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Ground temperature changes on the Kaffiøyra Plain (Spitsbergen) in the summer seasons, 1975–2014

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Abstract: This paper provides an overview of the results of research on changes in ground temperature down to 50 cm depth, on the Kaffiøyra Plain, Spitsbergen in the summer seasons. To achieve this, measurement data were analysed from three different ecotopes (CALM Site P2A, P2B and P2C) – a beach, a moraine and tundra – collected during 22 polar expeditions between 1975 and 2014. To ensure comparability, data sets for the common period from 21 July to 31 August (referred to as the "summer season" further in the text) were analysed. The greatest influence on temperature across the investigated ground layers comes from air temperature (correlation coefficients ranging from 0.61 to 0.84). For the purpose of the analysis of the changes in ground temperature in the years 1975–2014, missing data for certain summer seasons were reconstructed on the basis of similar data from a meteorological station at Ny-Ålesund. The ground temperature at the Beach site demonstrated a statistically-significant growing trend: at depths from 1 to 10 cm the temperature increased by 0.27–0.28°C per decade, and from 20 to 50 cm by as much as 0.30°C per decade. On the Kaffiøyra Plain, the North Atlantic Oscillation (NAO) has a greater influence on the ground and air temperature than the Arctic Oscillation (AO).

Key words: Arctic, Spitsbergen, Kaffiøyra, ground temperature, multi-annual variability, atmospheric circulation.

Introduction

The permafrost that occurs on Spitsbergen reaches a depth of 100 m in larger non-glacierized valleys, and in the high mountains situated in the interior it occasionally exceeds 500 m (Humlum *et al*. 2003). The top layer of the permafrost undergoes thawing, and the thickness of the active layer changes as the weather conditions change. Studies of the physical properties of permafrost, including its active layer, have been considerably intensified in recent years. Quite substantial warming has been observed at high latitudes in the northern hemisphere (Przybylak 2007; Walsh *et al*. 2011; Nordli *et al*. 2014), resulting in higher ground temperatures and an increased degradation of permafrost, for example in Alaska (Osterkamp 2008; Romanovsky *et al*. 2010a; Smith *et al*. 2010), Canada (Smith *et al*. 2010), Siberia (Oberman 2008; Romanovsky *et al*. 2010b) and Svalbard (Isaksen and Sollid 2002; Humlum *et al*. 2003; Isaksen *et al*. 2007a, b; Christiansen and Humlum 2008; Etzelmüller *et al*. 2011; Marsz *et al*. 2013), which must have contributed to this growth in interest. The extent of the economic and social effects of these changes is so profound that financing of relevant research has greatly increased in countries where permafrost is a common phenomenon (Streletskiy *et al*. 2015).

On Spitsbergen, research carried out by Polish scientists mainly focused on changes in the active layer of the permafrost and – primarily – on its thermal conditions (examples: Czeppe 1960, 1961, 1966; Jahn 1961; Baranowski 1963, 1968; Wójcik and Marciniak 1987; Wójcik *et al*. 1988, 1990; Miętus 1988; Miętus and Filipiak 2001, 2004; Leszkiewicz and Caputa 2004; Rachlewicz and Szczuciński 2008; Przybylak *et al*. 2010; Dolnicki 2010; Dolnicki *et al*. 2013; Sobota and Nowak 2014). This direction of research was determined by the fact that measurements of thermal conditions of the ground to 50 cm depth are part of the standard observations conducted at all meteorological stations, and so were also included in the programmes of most polar expeditions.

A list of published works describing the general weather conditions on the Kaffiøyra Plain during expeditions until 2011 can be found in Przybylak *et al*. (2012). Additionally, other detailed studies have been published concerning the permafrost in that area (including Klimaszewski 1960; Marciniak and Szczepanik 1983; Kejna 1991; Araźny and Grześ 2000; Grześ 2005; Sobota and Nowak 2014), and on the thermal conditions of the ground alone (*e.g.* Wójcik and Marciniak 1987; Wójcik *et al*. 1988, 1990; Kejna 1990, 1991; Kejna *et al*. 1993; Marciniak *et al*. 1991; Araźny 2001, 2012).

Until now, only three synthetic elaborations have been published concerning the ground temperature on the Kaffiøyra Plain based on data from at least a few summer seasons (Wójcik *et al*. 1988, 1990; Przybylak *et al*. 2010). This article, on the other hand, attempts to present a climatological approach to the problem and the response of the active layer of the ground to the dramatic warming of the Arctic, which exceeded 1°C in the last 20 years, as compared with the average temperature in the multi-annual period of 1951–1990 (Przybylak 2007).

The main aim of this paper is to describe ground temperature changes in the analysed region that occurred in the years 1975–2014. The influence of principal meteorological elements and atmospheric circulation on the basis of the North Atlantic Oscillation (NAO) and the Arctic Oscillation (AO) circulation indices on the ground temperature changes within the active layer was also analysed.

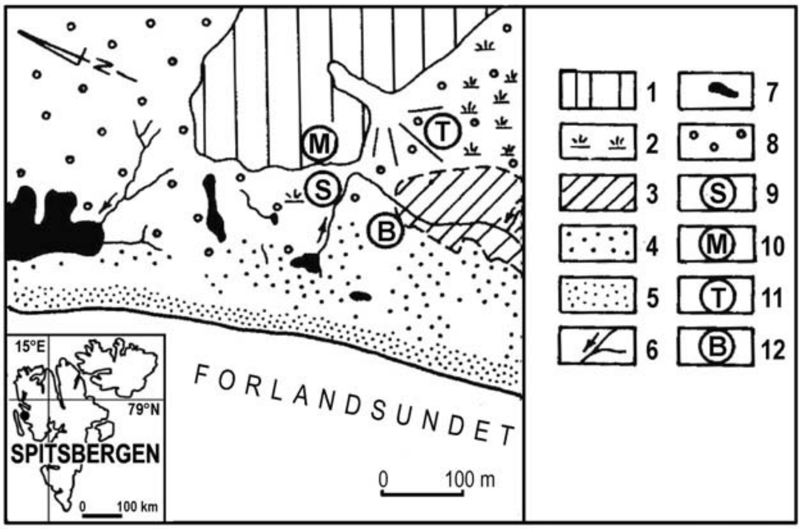

Fig. 1. A morphological sketch of the area of the Nicolaus Copernicus University Polar Research Station and the location of the measurement sites. Key: 1 – moraine, 2 – alluvial fan, 3 – area subject to occasional flooding during high tides, 4 – storm ridges, 5 – beach area subject to occasional flooding during high tides, 6 – creek, 7 – lake, 8 – glacial outwash (sandur), 9 – Nicolaus Copernicus University Polar Research Station, 10, 11, 12 – ground temperature measurement sites: Moraine (M), Tundra (T), Beach (B).

Research area, data and methods

Standard meteorological observations and measurements of ground temperature conditions have been carried out at the NCU Polar Research Station on the Kaffiøyra Plain (NW Spitsbergen) since 1975 (Fig. 1). The meteorological site is situated on the terminal-lateral moraine of the Aavatsmark Glacier (φ = 78°40’34”N, λ = 11°49’39”E) at 11.5 m a.s.l. and at a distance of 200 m from the sea (Przybylak and Araźny 2006). Ground temperature observations in the vicinity of the station have been conducted in 22 summer seasons (the common period being 21 July – 31 August) in the following years: 1975, 1977–1980, 1982, 1985, 1989, 1997–2000 and 2005–2014. The missing mean values of ground temperature were reconstructed using air temperature data from the Kaffiøyra station. The method of reconstruction of air temperature series from Kaffiøyra has been presented in detail by Przybylak *et al.* (2011).

Throughout all of the NCU’s Spitsbergen expeditions, researchers employed a uniform methodology for ground temperature measurement. The measurements were taken at depths of 5, 10, 20 and 50 cm using bent tube (mercury) thermometers, and at 1 cm by means of a regular thermometer, four times a day (at 00.00, 06.00, 12.00 and 18.00 UTC). The measurement points were located at three sites: a sandy beach, the flat top of the terminal-lateral ice-cored moraine of

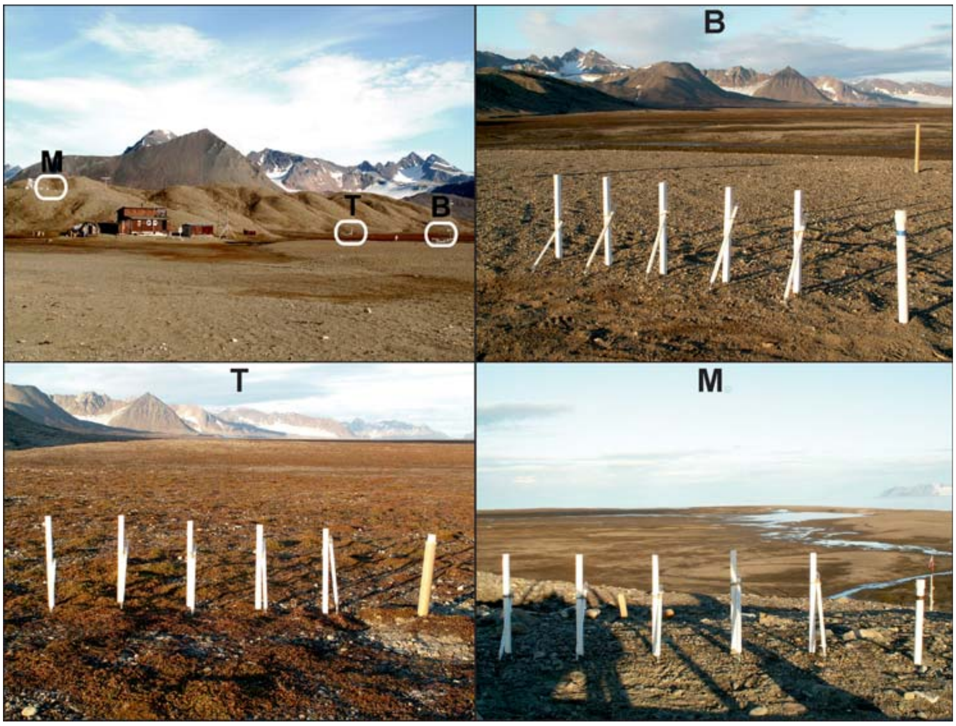

Fig. 2. Clockwise from top left: The Nicolaus Copernicus University Polar Research Station on the Kaffiøyra Plain, with the ground temperature sites: B – Beach, M – Moraine, T – Tundra. (Photo by A. Araźny).

the Aavatsmark Glacier, and in the tundra (Figs 1–3). At the same sites the maximum thickness of the active layer (ALT) was also measured as part of the *Circumpolar Active Layer Monitoring* (CALM) programme for the main database of ALT information for different areas of the world (Brown *et al*. 2000). The beach, tundra and moraine sites are identified in the CALM database as P2A, P2B and P2C, respectively.

- The Beach site (B) is situated on an accumulation coastal Plain out of reach of the greatest tidal motions of the Greenland Sea. The Plain is formed from sand and gravel deposits and its surface layer is dry and devoid of vegetation.
- The Moraine site (M) is situated on the flat top of the terminal-lateral ice-cored moraine of the Aavatsmark Glacier, and is formed of sandy, loamy and gravely clay and sand. About 20% of the surface of the moraine is covered with vegetation, which forms patchy clusters of a few centimetres in diameter.
- The Tundra site (T) is situated on an outwash fan, being an extension of the arch of the Aavatsmark Glacier's moraines. The fan mainly comprises sand and gravel deposits with an abundance of rock crumbs and loams. Its surface is 70% covered with tundra-specific moss and lichen plants. The ground is very moist at this site.

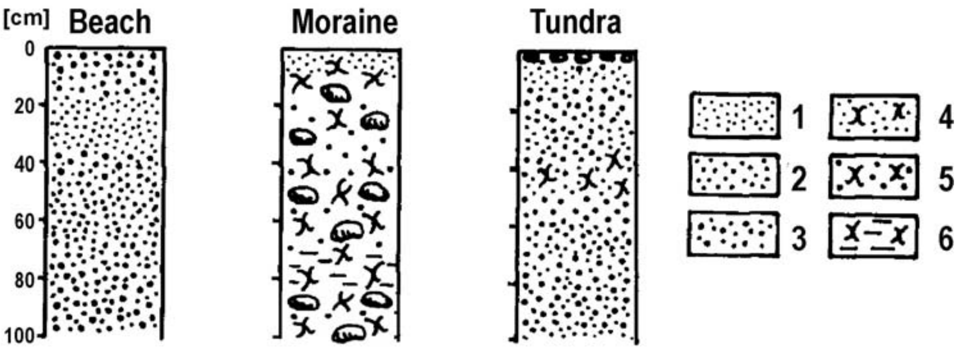

Fig. 3. Ground structure of the ecotopes (Beach, Moraine and Tundra) where ground temperature was measured. Key: 1 – fine sand, 2 – medium-grain sand, 3 – sand gravel, 4 – sand till, 5 – gravel till, 6 – silt till. (Source: Wójcik and Marciniak 1987).

Long-term observations demonstrate that the average thickness of the permafrost active layer at the end of the summer seasons is the greatest on the moraine (> 200 cm), and the smallest on the beach (just over 120 cm) (Araźny and Grześ 2000; Sobota and Nowak 2014). More details about the physical and chemical characteristics of the above-mentioned surfaces can be found in the works of Wójcik and Marciniak (1987), Kejna *et al*. (1993), and Sobota and Nowak (2014).

Influence on ground and air temperature was evaluated using the NAO and AO indices. The NAO teleconnection pattern is the best known index of atmospheric circulation for the north Atlantic and Europe (Hurrell 1995; Hurrell and Deser 2009). Additionally, the influence of the AO index (Thompson and Wallace 1998) on thermal conditions in the ground and air in that area was described. In this paper, diurnal values of NAO and AO for the period from 21 July to 31 August of 1975–2014 were used for the analysis. The data were sourced from the NOAA archives (http://www.cpc.ncep.noaa.gov).

Results and discussion

The influence of permafrost and weather conditions on ground temperature. — In Polar areas it is much more difficult to determine the extent of the influence of individual factors affecting ground temperature than it is at lower latitudes. This is because of the occurrence of permafrost and – essentially – the depth of the permafrost table, which in turn depends, for example, on atmospheric conditions and the mechanical composition and moisture content of the ground. As mentioned earlier, the depth of the thaw is an important factor influencing ground temperature. In 1979–2014 (24 summer seasons), measurements of the thickness of the active layer were carried out at the Beach site (Fig. 4) using a metal rod every 2–3 days. The average ALT was 118 cm, ranging from 88 cm in 1979 to 154 cm in 2007. The trend of maximum thickness of the layer there was 0.75 cm yr^{-1} in

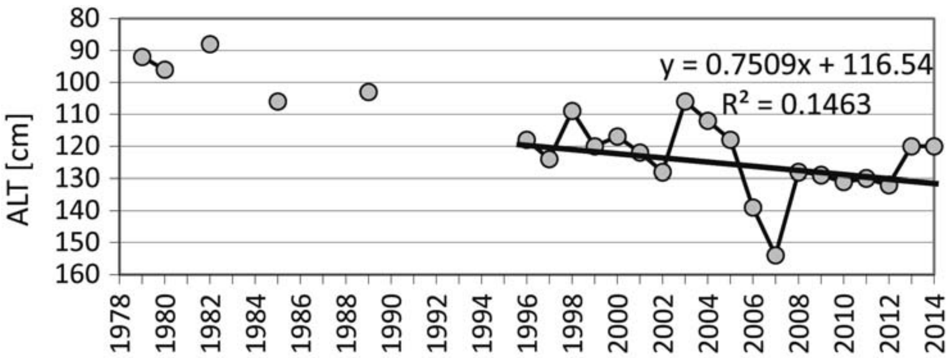

Fig. 4. Depth active-layer thickness (ALT) at the Beach site on the Kaffiøyra Plain.

1996–2014. The Tundra and Moraine sites also revealed an increased ALT (by 0.66 and 2.52 cm yr^{-1}, respectively) but in a slightly shorter period (1996–2012) (Sobota and Nowak 2014).

Air temperature is the meteorological element which – in the summer season – has the greatest effect on the ground thermal regime in polar areas, including Spitsbergen (Miętus and Filipiak 2004; Dolnicki 2010; Marsz *et al*. 2011; Dolnicki *et al*. 2013). Besides air temperature, cloudiness and sunshine duration (the amount of solar radiation) also significantly affect ground temperature, along with precipitation, which modifies humidity and the thermal conditions (heat conductivity and capacity) of the ground. Table 1 shows mean values of these meteorological elements for the period of 21 July – 31 August in 1975–2014. The mean air temperature on the Kaffiøyra Plain in the analysed period was 4.9°C, ranging from 6.3°C in the warmest summer of 1998 (according to www.ncdc.noaa.gov, 1998 was the world's warmest year of the 20th century and the third warmest – after 2005 and 2010 – in the history of instrumental observations), to just 3.3°C in the coldest, 1982 (which was probably a consequence of the El Chichon eruption, Písek and Brázdil 2006). However, the highest air temperature recorded to date, 18.9°C, was measured on 15 August 1979, when a strong foehnic wind was blowing (Wójcik and Przybylak 1985). The lowest temperature (-4.2°C) occurred on 30 August 1982, during the coldest summer. It is noteworthy that the warmest summer on the Kaffiøyra Plain was at the same time the cloudiest and most humid. This means that it resulted from an exceptional inflow of warm, humid air masses from the southern sector (Przybylak *et al*. 2012). As demonstrated by Przybylak (1992), cloudiness in Hornsund does not have a diversifying influence on thermal conditions in the summer when mean diurnal values are concerned. Its negative influence is visible only in the case of the maximum temperature value.

Another key meteorological element affecting ground temperature is precipitation, the influence of which consists in, among other things, modification of the thermal properties of the ground. Essentially, the greatest amount of precipitation was observed in three summer seasons: 2013 (141.4 mm), 1997 (122.5 mm) and

Table 1

Mean values of selected meteorological elements from the summer season (21st July – 31st August) on the Kaffiøyra Plain (Spitsbergen), 1975–2014.

Year	V [ms^{-1}]	C [0-10]	SS [h]	SS [%]	Tmax abs [°C]	Tmax [°C]	Ti [°C]	Tmin [°C]	Tmin abs [°C]	DTR [°C]	e [hPa]	f [%]	Δe [hPa]	P [mm]
1975	4.3	8.7	112.9	11.5	11.5	6.7	4.9	3.3	1.4	3.4	7.8	90	0.9	66.5
1977*	3.2	8.7	146.6	15.9	13.5	7.0	5.0	3.5	0.6	3.5	7.8	89	1.0	44.4
1978	4.6	8.8	119.9	12.1	10.0	6.3	4.7	3.1	0.7	3.2	7.7	89	0.9	44.2
1979	5.0	7.3	281.9	29.0	18.9	6.6	4.5	2.5	-0.5	4.1	7.6	89	0.9	17.7
1980	5.5	9.1	90.9	9.1	12.5	5.6	4.1	2.6	-0.8	3.0	7.3	88	0.9	108.0
1982	4.2	8.8	91.3	9.2	10.4	4.8	3.3	1.8	-4.2	3.0	6.8	88	1.0	54.5
1985	3.2	7.2	309.5	32.2	16.0	6.9	5.4	4.0	0.9	2.9	8.1	89	1.0	13.9
1989	5.0	8.3	203.0	20.5	11.5	5.5	4.0	2.7	-3.6	2.8	7.4	90	0.8	27.0
1997	5.4	8.4	165.0	16.8	10.8	5.4	4.2	2.7	-0.2	2.7	7.5	90	0.8	122.5
1998	4.0	9.1	93.5	9.5	14.0	7.6	6.3	5.0	1.8	2.6	8.7	91	0.9	16.0
1999	3.8	8.9	150.1	15.2	10.3	6.4	4.9	3.5	0.0	2.9	7.3	85	1.3	58.4
2000	4.6	7.2	213.3	21.6	8.8	5.9	3.9	2.2	-3.6	3.7	7.2	88	1.0	29.1
2005	3.8	9.1	149.4	15.1	12.1	7.5	5.8	4.1	1.4	3.4	8.1	87	1.2	49.9
2006	4.9	8.3	158.8	16.0	11.9	7.0	5.2	3.9	1.0	3.1	8.1	91	0.8	25.0
2007	3.7	8.7	132.0	13.3	14.9	7.4	5.5	4.0	-1.3	3.6	7.8	85	1.4	12.3
2008	5.4	8.9	131.7	13.3	12.4	6.1	4.5	2.9	-0.8	3.2	7.5	88	1.0	22.2
2009	3.1	7.9	220.0	22.2	12.7	7.9	6.1	4.3	0.9	3.5	8.2	87	1.0	12.5
2010	5.8	8.2	219.9	22.2	10.8	6.1	4.1	2.7	-0.6	3.4	7.2	87	1.1	8.5
2011	5.0	7.9	200.0	20.2	16.8	7.9	5.7	4.1	1.0	3.8	8.1	89	1.2	28.1
2012	6.1	8.4	185.6	18.8	13.8	7.2	5.2	3.5	0.5	3.7	7.7	86	1.2	43.9
2013	4.9	8.8	67.5	6.8	15.5	8.0	6.1	4.1	-1.2	4.0	8.2	87	1.3	141.4
2014	5.0	7.4	260.9	26.4	12.0	7.3	5.3	3.7	-1.0	3.6	7.5	84	1.4	12.1
1975–2014	4.6	8.4	168.4	17.1	18.9	6.7	4.9	3.4	-4.2	3.3	7.7	88	1.0	43.6

Key: * – 21.07–28.08, V – wind speed, C – cloudiness, SS – sunshine duration, Ti – mean daily air temperature, Tmax – mean daily maximum temperature, Tmin – mean daily minimum temperature, Tmax abs – absolute maximum temperature, Tmin abs – absolute minimum temperature, DTR – daily temperature range, f – relative humidity, e – water vapour pressure, e – saturation deficit; P – atmospheric precipitation.

1980 (108.0 mm). Very small amounts of precipitation occurred in further years, with totals of 20 mm or less recorded in the following years, listed from the driest first: 2010, 2014, 2007, 2009, 1985, 1998 and 1979 (Table 1). When the ground temperature exceeds its standard value the ground temperature lapse rate decreases in the vertical profile, provided that no abnormal influences from other factors occur. This is evident when looking at the lapse rate from, for example, the Beach site in the first three wettest and driest years listed above (the mean value was -0.67 and -0.74°C per 10 cm, respectively).

The most extensive and complete data series for the years 1975–2014 is available for the Beach only (Table 2). Therefore, averaged values from all 22 seasons are presented for this site in the form of thermo-isopleths in Fig. 5. The highest val-

Table 2

Mean summer (21st July to 31st August) ground temperature (°C) at depths of 1, 5, 10, 20 and 50 cm near the NCU Polar Station (Kaffiøyra Plain), 1975–2014.

	Beach (B)					Moraine (M)					Tundra (T)				
Depth	1 cm	5 cm	10 cm	20 cm	50 cm	1 cm	5 cm	10 cm	20 cm	50 cm	1 cm	5 cm	10 cm	20 cm	50 cm
1975	6.3	5.7	5.4	4.2	2.6	–	–	–	–	–	–	–	–	–	–
1977	6.7	6.1	5.8	4.9	2.7	–	–	–	–	–	–	–	–	–	–
1978	5.8	5.2	4.4	4.1	1.8	5.7	5.7	5.5	5.3	4.6	5.7	5.5	5.2	4.7	3.4
1979	6.3	5.8	5.4	4.5	2.2	6.0	5.8	5.7	5.4	4.7	4.8	4.5	4.3	3.8	2.4
1980	5.7	5.1	4.8	4.0	2.2	5.3	5.1	5.1	4.9	4.3	–	–	–	–	–
1982	5.2	4.7	4.2	3.6	1.7	–	–	–	–	–	–	–	–	–	–
1985	7.2	6.8	6.6	5.8	3.4	7.1	6.9	6.8	6.7	6.0	6.8	6.7	6.1	5.5	4.1
1989	6.0	5.6	5.2	4.4	2.2	5.3	5.4	5.2	5.0	4.6	5.3	4.9	4.6	4.2	2.9
1997	*4.6*	4.2	4.1	3.4	1.9	5.1	4.8	4.8	4.6	4.2	4.3	4.1	*3.8*	3.4	2.4
1998	8.1	7.5	6.6	5.4	2.4	8.1	8.0	7.9	7.6	6.7	7.4	6.7	6.2	5.5	3.6
1999	6.7	6.4	5.9	5.2	3.4	6.5	6.5	6.6	6.2	5.6	6.2	6.0	5.8	4.5	3.3
2000	5.6	5.5	5.0	4.4	2.1	5.3	5.1	5.0	5.0	4.3	4.9	4.9	4.5	3.9	2.2
2005	8.0	7.4	6.9	5.9	3.5	7.5	7.3	7.1	6.9	6.2	7.0	6.4	6.0	5.4	4.0
2006	7.1	6.7	6.8	5.9	4.2	6.8	6.6	6.5	6.3	5.7	6.4	6.1	6.1	5.6	4.3
2007	8.3	7.8	7.4	6.4	4.4	8.1	7.8	7.7	7.6	7.2	7.1	6.9	6.7	6.1	4.6
2008	6.0	5.7	5.4	4.7	2.8	5.9	5.6	5.4	5.4	5.0	5.6	5.2	5.1	4.8	3.4
2009	7.9	7.1	6.6	5.9	3.5	7.8	7.6	7.4	7.3	6.7	7.0	6.5	6.4	5.6	3.7
2010	5.8	5.3	5.0	4.2	2.4	5.9	5.8	5.8	5.6	5.1	5.5	5.1	5.0	4.4	3.1
2011	7.3	6.8	6.5	6.0	3.9	7.2	7.0	7.0	6.5	6.1	6.7	6.3	6.1	5.8	4.5
2012	6.4	6.0	5.6	5.1	3.0	6.3	6.2	6.1	6.1	5.7	5.7	5.5	5.4	5.0	3.6
2013	7.2	6.4	5.9	5.3	3.5	7.0	6.3	6.1	6.0	5.7	6.2	6.0	5.8	5.4	4.3
2014	7.2	6.4	6.0	5.5	3.6	6.7	6.4	6.3	6.1	5.7	6.4	6.0	5.8	5.4	4.1
1978–2014*	6.8	6.3	5.9	5.1	3.0	6.6	6.4	6.3	6.1	5.5	6.1	5.7	5.5	4.9	3.5

Key for the shorter periods: B – 21.07 – 28.08.1977; B, M, T – 24.07 – 31.08.1978; B – 28.07 – 31.08.1997; T – 01.08 – 31.08.1997; B, M, T – 21.07 – 29.08.2007; * – without 1980, 1982; estimated values are given in italics.

ues of ground temperature in the summer season occurred in the third decade of July, when they exceeded 10°C at a depth of 1 cm. At the same time, the temperature at 50 cm depth dropped below 4°C, which means that the mean lapse rate of temperature is quite high, even exceeding -1°C per 10 cm. From about 25 July onwards, the ground temperature at all measured depths gradually fell, with the exception of the very end of July, when frequent breaks in the weather were observed, resulting in substantial cooling. This is particularly evident in the 20 cm depth layer. At the end of August, the variability – and thus the lapse rate – of ground temperature decreases, which is most apparent in the 10 cm depth layer (Fig. 5). The ground temperature in the subsequent layer (20 cm) at that time did not exceed 4°C on average, and at 50 cm depth it dropped to approx. 2°C.

The temperature of the surface layer of the ground demonstrates substantial spatial variability. The measuring points selected for ground temperature measure-

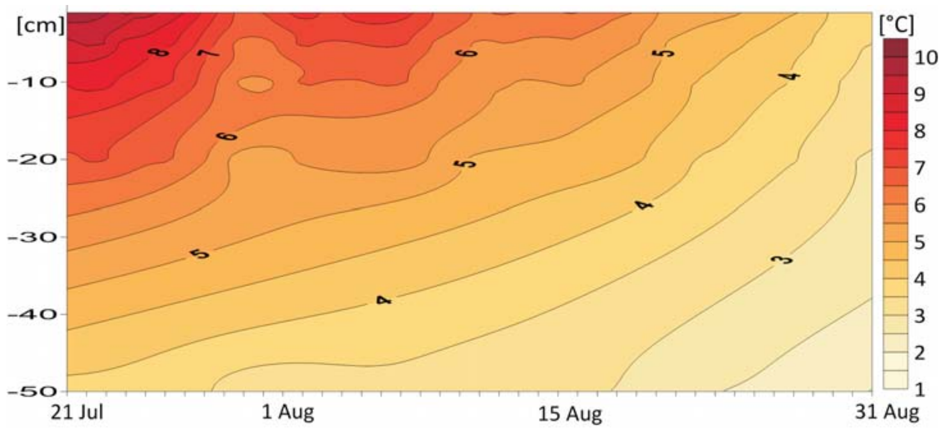

Fig. 5. Mean values of thermo-isopleths at Beach site on the Kaffiøyra Plain in the period from 21st July to 31st August (1975, 1977–1980, 1982, 1985, 1989, 1997–2000, 2005–2014)

ments were situated a very short distance from one another (Figs 1 and 2). This means that the atmospheric conditions were the same at each of them, as was their exposure. Therefore, any differences observed in the thermal conditions of the ground (Table 2) were caused by other factors, for example: albedo (Kejna *et al*. 2012), vegetation cover (Gugnacka-Fiedor and Noryśkiewicz 1982); different thermal characteristics of the ground, including mechanical composition (Wójcik and Marciniak 1987; Kejna *et al*. 1993) and – to a large extent – consequential various rates and depth of thaw, and thus the depth of permafrost table (Araźny and Grześ 2000; Sobota and Nowak 2014).

The mean values of ground temperature for the entire analysed period and all measurement sites are presented in Table 2, and their differences with regard to the Beach site are shown in Fig. 6. In nearly all years except 1997, the Beach was the warmest 1 cm below the surface. However, in 1997 ground temperature measurements did not begin at that site until 28 July and the 1 cm measurement was not taken at all. The mean value shown in the table was deduced from its correlation with the 5 cm measurement. The mean differences of ground temperature at 1 cm between the Beach and the Moraine and Tundra throughout the years were 0.2°C and 0.7°C, respectively (Table 2). At a depth of 5 cm, the Moraine was slightly warmer than the Beach (0.1°C), but the Tundra clearly remained the coldest, except for 1978 when the measured temperatures were higher there than on the Beach (Table 2, Fig. 6). At 10 cm and 20 cm depth, the thermal variability clearly increases in favour of the Moraine site, whereas the differences between the Beach and the Tundra decrease, and in some years the Tundra, reveals higher temperatures than the Beach at 20 cm. Nevertheless, the mean values remain higher on the Beach. At a depth of 50 cm, the Beach is evidently the coldest ecotope. As compared with the Moraine, the difference increases to 2.5°C on average, whereas the Tundra is just 0.5°C warmer (Table 2, Fig. 6). Across the analysed layer of the

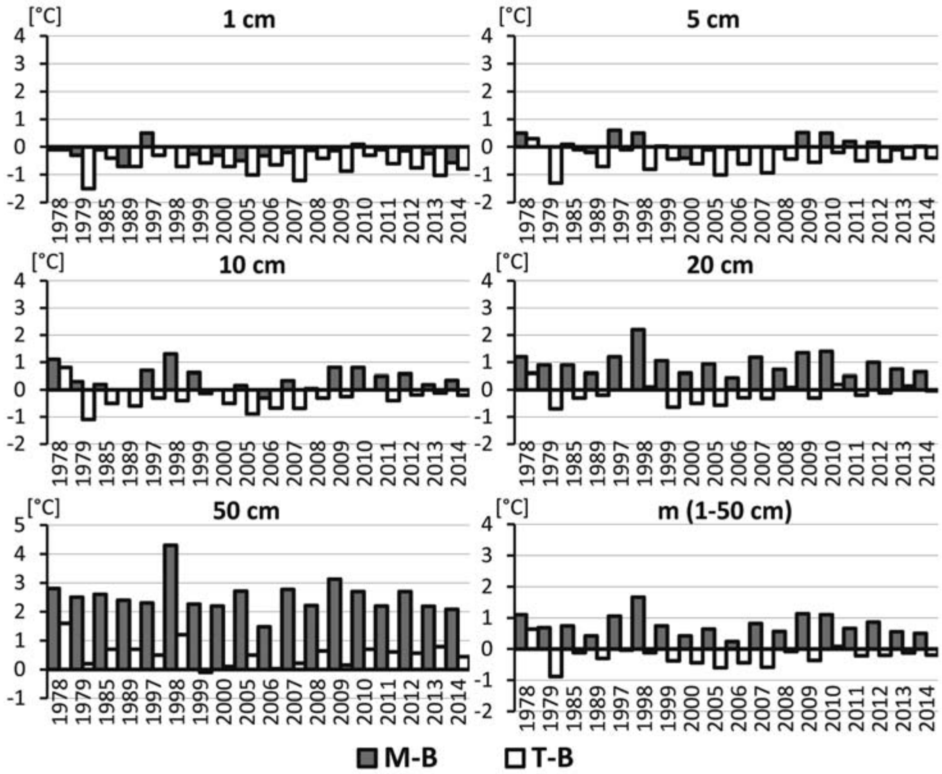

Fig. 6. Differences between mean seasonal (21st July – 31st August) values of ground temperature at different depths (1, 5, 10, 20 and 50 cm), and for the 1–50 cm layer between analysed ecotopes from 1978 to 2014. Key: B – Beach, M – Moraine, T – Tundra, m – mean.

ground, the mean temperatures were the highest on the Moraine (6.2°C), then on the Beach (5.4°C), and lowest on the Tundra (5.2°C).

What follows from the results presented so far is that depending on the site, the ground temperature decreases with the depth of measurement at different rates. This phenomenon is shown in Fig. 7, in which mean calculated lapse rates of temperature can be seen to decrease every 10 cm. In 1978–2014 (but not 1980 and 1982) the biggest mean drop in temperature from the surface towards the depth of 50 cm occurred at the Beach site (-0.76°C per 10 cm). Two things contributed to the drop: the surface layer there was the driest of all the sites, and the permafrost table was the shallowest (cooling effect). At the Tundra site, the mean lapse rate was -0.51°C per 10 cm, and the smallest was recorded at the Moraine (-0.21°C per 10 cm), where the driest conditions occurred across the profile, except for the surface layer, and where the permafrost remained the deepest (< 2 m depth).

In order to analyse changes in ground temperature in a diurnal course for each hour of the four measurement times, *i.e.* for 00.00, 06.00, 12.00 and 18.00 UTC, vertical profiles of the temperature were drawn. Two summer seasons with extreme val-

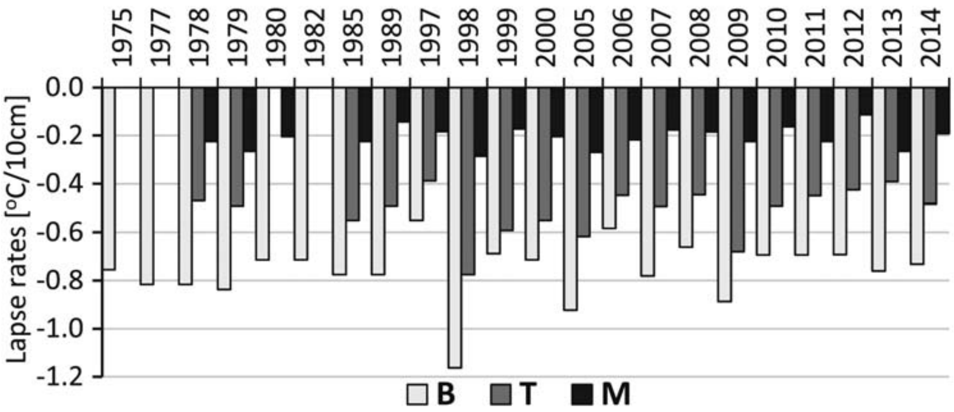

Fig. 7. Courses of mean lapse rates of summer (21st July to 31st August) ground temperature (°C/10 cm) on the Kaffiøyra Plain, 1975–2014.

ues of ground temperature were compared: the warmest (2007) and the coldest (1997). In the warmest summer, the diurnal variability of ground temperature is clearly greater at all the sites than in the coldest summer season (Fig. 8). This is particularly evident in the ground layer to 20 cm depth. The night-time inversion is also more characteristic. Noticeably greater variability of the diurnal amplitude of temperature at different depths between the sites is also observed in the warmest season. The diurnal course is the most distinctive at the Beach site, and the least developed on the Tundra. In the warmest summer of 2007, the Beach reveals strong correlations between the series of diurnal mean values of ground temperature at each level taken from the 1–50 cm layer and air temperature ($r > 0.90$ with statistical significance $p < 0.05$). On the other hand, no statistically significant correlations were found between the series of ground temperature and precipitation or relative air humidity, because the summer of 2007 was very dry. Furthermore, in the coldest summer of 1997 the connection between ground and air temperature at the Beach site was weaker ($r = 0.50$–0.80), yet statistically significant. However, statistically significant correlations ($p < 0.05$) were observed between ground temperature at all depths, and precipitation ($r > 0.40$) and air humidity ($r > 0.60$), because the summer of 1997 was very wet (Table 1). In the coldest summer season, the variability between the sites essentially disappears (Fig. 8).

The greatest thermal differences between the analysed sites occurred at 12.00 and the smallest at 00.00 UTC. This is especially evident in the warmest season. It is interesting to note the change of the differences between the Beach and the Tundra sites with the nature of the summer: as the summer grows warmer the Beach also becomes relatively warmer (compared with the Tundra), particularly in the 20 cm layer, but deeper than that of the Beach only a little colder. In the colder summers, there are no striking differences between the two sites down to 20 cm depth, but at 50 cm the Tundra is clearly warmer (Fig. 8).

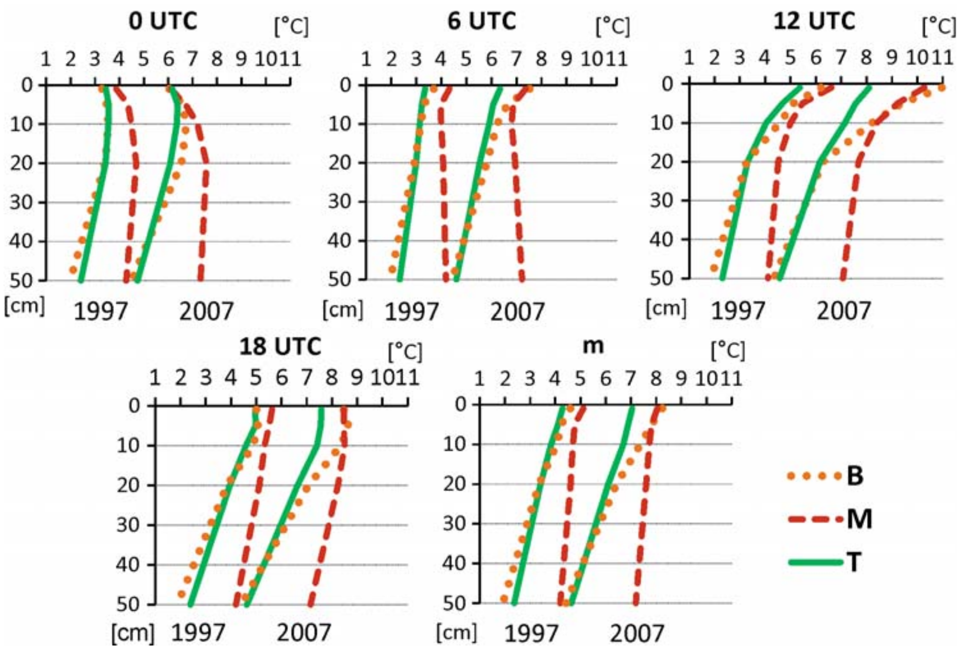

Fig. 8. Mean seasonal vertical ground temperature profiles in the 1–50 cm layer in the three analysed ecotypes (B – Beach, M – Moraine, and T – Tundra) on the Kaffiøyra Plain at selected hours (0, 6, 12 and 18 UTC) and for the daily mean (m) in the warmest (2007) and coldest (1997) according to the ground thermals summer seasons.

Correlations between ground temperature and meteorological elements. — There are very strong calculated correlations between series of mean diurnal values of ground temperature for all depths and sites in the common years of observations (Table 3). For the three analysed sites, the strongest correlations were found between the data series concerning the depths from 1–20 cm depth (correlation coefficients usually exceeded 0.95). As expected, the weakest (but still very sound) positive correlations ($r > 0.70$) were observed between the series of ground temperature at 1–5 cm and 50 cm (all were statistically significant at $p < 0.05$).

The data from the Beach were used to evaluate which meteorological element had the greatest influence on ground temperature. Table 4 contains the results of calculations of the Pearson's linear correlation coefficients between selected meteorological elements and the ground temperature, and clearly shows that air temperature is most correlated with ground temperature. For the series of ground temperature within the 20 cm layer, the correlation coefficients range from 0.82 to 0.84. The weakest correlation ($r = 0.61$) was obviously determined between the air temperature and the temperature of the deepest layer (50 cm). All the correlations are statistically significant at $p < 0.05$.

Looking at the extreme values of temperature, greater correlations with the temperature across the analysed ground profile can be seen in the case of the mini-

Table 3

Matrix of correlation coefficients for mean daily values of ground temperature (between the sites: Beach, Moraine and Tundra) at different depths (1, 5, 10, 20 and 50 cm) in the summer seasons: 1978,1979, 1985, 1989, 1997–2000, 2005–2014.

Site		Beach					Moraine					Tundra				
		1 cm	5 cm	10 cm	20 cm	50 cm	1 cm	5 cm	10 cm	20 cm	50 cm	1 cm	5 cm	10 cm	20 cm	50 cm
Beach	1 cm		0.99	0.97	0.91	0.71	0.98	0.97	0.96	0.93	0.81	0.97	0.96	0.95	0.91	0.76
	5 cm			0.99	0.93	0.75	0.97	0.98	0.97	0.95	0.85	0.97	0.97	0.97	0.93	0.79
	10 cm				0.96	0.81	0.95	0.97	0.97	0.96	0.88	0.96	0.97	0.97	0.95	0.84
	20 cm					0.85	0.90	0.92	0.93	0.94	0.89	0.91	0.93	0.94	0.95	0.87
	50 cm						0.71	0.74	0.77	0.81	0.85	0.73	0.77	0.81	0.85	0.88
Moraine	1 cm							0.99	0.97	0.94	0.82	0.97	0.96	0.95	0.91	0.76
	5 cm								0.99	0.97	0.87	0.98	0.97	0.97	0.94	0.79
	10 cm									0.99	0.91	0.97	0.98	0.98	0.95	0.82
	20 cm										0.95	0.95	0.96	0.97	0.96	0.85
	50 cm											0.85	0.88	0.90	0.92	0.88
Tundra	1 cm												0.99	0.98	0.95	0.81
	5 cm													0.99	0.96	0.84
	10 cm														0.98	0.87
	20 cm															0.92
	50 cm															

Key: All values of correlation coefficients are statistically significant at the level of 0.05.

Table 4

Correlation coefficients between the Beach site (at different depths: 1, 5, 10, 20 and 50 cm) and mean daily values of selected meteorological elements on the Kaffiøyra Plain in the summer seasons: 1975, 1977–1980, 1982, 1985, 1989, 1997–2000 and 2005–2014.

Variable	Ground temperature – Beach site				
	1 cm	5 cm	10 cm	20 cm	50 cm
Ti	**0.84**	**0.84**	**0.83**	**0.82**	**0.61**
Tmin	**0.78**	**0.80**	**0.81**	**0.81**	**0.62**
Tmax	**0.79**	**0.79**	**0.77**	**0.75**	**0.55**
f	**-0.10**	**-0.07**	-0.05	-0.03	0.00
e	**0.69**	**0.71**	**0.71**	**0.70**	**0.53**
V	**-0.30**	**-0.28**	**-0.25**	**-0.21**	**-0.10**
C	**-0.25**	**-0.21**	**-0.20**	**-0.17**	-0.04
P	**-0.10**	**-0.10**	**-0.10**	**-0.09**	-0.01
SS	**0.35**	**0.31**	**0.29**	**0.24**	**0.08**

Key: Correlation coefficients statistically significant at the level of 0.05 are shown in bold. Explanations of variables as in Table 1.

mum temperature ($r > 0.7$ down to 20 cm depth). It should be pointed out that the minimum temperature affects the ground temperature at 50 cm depth more than the mean diurnal value of temperature (Table 4). All the correlation coefficients are statistically significant at $p < 0.05$, just as with the mean diurnal temperature.

The high values of correlation coefficients ($r > 0.5$ across the profile) obtained for the water vapour pressure result from a strict correlation of this element with the air temperature. Other analysed meteorological elements that substantially influence the values of ground temperature are cloudiness and sunshine duration, however in both cases the correlation coefficients are not very high (ranging from 0.17 to 0.35 for the upper 1–20 cm depth layers), yet still they are statistically significant. Cloudiness decreases and sunshine increases the ground temperature, however these elements hardly contribute to the changes in ground temperature at 50 cm depth (Table 4). On the other hand, wind speed has a slightly greater influence on the ground temperature than the two elements mentioned above. Moreover, this element affects the ground temperature at 50 cm depth as well. Precipitation has very little cooling effect on surface layers down to 20 cm (its correlation coefficient amounts to -0.1, however it is statistically significant at $p < 0.05$). Finally, the relative air humidity only has a limited influence on the temperature of the top layers of the ground to 5 cm depth (Table 4).

The reconstructed series of ground and air temperature in 1975–2014. — In the so-called High Arctic, one of the longest meteorological data series is the air temperature series from the Svalbard Airport in Spitsbergen. From 1898 to 2012, the trend of mean annual values of air temperature at the weather station there was 2.68°C per 100 years (Nordli *et al*. 2014). The greatest air temperature trend was observed in the spring (3.98°C), while the winter trend (2.98°C) was much greater than in the summer (1.08°C per 100 years), see Nordli *et al*. (2014). The variability of air temperature in Spitsbergen is much greater in the winter than in the summer (Araźny 2008; Christiansen *et al*. 2013; Nordli *et al*. 2014). In this paper, the analysed ground and air temperature regime in the summer season covers the warmest period of instrumental measurements in Spitsbergen.

The changes in mean values of ground temperature at all 5 analysed depths at the Beach site were presented with respect to the changes in air temperature (Fig. 9). The diurnal mean, maximum and minimum air temperature in all 40 summer seasons was: 4.9°C, 6.7°C and 3.4°C, respectively (Table 5), making it the same as in the 22 seasons of instrumental measurements (Table 1). In the period from 1975 to 2014, a statistically significant 1.0°C increase of Ti was noted. An analysis of the change in air temperature in the first 20 years shows that by 1994, changes in Ti were minor and even a slight falling trend was observed (trend -0.01°C per decade). This was characteristic for the whole Arctic (cf. Przybylak 2007). A sudden increase of air temperature in the summer (trend 0.37°C per decade) was observed from 1995 to the end of the analysed period in 2014. Regarding extreme temperatures, throughout the 40 years of observation, more major changes were observed in Tmax than in Tmin (0.28 and 0.18°C per decade, respectively – both trends are statistically significant at $p < 0.05$). As a result of the different rates of change in Tmax and Tmin, diurnal amplitudes of air temperature were distinctly increased.

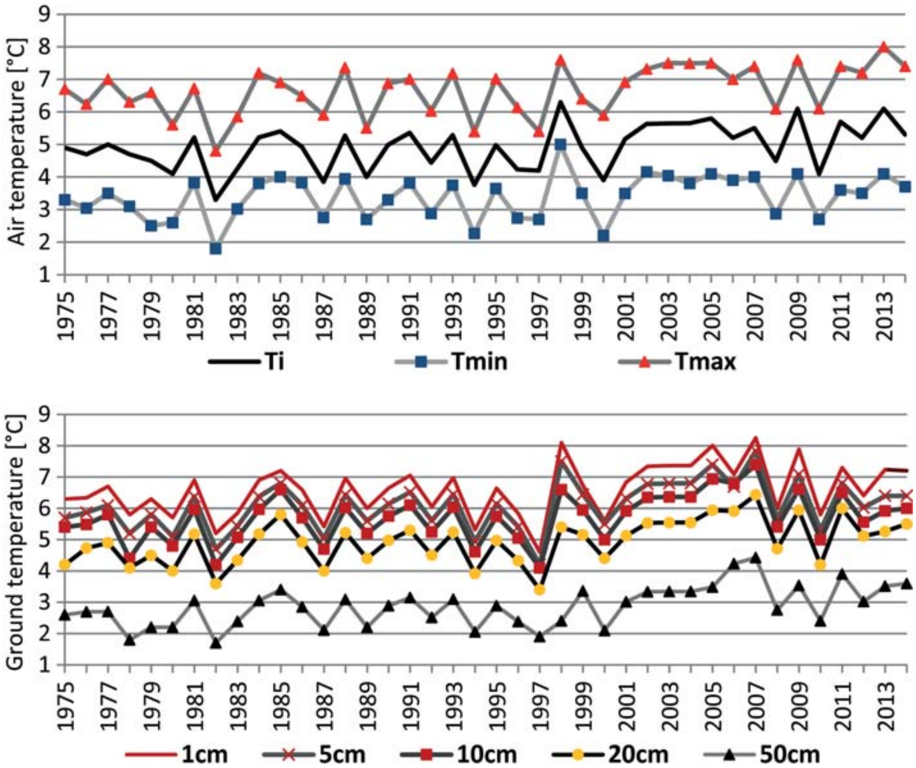

Fig. 9. Reconstruction of mean seasonal (21st July–31st August) air temperature (Ti, Tmax and Tmin) and ground temperature at the Beach site, at depths of 1, 5, 10, 20 and 50 cm on the Kaffiøyra Plain, 1975–2014.

The mean values of the reconstructed series of ground temperature at the Beach at 1 cm, 5 cm, 10 cm, 20 cm and 50 cm depths are 6.6°C, 6.1°C, 5.7°C, 4.9°C and 2.9°C (Table 5). When compared to the mean value of temperature from the 22 NCU expeditions, these are 0.2°C higher at depths from 1 cm to 20 cm, and 0.1°C higher at 50 cm (Table 2 and 5). The ground temperature at 20 cm depth at this site is the same as the air temperature at 200 cm a.g.l. (Table 5). Similarly, a clear increase in ground temperature at all depths was noticed in the analysed period. In the course of their mean values in 1975–2014, the increase at 1–10 cm depths is 0.27–0.28°C per decade – and at 20–50 cm depths increased by 0.30°C per decade. The values of calculated linear trends are statistically significant at $p < 0.05$. In the analysed period, the warming of the ground across the profile is on average approx. 0.2°C greater than the warming of the air. This process began in the first twenty-year part of the multi-annual period, and reached its peak in the first ten years of the 21st century (Table 5, Fig. 9).

The increase of the ground temperature on the Kaffiøyra Plain in the deepest 50 cm layer corresponds with changes that have been occurring deeper in the ground in this part of the Arctic. At the permafrost borehole on Spitsbergen (at Janssonhaugen)

Table 5

Mean values and linear trends of reconstruction of air temperature and ground temperature at the Beach site in the summer seasons (21st July to 31st August) on the Kaffiøyra Plain in the 1975–2014.

	Element	Parameter	1975–1994	1995–2014	1975–2014
Mean values	Air temperature (°C)	Tmax	6.4	7.0	6.7
		Ti	4.7	5.2	4.9
		Tmin	3.2	3.6	3.4
	Ground temperature (°C)	1cm	6.3	6.9	6.6
		5cm	5.8	6.4	6.1
		10cm	5.4	6.0	5.7
		20cm	4.7	5.2	4.9
		50cm	2.6	3.1	2.9
Linear trends	Air temperature (°C/decade)	Tmax	0.00	0.52	**0.28**
		Ti	-0.01	0.37	**0.25**
		Tmin	0.08	0.16	**0.18**
	Ground temperature (°C/decade)	1 cm	0.07	0.45	**0.28**
		5 cm	0.14	0.32	**0.27**
		10 cm	0.16	0.36	**0.27**
		20 cm	0.20	0.50	**0.30**
		50 cm	0.17	**0.59**	**0.30**

Key: trends statistically significant at the level of 0.05 are shown in bold.

a ground surface temperature reconstruction based on a heat conduction inversion model of the ground temperature profile indicated a near surface warming of 1.5°C±0.5°C in the last 60–80 years (Isaksen *et al.* 2000). Most of that warming has occurred in recent years: for example, from 1999 to 2009 the temperature of the permafrost at Janssonhaugen increased by 0.9°C at 20 m depth (Etzelmüller *et al*. 2011).

In other areas of the Arctic, ground temperatures have also been found to increase along with degradation of the permafrost. In Alaska, Romanovsky *et al*. (2010a) and Smith *et al*. (2010) recorded an increase of the permafrost temperature by 0.5–3.0°C during the last 30 years. Northern Russia and Northwest Canada show increases in permafrost temperature similar in magnitude to those in Alaska for the last 30–35 years (Romanovsky *et al.* 2010b; Smith *et al.* 2010).

The influence of atmospheric circulation on ground temperature. — Atmospheric circulation in the Arctic plays a much bigger role as a climate-shaping factor than it does in other parts of the globe (Araźny 2008). The values of the NAO and AO were compared with mean values of ground temperature at 20 cm depth at the Beach site, and the mean diurnal air temperature (Fig. 10). NAO and AO are generally strongly correlated (Mysak 2001). In the summer seasons from 21 July to 31 August of 1975–2014, the correlation was very strong indeed ($r = 0.48$), and statistically significant (at $p < 0.05$).

The values of correlations between NAO and ground and air temperature were negative for the analysed area and amounted to -0.32 and -0.18 respectively, how-

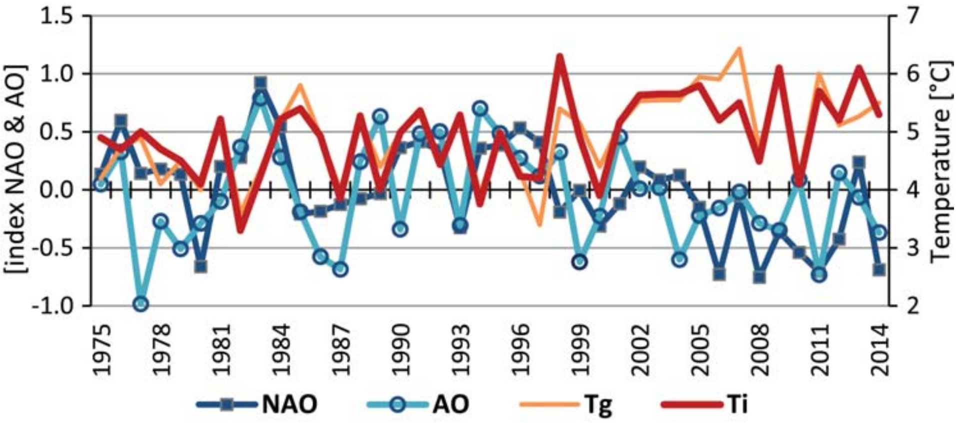

Fig. 10. North Atlantic Oscillation (NAO), Arctic Oscillation (AO) indices, ground temperature (Tg) at Beach site at depths of 20 cm and air temperature (Ti) series in the Kaffiøyra Plain, 21 July – 31 August in the period 1975–2014.

ever the relationship between the ground temperature and NAO was statistically significant at the level of $p < 0.05$. This means that during a positive phase of NAO, when the air pressure in the centre of the Azores High is higher than average and the Icelandic Low is very deep, warmer air masses flow to the Norwegian Arctic, causing both air and ground temperature to increase.

The Arctic Oscillation has a smaller influence on the air and ground thermal regime on the Kaffiøyra Plain than the NAO. The correlation indices between mean values of ground and air temperature in the summer and the AO index are not statistically significant (their values are -0.26 and -0.23, respectively).

There are no studies of the influence of NAO and AO on ground temperature in Spitsbergen in literature. The few available studies concern analysis of correlations between these indices and the active layer thickness, *cf.* Marsz *et al.* (2011, 2013), where no significant correlations were found between ALT and the variability of the NAO and AO indices in Spitsbergen (the Bellsund region).

Conclusions

In the analysed summer season, ground temperature on the Kaffiøyra Plain usually reaches the highest values in the first days of the last third of July, when it exceeds 10°C at a depth of 1 cm. After 25 July, the temperature begins to decrease gradually, and dramatically at the end of July when breaks in the weather and substantial cold are very often observed.

From 1978 to 2014, on average the warmest ground across the analysed profile was at the Moraine site (6.2°C), whereas the Tundra was the coldest (5.2°C). However, in the shallowest layer of the ground (down to 1 cm depth) the Beach site was definitely the warmest, which – in turn – revealed the lowest temperatures at 50 cm depth, which results from the permafrost table having the shallowest depth at that site. In consequence, it was the Beach site where the highest lapse rate of temperature decrease with depth was observed (-0.76°C per 10 cm).

In the warmest seasons the diurnal variability of ground temperature is evidently greater at all the analysed sites, compared to the coldest seasons. This is particularly clear in the shallow layers, down to 20 cm depth.

A very strong, statistically significant correlation was found between diurnal series of ground temperature at all measurement depths and all sites.

Air temperature, and the related water vapour pressure, has the greatest influence on the ground thermal regime (r between 0.61 and 0.84 for its mean diurnal values). A smaller but still statistically significant importance was found for wind speed, cloudiness and sunshine duration. The variability of these meteorological elements – each of them individually – accounts for 1% to 7% of the total variability of the ground temperature.

In the reconstructed data series for 1975–2014, a statistically-significant increase of ground temperature at the Beach site was identified. Over a period of 40 years, the ground temperature increased between 1.1°C at 1–10 cm depths and 1.2°C at 20–50 cm depths. Faster warming of the deep layers of the ground lead to an increase in the thickness of the active layer at that site. In the last 20 years under consideration, the permafrost table subsided at an average of 0.75 cm per year.

The significant influence of atmospheric circulation, represented by the NAO index, on ground temperature was demonstrated. The hemispheric circulation, on the other hand, represented by the AO index, turned out to be statistically insignificant.

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