and Tmax). At the subsurface layer (to 20 cm b.g.l.), the highest correlation coefficients were determined for summer and autumn (0.90–0.68). On the ground surface, strong correlations (r=0.40–0.26) were also observed between the ground temperature and the thickness of snow cover, when it occurred, i.e. in the winter and spring seasons. Positive correlations were also ascertained with solar radiation.

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