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Variability of temperature and thickness of permafrost active layer at coastal sites of Svalbard

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Abstract: We present the variability of the thermal state and thickness of permafrost active layer at the raised marine beaches in Svalbard. The investigations were carried out using direct probing, thaw tube, ground temperature and radar soundings at Holocene strand plains 10–20 m a.s.l. in Fuglebergsletta (SW Spitsbergen) and at the shore of Kinnvika Bay (Nordaustlandet). Their results were compared to those obtained at other coastal sites in Svalbard. The ground temperature measurements were conducted in 2009 on August, recognized as the standard month for the maximum thawing during the last decade. The studied sites are typical for close to extreme active layer conditions on Svalbard. In Hornsund, the thawing depth exceeded 2 m, while in Kinnvika the active layer was thinner than 1 m. In Svalbard, the depth of thawing decreases generally from south to north and from the open sea coast to the central parts of islands. These differences are the consequence of diverse climatic conditions strongly determined by the radiation balance modified by a number of regional (*e.g.* ocean circulation) and local (*e.g.* duration of snow deposition) conditions.

Key words: Arctic, Spitsbergen, Nordaustlandet, active layer, ground penetrating radar, permafrost.

Introduction

Permafrost defined as the ground at sub-zero temperature during at least a two-year period (French 2007) reflects the past as well as present climatic condi-

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tions. The outer ground layer is a subject of seasonal thawing producing the so-called active layer of permafrost. The present evolution of permafrost is associated with observed climatic changes. The trend of active layer thickening in the last decade (Christiansen *et al.* 2005) has accelerated intensity of geomorphologic processes in the periglacial zone. Widely studied processes of basins desiccation (Smith *et al.* 2005; Smol and Douglas 2007), groundwater drainage (Haldersen and Heim 1999; Haldersen *et al.* 2010; Walvoord and Striegel 2007) and shoreline erosion (Etzelmüller *et al.* 2003; Zagórski 2011) are strongly related to permafrost conditions. Geological investigations and engineering works aiming at prospecting mineral resources (Humlum *et al.* 2003) are also carried out in respect to permafrost aspects.

The Svalbard Archipelago is located generally in the zone of continuous permafrost except for areas below glaciers at pressure melting point temperature (Liestøl 1976). The unglaciated area (27 200 km²) is characterized by spatially variable permafrost and the active layer thickness. Permafrost reaches the depth of 100 m in the coastal zone, whereas in the highly elevated interior it exceeds 500 m (Humlum 2005). The thickness of permafrost and its fluctuations are strictly correlated with thermal conditions of the ground. On the other hand, a thermal state of the ground depends on climatic factors determining the energy supply to the ground (Migała 1991).

The main objective of the paper is to depict the permafrost active layer properties of the raised beaches of Svalbard in the summer season. The most important factors determining the depth of permafrost thawing have been pointed out. The paper shows the results of the measurements of temperature and the active layer thickness in the northern and southern regions of Svalbard exemplified by Fuglebergsletta at the northern coast of Hornsund and the coastal accumulation plain at Kinnvika Bay (Nordaustlandet) and compare them with the data from other coastal sites on Svalbard.

Previous works on the thermal conditions of the active layer on Svalbard

The measurements of variability of thermal conditions of the ground and thickness of the active layer have been taken in several reference points in Svalbard, particularly in the vicinity of Ny-Ålesund, Sarkofagen (Kristensen 1988; Humlum 2005), Kapp Linnè 1,5 km NE from Isfjord Radio (Akerman 2005), sites in Adventdalen *e.g.* UNISCALM (Christiansen and Humlum 2008) and Janssonhaugen (Harris *et al.* 2009). The perennial investigations of the active layer have been carried out in Calypsostranda, at Recherchefjorden (Repelewska-Pękalowa 2004; Christiansen *et al.* 2005), where a significant increase of the active layer thickness has been observed over last years (in 2003 over 2 m; Kazimierz Pękala, per-

sonal communication 2003). Other sites of the active layer monitoring are located on Kaffiøyra (NW Svalbard), where the measurements started in 1975. Thereafter, the measurements of ground temperature had been performed for several summer seasons (Przybylak *et al.* 2010). The permafrost boreholes and ground temperature monitoring have also been carried out at Crednermorenen in the inner part of Van Mijenfjorden, Reindalen-Lunkefjellet, Brenoisa, Longyeardalen, Gruvafjellet and Colesdalen. Changes in permafrost and active layer temperatures in central Spitsbergen were modeled for 20th century and predicted for the next century by Etzelmüller *et al.* (2011). They depicted substantial warming of the ground since the end of the Little Ice Age by 1.5–2°C and possible permafrost degradation on low-lands. Most of the sites of the active layer discernment are included in the Circumpolar Active Layer Monitoring – CALM (Brown *et al.* 2000; www.gwu.edu/calm/) and the Norwegian Permafrost Database (Permafrost Observatory Project 2012; Christiansen *et al.* 2010).

Due to long-term permafrost observations in the vicinity of Hornsund, this region became an excellent testing area for permafrost research. The first data referring to the thermal state of the ground in Hornsund area were presented by Baranowski (1968). General characteristics of geomorphological processes driven by freezing of the ground in the discussed area are presented in Jahn (1983, 1988) and Grześ (1984). The influence of radiation on changes of the temperature in the active layer has been investigated by Głowicki (1985), Angiel (1994), and Leszkiewicz and Caputa (2004). These authors affirmed that the strongest correlation between total solar radiation and the ground temperature occurs in July. The influence of variable seasonal snow cover and its irregular decline on a specific temperature of the active layer in the ablation period was raised by Mięła (1991) and Dolnicki (2005). They discussed spatial relations between the thickness of the active layer, areas favorable for snow erosion/deposition and surface morphology. Miętus (1988) and Miętus and Filipiak (2001) presented long-term (1979–1999) analysis of the ground temperature in Hornsund based on the measurements obtained in the vicinity of the Polish Polar Station. They determined a positive tendency of the changes in the studied period, and using statistical methods estimated the maximum depth of thawing of the ground at -1.85 m. Marsz and Styszyńska (2013) supplemented the thermal characteristics of the active layer in Hornsund by 2000–2005, when the ground temperature insignificantly decreased. However, in the following seasons (2006–2009) the ground temperature decrease accelerated (Dolnicki 2010). In the period of 2007–2010, a set of geophysical surveys (vertical electroresistivity soundings, refraction seismics, radio-echo soundings) focused on permafrost properties were carried out (Dobiński 2011; Dobiński *et al.* 2011) at different environments of Hornsund area, including raised beaches, taluses, glaciers and its forefields. Basing on geophysical studies, Dobiński (2011) brought the occurrence of the permafrost on raised beach near the Polish Polar Station in Hornsund into question due to proximity of fiord water. At other sites, the exist-

tence of permafrost is undeniable. In glacier-forefield transition zone, the permafrost interacts with the glacier as the front recession favors permafrost aggradation and permafrost continues within the polythermal glacier as cold ice layer (Dobiński 2011; Dobiński *et al.* 2011). Properties of the permafrost active layer in the Western Nordaustlandet (Kinnvika) have not been investigated until now, hence the studies presented in this paper are unique in that respect.

Study area

The investigations, including radar soundings and measurements of the active layer thickness and ground temperature, were focused on the southern (Hornsund) and northern (Kinnvika) parts of Svalbard. The study sites are located on the elevation of *c.* 5–12 m a.s.l. in the zone of Holocene marine beaches. Fuglebergsletta plain is situated at the northern shore of Hornsund (77°00' N), in south-western Spitsbergen, while the marine plain at the Kinnvika Bay (80°03' N) is located in the western part of Nordaustlandet (Fig. 1). According to radiocarbon ¹⁴C dating, the lower parts of the terraces (up to 7–9 m a.s.l.) at both sites emerged above sea level after mid-Holocene transgression dated at 7000–4000 years BP (Chmal 1987; Forman *et al.* 2004). Raised terraces coincide with the Holocene climatic optimum with July temperature *c.* 2°C higher than at present (Briks 1991). Finally the spread of glaciation and permafrost aggradation on low-lying Svalbard areas was promoted by the late-Holocene cooling of the Atlantic sector of the Arctic with culmination during the Little Ice Age (Svendsen and Mangerud 1997). The mean annual air temperature over Svalbard in the late 19th and early 20th century was about 2.4°C lower than the average of 1912–1996 (van de Wal *et al.* 2002). As a result, the permafrost age on raised beaches is estimated at approximately 3000 BP, and the average aggradation rate was *c.* 3 cm/year (Humlum 2005). Although the post Little Ice Age warming of Svalbard at rate 0.23°C/decade for 1912–2010 (Humlum *et al.* 2011) resulted in warming the ground by 1.5–2°C (Etzelmüller *et al.* 2011), it did not interrupt the progressing aggradation of the permafrost (Humlum 2005).

Ground penetrating radar (GPR) profiles, as well as ground temperature control points were deployed in coastal tundra in both Hornsund and Kinnvika areas. According to Kuc (1996), the vicinity of the Polish Polar Station represents Coastal Flat-Land Vegetation Zone. About 80% of Fuglebergsletta Plain is covered with vegetation, mainly lichens (*c.* 50%) – predominant in dry tundra, mosses (*c.* 20%) – preferring wetter areas, and vascular plants (Grodzińska and Grodzik 1993; Kuc 1996). The surficial ground layer comprises a sand-gravel mixture with pebbles of diameter up to 0.1 m. The upper 0.2 m layer is formed of loose material.

The vegetation at Kinnvika Bay coastal zone is described as Arctic polar desert, as plant cover is sparse due to a short growth period and dry soil conditions (Cooper 2011). The total plant cover ranged between 1% at dry sites to full cover-

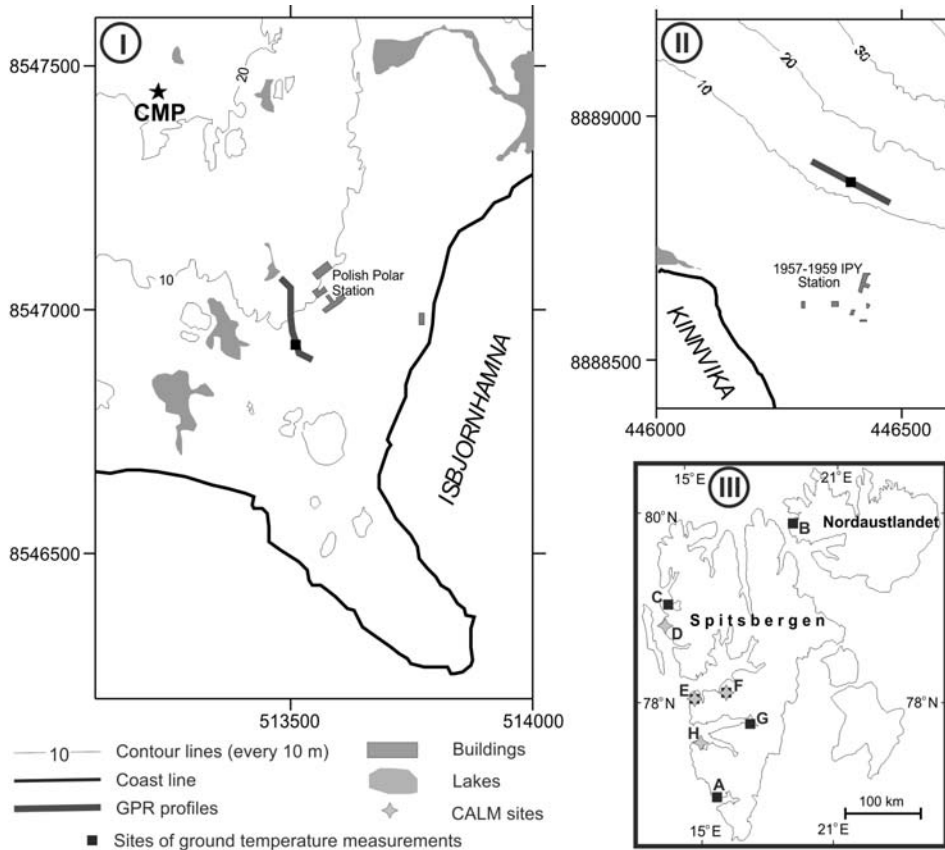


Fig. 1. Study area: I – area of Fuglebergsletta (CMP – site of common mid-point measurement); II – area of Kinnvika; III – overview map of Svalbard: A – Hornsund – Fuglebergsletta, B – Kinnvika, C – Ny-Ålesund (the Thermal State of Permafrost (TSP) ID: NA-B-1), D – Kaffiøyra, E – Kapp Linnè (TSP ID: KL-B-2), F – UNISCALM (TSP ID: TINY-23), G – Svea (TSP ID: SV-B-5), H – Calypso-stranda. Maps I and II datum and coordinate system WGS84, UTM 33X.

age under bird cliffs and in moist areas (Cooper 2011). At the site *c.* 400 m SW from the permafrost measurement area, Cooper (2011) calculated 24% of vegetation coverage with a dominant cyanobacterial crust (17%) and vascular plants (6%). The direct observations at our study site were consistent with the vegetation described above. Non-layered pebbles with a diameter less than 0.3 m occur up to the depth of 0.9 m. The lithological structure of the ground is homogeneous.

In summer, the most energy supplied to the ground surface in Svalbard is delivered by solar radiation (Vowinckel and Orvig 1970). The spatial variability of incoming solar radiation in summer is determined mainly by the incidence angle of solar beam (decreasing towards the North) and cloudiness. Comparing Hornsund and Ny-Ålesund (1989–2003), the average sums of short-wave solar radiation in June and August amounted to 769 and 718 MJm⁻² respectively (Marsz and

Styszyńska 2013; Budzik 2004). At Isfjord Radio, in 1951–1960, the July–August sum of short-wave radiation was 703 MJm^{-2} (Markin 1975). As in all the cases the average cloudiness was almost the same, numbering 6.4 to 6.5 octants (Marsz and Styszyńska 2013), hence the differences may be explained through changes of latitudinally dependent incidence angle of solar beam. Due to the surface albedo, this energy is only partially consumed to heat up and thaw the ground layer. The albedo of the tundra covered surface on the coastal sites of Svalbard (Hornsund, Ny-Ålesund) in July and August ranges between 11% and 20% (Głowicki 1985; Budzik 2004; Budzik *et al.* 2009). The net long-wave radiation balance in summer is negative over Svalbard. The long-wave downward radiation is modified by atmospheric properties such as cloudiness, humidity and temperature, while the long-wave outgoing radiation is a function of the ground temperature. The average sum of net long-wave radiation in July and August 2008 at Ny-Ålesund amounted to -232 MJm^{-2} , whereas in Hornsund it was -239 MJm^{-2} (Budzik *et al.* 2009). The sum of the surface radiation balance in summer (July–August) at Svalbard is the sum of both the net short-wave and net long-wave radiations, and it is positive. The sums of July–August radiation balance in 2008 in Hornsund and Ny-Ålesund were 408 and 412 MJm^{-2} , respectively.

The elements of the radiation balance significantly influence the ground temperature. Leszkiewicz and Caputa (2004) found in Hornsund a strong correlation in summer between the ground temperature in the upper 0.2 m layer and the net short-wave radiation, with correlation coefficients $r > 0.6$. They also connect the net short-wave radiation to the maximum and minimum air temperature to obtain multiple regression models of the ground temperature. Up to -0.2 m, the determination coefficient of the regression models was $r^2 \geq 0.78$.

The strongest relations between the net short wave radiation and ground temperature, occur with few hours of temporal shift. In Hornsund, during the summer of 2006, the highest correlation coefficient ($r = 0.7$) at -0.05 m was recorded with a 3–4 h offset, at -0.1 m ($r = 0.6$) with a 6 h shift, at -0.2 m ($r = 0.6$) with an 8 h shift and at -0.5 m ($r = 0.3$) with a 12 h offset. A reverse of the heat flux direction in the active layer and decrease of air temperature in Hornsund area begin between 10 and 20 September (Dolnicki 2010), while in Kinnvika these processes occur in the second half of August.

The active layer development and thickness is significantly determined by the snow cover thickness and duration. According to Hagen *et al.* (1993), the annual precipitation sum on the western coast of Nordaustlandet is comparable to that on north-western Spitsbergen recorded by Ny-Ålesund meteorological station. Hornsund and Ny-Ålesund documented very similar average winter precipitation totals of 235 mm and 255 mm, respectively (Grabiec *et al.* 2011). In May 2003, the average snow thickness on Fuglebergsletta was measured at 0.55 m (Dolnicki 2005). Snow cover patches survived until 10–20 June in places of strong wind re-deposition. The active layer thickness was *c.* 0.6 m thinner than the average under-

neath a long-lingered snow cover (Dolnicki 2005). Despite the fact that winter snow accumulation on the southern and northern parts of Svalbard is similar to Nordaustlandet, the duration of the snow cover on the latter is longer due to much colder spring and summer conditions as well as earlier fall cooling.

The results obtained from the two basic sites described above are supplemented by the ground temperature data and thawing depths available for the same time from other coastal sites on Svalbard (Fig. 1). These sites are Svea, Kapp Linnè, UNISCALM and Ny-Ålesund. Short descriptions of all the sites included are set together in Table 1. Detailed information on particular locations is provided by the Norwegian Permafrost Database (Permafrost Observatory Project 2012).

The S-N angular distance between Hornsund and Kinnvika is *c.* 3° equaling to *c.* 350 km, what significantly determines differences in climatic conditions, *e.g.*

Table 1
Description of sites studied.

ID	Site name	Coordinates (Lat., Long.)	Elevation (m a.s.l)	Surface characteristics	Type of the active layer measurements	References
A	Hornsund	77.00°N 15.54°E	8	flat raised beach, sand-gravel deposits, tundra	temperature string, thaw tube, mechanical probing, GPR	Institute of Geophysics PAS database
B	Kinnvika	80.03°N 18.00°E	12	flat raised beach, non-layered pebbles, no vegetation	temperature string, mechanical probing, GPR	this work
C	Ny-Ålesund (TPS ID: NA-B-1)	78.92°N 11.93°E	46	plain, marine sediment, tundra	borehole temperature	Permafrost Observatory Project 2012
D	Kaffiøyra (CALM code: P2 A-C)	78.73°N 11.71°E	1-15	raised beaches and lateral moraine, marine (sand, gravel) and glacial (till) deposits, no vegetation or poor tundra	mechanical probing at fixed points (3 points)	CALM
E	Kapp Linnè (TSP ID: KL-B-2; CALM code: S1)	78.05°N 13.63°E	20	flat raised beaches, glaciomarine sediment, discontinuous vegetation	borehole temperature, mechanical probing in 100 m grid	Permafrost Observatory Project 2012; CALM
F	UNISCALM (TSP ID: TINY-23; CALM code: N3)	78.20°N 15.84°E	9	fat terrace-like loose deposit (laminated silty sand), dominant willow	borehole temperature	Permafrost Observatory Project 2012; CALM
G	Svea (TPS ID: SV-B-5)	77.88°N 16.80°E	20	top of moraine on the peninsula, till, 0.15 m ice lens in <i>c.</i> 2 m depth, no vegetation	borehole temperature	Permafrost Observatory Project 2012
H	Calypsostranda (CALM code: P1)	77.57°N 14.50°E	25	raised beach from flat to <i>c.</i> 15° slope, marine, fluvio-glacial and fluvial sediments, dominant lichen-moss tundra	mechanical probing at fixed points (23 points)	CALM

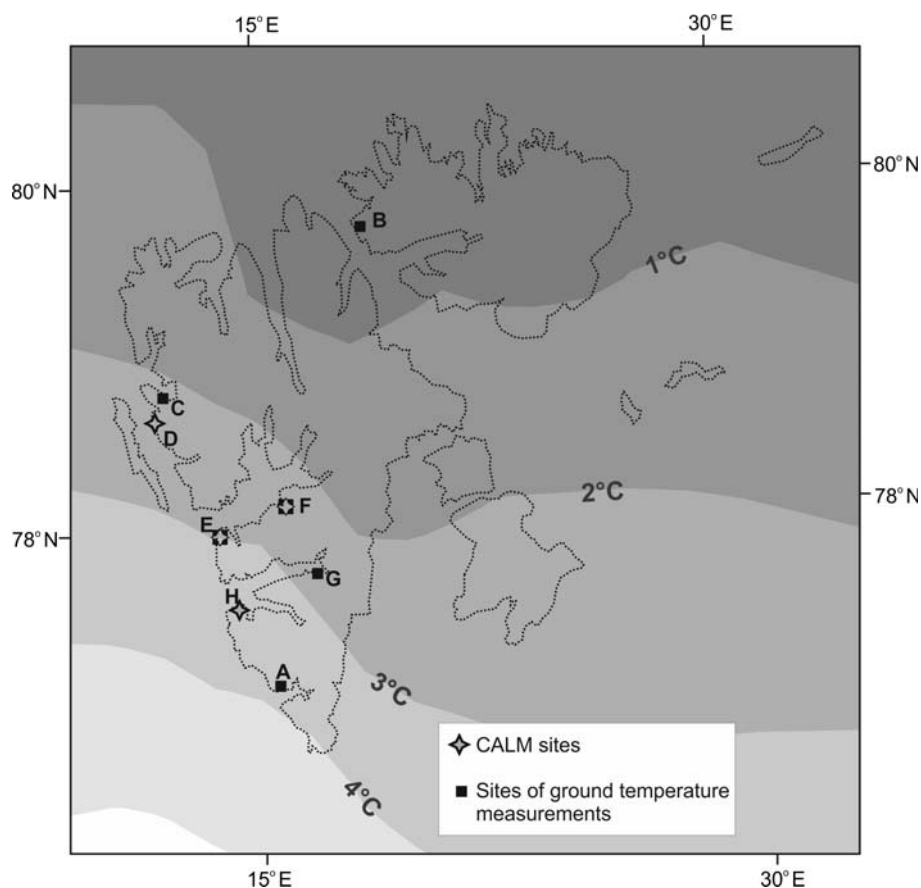


Fig. 2. Average air temperature of summer (July–September 1989–2010) on Svalbard based on ERA Interim re-analysis. Site symbols as on Fig. 1 and in Table 1.

temperature, incoming radiation, precipitation, the snow cover thickness and duration, and in consequence the active layer properties. The difference between the mean long-term temperature of summer seasons (July–September) in the studied areas is *c.* 3°C (Fig. 2).

Data and methods

Ground temperature in Hornsund was measured by mercury nodal thermometers at -0.05, -0.1, -0.2 and -0.5 m in three synoptic terms. Additionally, once a day at 12.00 at -1 m depth, the measurement was taken with an extractive thermometer. The results presented in this paper are daily average values. At Kinnvika, calibrated thermistors were pushed down at the depth of 0.0, -0.1, -0.3, -0.4, -0.5, -0.7 and -0.9 m. The temperature is presented as the daily mean averaged from hourly records.

The ground temperatures at Svea, Kapp Linnè, UNISCALM and Ny-Ålesund were also measured in vertical profiles at several levels. Detailed description of the survey method is provided by the Norwegian Permafrost Database (Permafrost Observatory Project 2012).

For most of the sites, the ground temperature monitoring has been carried out for a longer time (*e.g.* Hornsund since 1978, UNISCALM since 2006, Svea 2005–2009, Kapp Linnè since 2008), whereas at Kinnvika the measurements lasted only for five days in August 2009. Taking into consideration problems with stabilization of temperature records after installation, we assume that the most reliable results are related to 11 August 2009. In the next section of this paper, we discuss how one-day ground temperature data are typical for a longer period. Due to the pioneering character of the investigations at the western coast of Nordaustlandet, the results cannot be compared with long-term temperatures or other meteorological elements recorded at the analyzed area. Nevertheless, even these fragmentary data provide essential information.

The heat flux in the ground is induced mainly by thermal differences in the vertical profile. Basing on the ground temperature data, the daily average heat flux G [Wm^{-2}] was calculated by using Fourier equation:

$$G = -\lambda \frac{\Delta T}{\Delta x};$$

where λ [$\text{Wm}^{-1}\text{K}^{-1}$] is the thermal conductivity; ΔT [K] – the difference in temperature between the two ground levels; x [m] – the difference in the depth of the layers. In July 2006, on Fuglebergsletta, the heat flux in the ground layer was measured directly by Peltier plates extended between -0.1 m and -0.2 m. The soil thermal conductivity λ obtained from these measurements amounted to $0.9 \text{ Wm}^{-1}\text{K}^{-1}$, and in this work it was applied for computation of the heat flux in Hornsund area and Kinnvika. We assume that the heat transfer in the ground is largely controlled by the thermal conduction. The other methods of heat exchange through water motion, internal evaporation and condensation, changes of water phases *etc.* is less important (Putkonen 1998) and thus negligible in the calculations of the ground heat flux in this work. Three methods of the active layer investigation have been applied: direct soundings (Hornsund and Kinnvika), Danilin frost tube (thaw tube) measurements in Hornsund and radar soundings in both Hornsund and Kinnvika. Direct soundings were taken using a rod of 0.01 m diameter. The rod was inserted into the ground to the frozen level. The active layer depths were averaged from several point readings. The Danilin gauge is installed into the ground scaled rubber tube filled with pure water and outwardly sheltered by an ebonite tube (Golubev *et al.* 1969). The active layer thickness at Svea, Kapp Linnè, UNISCALM and Ny-Ålesund was interpolated from the ground temperature data in the vertical profile. Supplementary Circumpolar Active Layer Monitoring CALM dataset (<http://www.udel.edu/Geography/calm/data/north.html>) from coastal sites (Kapp

Linnè, UNISCALM, Calypsostranda and Kaffiøyra Plain) have also been used for comparison.

Radar soundings of the ground is a geophysical method of internal structure identification. Ground penetrating radar (GPR) system radiates electro-magnetic impulses of defined frequency into the ground through the transmitting antenna, while the receiving antenna gathers signals reflected from dielectric boundaries and other objects in the ground (Baker *et al.* 2007). The signal is recorded as a function of travel time to the object and back to the receiver. When the radio-wave velocity (RWV) in investigated material is known, the time record can be converted to the depth. Strongly contrasted dielectric properties of frozen and unfrozen, saturated sediments play crucial role in determining the active layer depth (Moorman *et al.* 2003).

The radio-echo sounding method has been applied in permafrost studies since the 70s of 20th century (Annan and Davis 1976). A wide set of GPR applications to periglacial studies was provided by Mühlh *et al.* (2002), Moorman *et al.* (2003) and Hauck and Kneisel (2008). The soundings have been carried out using the impulse radar system containing a control unit and 200MHz unshielded antennas. The transmitting and receiving antennas are linked with the control unit by optical fibers which assures undisturbed transmission of the signal. Settings and data recording are executed by PC connected with the control unit.

The internal structure of the ground was sounded by reflective GPR profiling. The common mid-point (CMP) measurement has been performed in order to determine the RWV in the ground (Baker *et al.* 2007). The GPR survey was completed in the autumn 2007 at Fuglebergsletta raised beach, see CMP location on Fig. 1. The velocity of a direct wave in the ground was determined at 0.102 m/ns. Afterwards, two reflections have been distinguished at the depth of 64 and 111 ns. The RWV between the ground surface and defined horizons were calculated at 0.102 and 0.108 m/ns, respectively. By the application of the resolved values of RWV, the depth of reflections was defined at 3.24 m and 5.8 m. An additional reflection can be specified above these boundaries, although velocity calculation was impossible due to superimposing of the direct waves. According to the foregoing analysis, the average RWV in the outer ground layer, containing the active layer, was adopted at 0.1 m/ns. This value was applied for time-to-depth conversion. The estimated RWV values demonstrate a relatively low water saturation of the active layer at the measuring point. The RWV of gravel-sand and clay layers recorded at the marine plains is assumed in the range of 0.06–0.09 m/ns for saturated sediments and 0.09–0.13 m/ns for dry sediments (Moorman *et al.* 2003; Neal 2004). Therefore, the RWV of 0.1 m/ns derived from the CMP may result for the depth being overestimated in the case of grounds more saturated than those at the investigated site. The vertical resolution of 200 MHz soundings, assumed as 1/4 of wavelength λ was calculated at 0.13 m.

A long-term (1990–2009) meteorological dataset for Hornsund (the Institute of Geophysics, Polish Academy of Sciences database, www.glacio-topoclim.org)

has been used in order to determine how typical the air and ground temperature records from 2009 are. The spatial variability of the air temperature in Svalbard was based on ERA Interim re-analysis dataset elaborated by the European Center for Medium-Range Weather Forecasts. ERA Interim re-analysis contains a meteorological database with $1.5^\circ \times 1.5^\circ$ spatial resolution based on climatic models, meteorological records as well as remote sensing data for the period of 1989–2010.

Results

The ground temperature and heat flux

The maximum ground temperature and maximum thawing depth on Svalbard occur in August. Therefore, most of the ground temperature data used in this paper are related to August 2009. The average air temperature in Hornsund in this month (4.3°C) was very close to the 20-year average of 4.2°C . The ground temperature at -0.05 m in August 2009 was 0.3°C higher than the long-term average (Fig. 3). Warming of the ground in the last two decades in Hornsund is clearly noticed at -1 m depth with the average rate of $0.6^\circ\text{C}/\text{decade}$ (Fig. 3). In August 2009, the temperature at -1 m amounted to 3.2°C and was 1°C higher than the 1990–2009 average.

The variability of the ground temperature decreases with the depth. However, in summer, the accumulation of heat in the active layer has influenced higher ground surface temperature in the time when air temperature has already fallen (Paszyński *et al.* 1999). Since the ground temperature data for Kinnvika refer to few days only, we put together the daily average temperatures on 11 August 2009 and monthly aver-

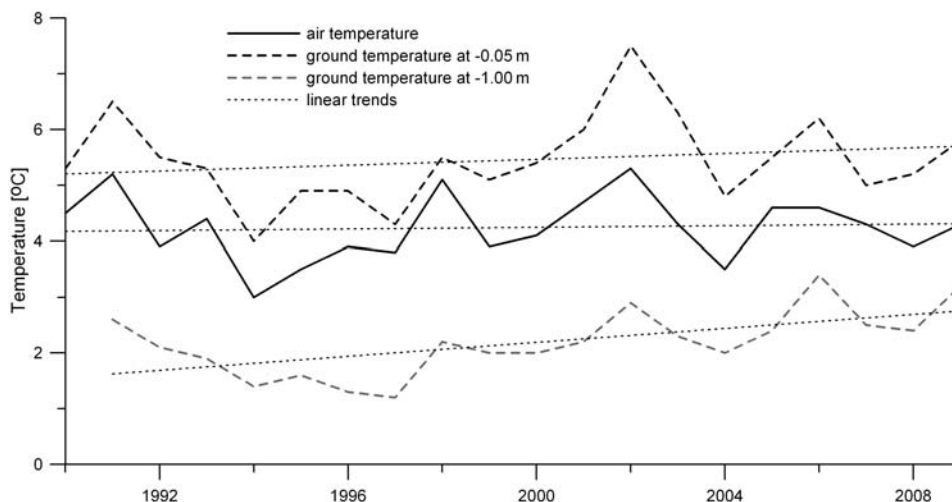


Fig. 3. Hornsund long-term (1990–2009) air and ground temperature in August.

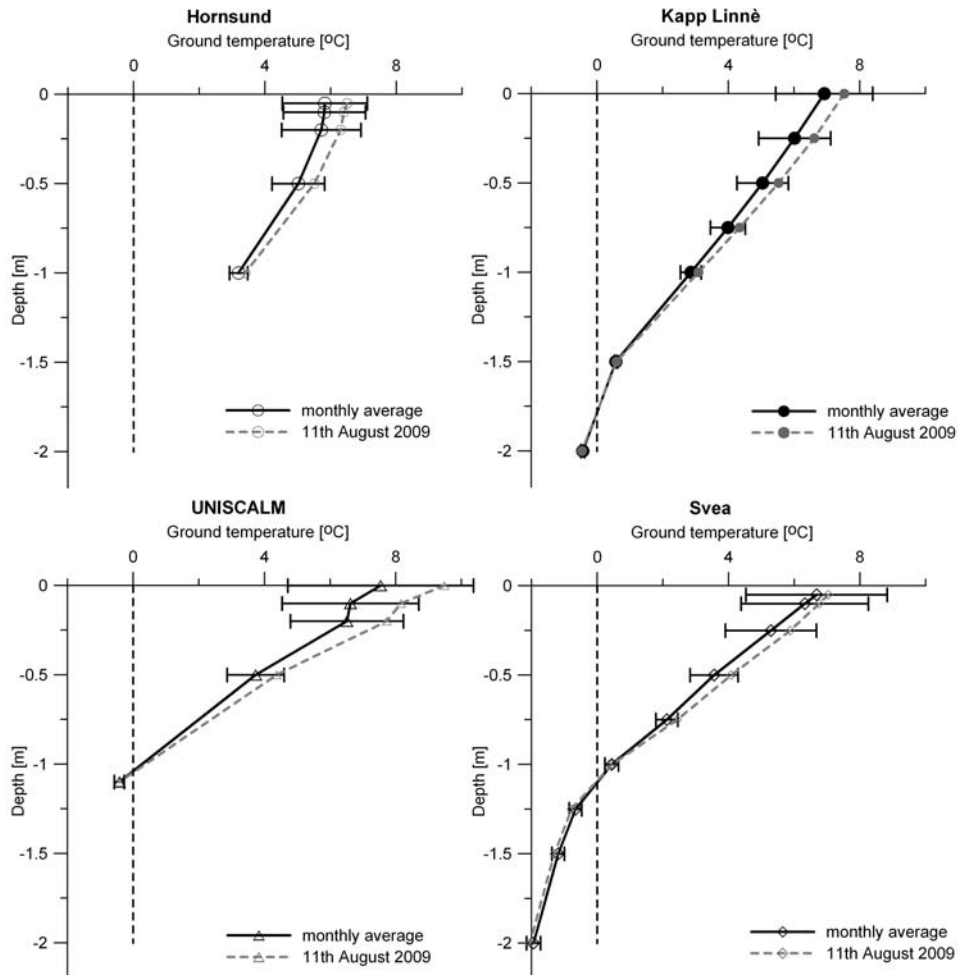


Fig. 4. Monthly (August 2009) and daily (11 August 2009) average ground temperature for selected coastal sites in Svalbard. Horizontal bars represent one standard deviation of daily records.

ages (August 2009) for available sites (Fig. 4), in order to settle how individual temperature could represent thermal conditions for a longer period. The mean daily ground temperatures on 11 August 2009 were slightly higher than the monthly average in upper layers and somewhat lower at deeper levels, however in all studied cases they fit into one standard deviation of daily records in the month. Hence, in further analysis, we will consider the 11 August 2009 data as typical for the period of the maximum ground temperature and the active layer thickness.

At Kinnvika, the average air temperature on 11 August 2009 amounted to 3.3°C, whereas the ground temperature varied with depth from 4.6°C at -0.1 m, to 0.1°C at -0.9 m (Fig. 5). At the same time, in Hornsund, the average daily air temperature was 5.2°C. The ground temperature ranged from 6.5°C at the depth of -0.05 m to 3.4°C at

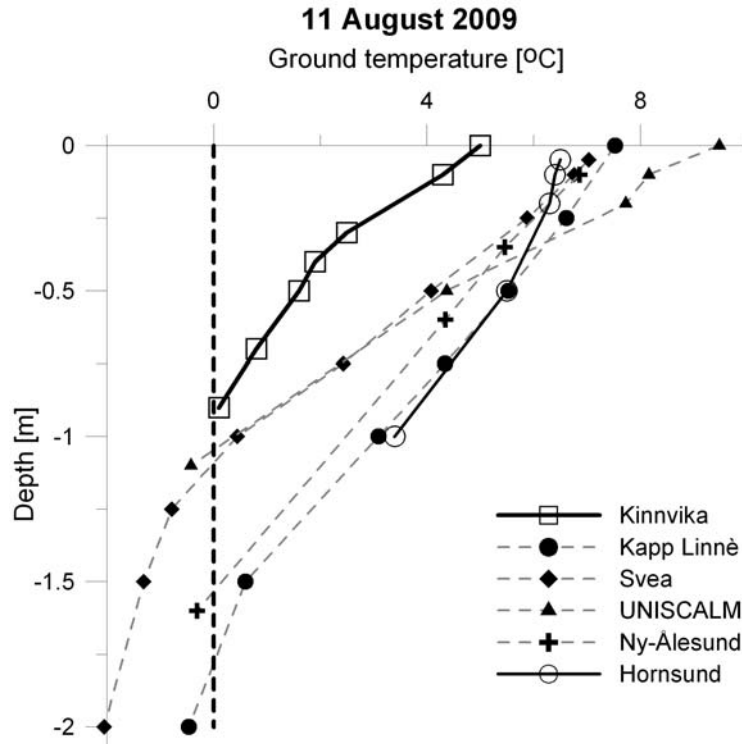


Fig. 5. Ground temperature on 11 August 2009. Solid lines refer to Fuglebergsletta and Kinnvika, dashed lines represent other coastal sites of ground temperature measurements on Svalbard. Site symbols as on Fig. 1 and in Table 1.

-1 m (Fig. 5). At the other Svalbard sites, the temperature of the superficial ground layer was warmer than at Hornsund, while the temperatures at -1 m were in the range between those characteristic of Hornsund and Kinnvika (Fig. 5).

Basing on the ground temperature interpolation the point of 0°C was estimated at the depth of -1.05 m at UNISCALM, -1.09 m at Svea, -1.53 m at Ny-Ålesund and -1.78 m at Kapp Linnè. At Kinnvika the freezing point was expected around -1 m, while in Hornsund, according to extrapolation of the ground temperature, the permafrost table was approximated at -2.04 m. On account of the fact that temperature through August 2009 at -1 m or deeper (compare standard deviations on Fig. 4) remained very stable, we can regard the obtained 0°C levels as very close to the maximum of seasonal thawing.

The heat flux was calculated in the upper 0.5 m ground layer, but 0.6 m in Ny-Ålesund. A relatively low heat flux was obtained at the sites on the western coast of Spitsbergen: 2 Wm⁻² for Hornsund, 3.6 Wm⁻² for Kapp Linnè, 4.5 Wm⁻² for Ny-Ålesund, while a high heat flux was noted in central Spitsbergen with 9.2 Wm⁻² for UNISCALM and 5.9 Wm⁻² for Svea, as well as in Nordaustlandet at 6.1 Wm⁻² in Kinnvika.

Interpretation of GPR profiles

Fuglebergsletta. — The GPR survey was carried out on 17 September 2007, 3–4 weeks after the maximum thawing depth. The average active layer thickness between 10 and 20 September 2007 calculated from the ground temperature at Kapp Linnè, Adventdalen and around Svea constitutes 64–90% of the average August 2007 thickness. The average daily air temperature on 17 September 2007 in Hornsund was 3.7°C and the ground temperature at -1 m was 0.8°C. We suppose that the thawing depth in Hornsund at this time was not more than several centimeters shallower than the maximum. In the season 2007, rapid freezing of the ground started after 20 September.

The GPR profile at Fuglebergsletta coastal plain runs from SE to NW at the distance of *c.* 280 m (Fig. 11). The profile is characterized by a clear three-layered structure (Fig. 6). In the first part of the profile, both horizons run together, then they split at *c.* 25 m of the profile. The lower horizon (b) is situated at the depth from -1.8 to -2.5 m. It forms a discontinuous boundary clearly marked at the beginning and in the middle part of the profile. The upper horizon (a) appears at *c.* -1.3 to -1.8 m. Between 80 and 120 m of the profile, the structure is blurred, probably due to a strong signal attenuation resulting from a high water content in the surface or within the superficial ground layer.

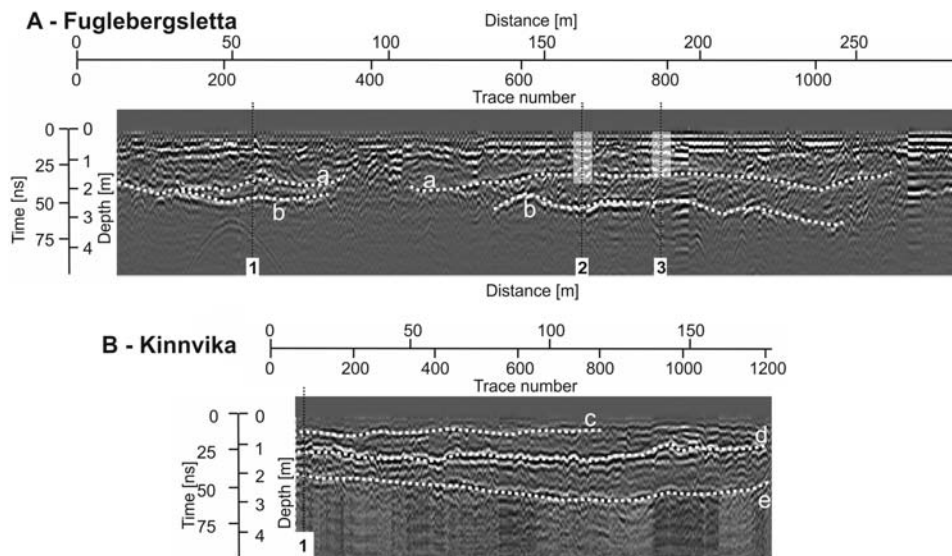


Fig. 6. GPR profiles on marine plains: Fuglebergsletta – Hornsund (A) and Kinnvika (B). 1 – sites of temperature measurements; 2, 3 – location of Danilin frost gauges, a–e – reflection horizons (interpretation in the text). Transparent rectangles show the depth range of frost gauges.

The upper horizon was interpreted as of sedimental origin, *e.g.* boundary between deposits of different grain fraction, or as a groundwater horizon. However,

this horizon cannot be recognized as the bottom of the active layer. Such interpretation was confirmed by results from a thaw gauge, measurements of the ground temperature and rod soundings. Two Danilin frost gauges have been installed along the profile line at the points marked as 2 and 3 (Fig. 6). The devices were pushed down to the depths of -1.8 and -1.6 m, and during the radar soundings were completely unfrozen, not reaching the permafrost table. The “a” horizon cuts profile 2 and 3 at the depth -1.29 m and -1.36 m, respectively. Therefore the bottom of the active layer must be located significantly deeper. The ground temperature at -1 m during the radar soundings was 0.8°C, that was much warmer than the freezing point. The temperature vs. depth, in the range from 0 m to -1 m, linear regression shows that the ground temperature reaches 0°C at the depth below -2 m. The rod soundings demonstrated the average active layer thickness at *c.* 2 m, as well. The lower reflection horizon was acknowledged as the permafrost table. At the point 1 (Fig. 6) the horizon is positioned at the depth -2.16 m, whereas at points 2 and 3 at -2.49 and -2.26 m, respectively. These values are comparable with results obtained by other investigation methods.

Kinnvika. — The radar soundings in Nordaustlandet were performed on 11 August 2009, thus around the time of the maximum thawing depth. The GPR profile has NW-SE direction and the length of *c.* 180 m (Fig. 1II). The profile shows a multi-layered structure, similar to the recorded at Fuglebergsletta. The lower horizon (e) lies at the depth of -1.7 m in the first part of the profile and -2.8 m in the middle part.

At Kinnvika, a distinct boundary (d) was located at the depth between -0.92 m and -1.54 m. A discontinuous horizon (c) could be distinguished in the outer ground layer, at depth *c.* -0.6 m. The ground temperature measured simultaneously to GPR sounding reached 0.1°C at the depth of -0.9 m. According to the rod probing, the active layer thickness amounted to -0.9 m. The obtained results enable interpretation of the middle horizon (d) as the permafrost table. The upper horizon may constitute a structural boundary or the groundwater level, while the lowest horizon may be explained as the bedrock.

Discussion

Our results indicate a significant spatial difference in the active layer thickness and temperature in the areas located at the Holocene raised beaches in Svalbard. As shown on Fig. 4, even short-term ground temperature investigations carried out in Arctic summer, *e.g.* as those performed in Kinnvika in 2009, could be regarded as typical for a longer period, one month for example, especially for deeper levels of -1 m or more, where thermal stability is considerably strong. Additionally, even a single measurement of a thermal state of the ground is very valuable for validation of a simultaneous geophysical study of the active layer base and permafrost table.

The spatial variability of the near surface ground temperatures is coupled to summer air temperature and radiation balance. The differences in the mean summer air temperature (1989–2010) over Svalbard was *c.* 3°C (Fig. 2). Hence, the maximum surficial ground temperature in summer occurs at sites in central and western Spitsbergen, whereas lower temperatures appear in Nordaustlandet. On the other hand, the temperature of the deeper layers of the ground is related to distribution of winter thermal conditions at the studied sites. At -1 m, lower temperature was noted at central Spitsbergen sites and Nordaustlandet, where winters are severe due to the location in inland and northernmost conditions. Warmer ground (-1 m or deeper) conditions are recorded at sites on the western coast where winters are relatively mild due to the influence of warm West Spitsbergen Current. Such ground thermal conditions control the temperature gradient, heat flux and its spatial variability.

The temperature gradient in the upper 1 m thick ground layer was much stronger in central Spitsbergen (UNISCALM 9°C/m, Svea 6.9°C/m) than at other sites (Fig. 5). A relatively weak ground temperature gradient was observed on the western coast with the increasing trend towards the North: in Hornsund 3.3°C/m, in Kapp Linnè 4.4°C/m and in Ny-Ålesund 5°C/m. Kinnvika located on western Nordaustlandet represents an intermediate ground temperature gradient of 5.4°C/m, between the western shore and the interior of Spitsbergen.

The heat flux in the ground is proportional to the temperature gradient and varies significantly at particular sites. The heat flux in the ground is stronger where the active layer is thinner in central Spitsbergen and Nordaustlandet. The temperature gradient and heat flux are also strongly determined by local conditions such as surface exposure, soil properties, its wetness and vegetation type. For example, a lower ground temperature gradient and heat flux in Hornsund may be produced by high heat losses due to evaporation process from widely spread tundra.

The thickness variability of unfrozen ground in Svalbard amounted to *c.* 1 m. Hornsund and Kinnvika determine the approximate maximum and minimum thawing depth limits on Svalbard. The thickest active layer was observed at the southernmost site – Hornsund in the range of 1.65–2.5 m (Dobiński 2011; this work). The results of GPR survey as well as other investigations of ground temperature, direct probing and thaw gauge in Hornsund area show the permafrost table layer between -2 m and -2.5 m in the middle of September 2007, *e.g.* after maximum thawing. In summer 2009, the point of 0°C was extrapolated from the ground temperature at 2.04 m. Independent geophysical investigations in a direct neighborhood conducted in the same season (Dobiński 2011) provided similar results showing the active layer being 2 m thick. Taking into consideration location of the measurement site, the results may be considered as typical for the area of eastern Fuglebergsetta (Dolnicki 2005).

Slightly shallower thawing depths (1.31–1.97 m) were recorded at Calypsostranda at the southern Bellsund shore (CALM database 1990–2011). On NW

coast of Spitsbergen, the active layer was detected between 1.08 m and 1.68 m at Kaffiøyra site (CALM database 1990–2011) and 1.78 m (2009) in Ny-Ålesund. At sites in central Spitsbergen *i.e.* Svea and UNISCALM, the thawing depths of 0.74–1.10 m are significantly shallower than at the above mentioned locations. A similar value of the active layer thickness of *c.* 1 m was observed at Kinnvika during the only record in summer 2009.

The thawing depth in 2009 at Kapp Linnè, estimated from temperature interpolation was -1.78 m (Fig. 4), while according to CALM database the active layer thickness was only 0.89 m. Such discrepancies occurred also in 2 consecutive seasons. The discrepancies may have resulted from various measurement methods and locations. At CALM site, the ITEX Active Layer measurement protocol (Molau and Mølgaard 1996) was implemented at 10 individual sites considered collectively. Each site was mechanically probed in a 100-metre grid. The 0°C level used in this work was derived from the ground temperature measured in a single 39 m long bore-hole (see http://geo.ngu.no/kart/permafrost_svalbard for site details).

The local variability of the active layer depth is also clearly demonstrated by GPR soundings carried out in Hornsund and Kinnvika (Fig. 6). In Hornsund, the horizon recognized as the permafrost table varied 0.33 m at a distance of 280 m, in Kinnvika the variability was 0.62 m at a 180 m long profile. Such considerable differences in the active layer thickness are determined by local factors, among which the most influential are *e.g.* site exposure, micro- and mesorelief that favors or makes difficult snow deposition and its duration, as well as soil and vegetation type. Because of local variations of the active layer conditions, an appropriate selection of a proper investigation method, and a site for monitoring, which would be representative for a larger area are still an open problem.

According to the permafrost definition, the temperature method seems to provide the most reliable information on the active layer thickness. However, in order to ensure the method is objective, high resolution sensors must be densely deployed in the vertical profile. Nevertheless, to resolve the 0°C level, interpolation of the temperatures recorded by particular thermistors is commonly used. All of that makes the method quite expensive to install and maintain. The rod probing and thaw gauge methods applied in the work gave comparable results, however they may identify only the aggregation state of the ground (frozen-thawed) instead of the thermal state. Those methods may be unreliable under cryotic conditions of unfrozen state in sub-zero temperature (Dobiński 2006).

The radar-sounding was successfully used in the active layer investigations. The results obtained from GPR survey were very close to the results achieved from other methods. However the radar method, in the same way as direct probing and thaw gauge, does not recognize the thermal state of the ground. The measurement consists in differences in dielectric properties of the frozen and unfrozen saturated layer with a high reflection coefficient between the materials.

The basic advantage of radar sounding is the possibility to identify the ground structure, and to conduct continuous, non-invasive measurements. Geophysical methods provide the image of the state and structure of ground materials in a relatively short time. It is very important in harsh conditions of remote regions of high latitudes (*e.g.* Nordaustlandet), where due to the weather and logistic conditions classical methods are not always feasible. However, direct measurements will remain essential as benchmark results.

The available data do not allow drawing conclusions on a coherent pattern of the active layer thickness on Svalbard. Major factors determining the thawing depth, such as solar radiation and temperature, are latitudinally dependent but modified by a set of regional as well as local factors. The most important regional factor is the ocean circulation. Differences in the ground thermal conditions between the western and eastern coasts of Svalbard are linked to warm and cold currents around the archipelago. Next regional elements are the ocean/inland influence and topography that make the thaw depth shallower at interior and elevated sites, not included within this work. Local factors, on the other hand, significantly modify thermal conditions of the ground and the thawing depth.

The active layer on Svalbard belongs to the thickest in the Arctic as the consequence of the West Spitsbergen Current warming-up effect. On Svalbard, the thaws measured near the shoreline are 0.5 to 1 m thicker than at comparable latitude in Canadian Arctic (Alexandria Fiord, Tanquary Fiord) or Greenland (Zackenberg) and deeper than elsewhere in North America and Russian Arctic, as compared with CALM database.

Conclusions

The paper describes spatial variability of thickness and thermal conditions of the active layer in selected sites on the raised beaches of Svalbard. The thermal comparison refers mainly to summer 2009 but the spatial relations obtained for this season can be regarded as typical. The relatively high stability of the summer ground temperature in the vertical profile, especially in August, allows assuming a single day measurement to be typical for a longer period, one month for example, and a state of maximum active layer thickness. This finding enables to use even sporadic records for more comprehensive analysis of the ground thermal properties in remote Arctic areas.

The spatial variability of the temperature of the upper ground layer in the summer season in Svalbard corresponds to the pattern of the summer air temperature, while the ground temperature at deeper levels, below -1 m, reflects spatial differences of the winter air temperature. The heat flux in the surficial 0.5 m ground layer is proportional to the temperature gradient and in the studied period ranged from 5.9–9.2 Wm⁻² at the sites in central Spitsbergen and Kinnvika to 2–4.5 Wm⁻²

at the locations along the western shore. In contrast to the heat flux distribution, the active layer in 2009 was the thickest at the sites placed on the western coast (1.53–2.04 m), and the thinnest around the inner parts of the fiords in central Spitsbergen and at Nordaustlandet (*c.* 1 m). The obtained values are in general agreement with a long-term CALM monitoring. The coherent active layer spatial pattern is difficult to build up due to superimposition of regional, *e.g.* ocean circulation, as well as local factors, *e.g.* soil properties and vegetation, on latitudinally dependent radiation and thermal conditions. Mainly due to the ocean warming effect, the near coast active layer in Svalbard is generally 0.5 to 1 m thicker than at other coastal sites located on the same latitude, *e.g.* Greenland, and even thicker than on much southerly located coastal sites in Eurasian and Canadian Arctic.

Among a wide range of methods, the temperature measurement seems to be the most reliable as it is the only method that investigates the ground thermal state which is a constitutive feature of the permafrost definition. Other methods for investigating thickness of the active layer are based on detection of different water states of aggregation in the ground (rod probing, thaw gauge), or dielectric properties of materials, which result from these states (radar sounding method).

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