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Short-term changes in thermal conditions and active layer thickness in the tundra of the Kaffiøyra region, NW Spitsbergen

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Abstract. This article describes and discusses the results of observations concerning short-term changes in the thermal conditions and the thickness of the active layer in a test field located in the tundra of the Kaffiøyra (NW Spitsbergen) during the summer season of 2015. One of the objectives was to find a correlation between the dynamic of the changes and the local topography. In recent years, thawing of the active layer in the Kaffiøyra region has been considerably varied in individual summer seasons. The test field area was 100 square meters, comprised 36 measurement points and was situated at approximately 3 m a.s.l. in the tundra. The measurements of the thickness and temperature of the active layer were carried out in July, August and early September of 2015. The greatest thickness of the active layer in the tundra was found near the moraine, in the area with the sharpest slope (156 cm to 212 cm). Ground temperatures were observed to follow the prevailing weather conditions with a delay, which amounted to about 24 h at a depth of 25 cm, and as much as 48 h at a depth of 75 cm. A greater thickness of the active layer was found in the western part of the test field, in the vicinity of a tidal channel, and in the eastern part of the field, bordering on the foot of the Aavatsmarkbreen's moraine. A considerable sloping of the land, combined with increased surface runoff and infiltration at the time of precipitation, makes the water penetrating into the active layer increase its temperature. This demonstrates that the local land forms (tidal channels and terminal moraines) have a substantial influence on the extent and rate of changes which occur in the active layer.

Key words:
permafrost,
active layer,
Kaffiøyra,
Svalbard

Introduction

The thickness of the active layer undergoes considerable temporal and spatial variability. Finding its reasons may be central to the understanding of the mechanisms of changes occurring in the cryosphere and should be helpful for the development of their models and forecasts (Repelewska-Pękalowa and Pękala 2007; Marsz et al. 2011). The disappearance of permafrost is accompanied by a number of morphogenetic processes which lead to rapid transformations of the surface features. Other components of the natural environment, such as hydrography, vegetation cover etc., are affected as well (Etzelmüller et al. 2011).

Research connected with the issue of permafrost and its thawing in Svalbard has been conducted by Jahn (1982); Migała (1991); Leszkiewicz and Caputa (2004); Repelewska-Pękalowa and Pękala (2004); Rachlewicz and Szczuciński (2008); Dobiński and Leszkiewicz (2010); Dolnicki et al. (2013); Repelewska-Pękalowa et al. 2013; Wawrzyniak et al.

(2014) and others. The explorations of the Kaffiøyra permafrost predominantly concern the size of seasonal thaw of the ground (thickness of the active layer and its dynamic) and its thermal conditions. Observations of this kind were first carried out in 1938 (Klimaszewski 1960) and they have been continued since 1975 (by, for example, Marciniak and Szczepanik 1983; Grześ 1985; Kejna 1991; Kejna et al. 1993; Araźny and Grześ 2000; Sobota 2013; Sobota and Nowak 2014). Since 1996, changes have been noted in the active layer thickness at three permanent measurement points, representing the following different ecotopes: the tundra, the beach and the moraine (Sobota and Nowak 2015).

This article describes the extent of short-term changes in the thermal conditions and thickness of the active layer during the summer season of 2015, observed in a test field located in the tundra. One of the goals was to find correlations between the dynamic of changes in the thermal conditions and thickness of the active layer and the local topography. The availability of remote sensing data allowed us to develop current orthophoto maps of the Kaffiøyra region and of the area around the NCU Polar Station, including the test areas located in the tundra and on the beach.

The meteorological data used to present individual weather elements were sourced from an automatic weather station operated all year round by the NCU Polar Station and from the meteorological station of the Norwegian Meteorological Institute, situated 30 km to the north, at Ny-Ålesund (eKlima).

Study area and methods

Kaffiøyra is a coastal plain of 310 km² situated on the eastern side of Forlandsundet (Lankauf 2002) (Fig. 1). The lowland is a part of Oscar II Land, in 70% covered by glaciers (1600 km²). The glaciated area consists of a few ice plateaux, from which 51 glaciers flow with a surface area of over 1 km² each. Approximately 19% (440 km²) of the area of Oscar II Land is covered by mountain ridges and massifs. Another element of the area's landscape is coastal plains, covering 12% of the surface area (280 km²), including the Kaffiøyra. Its natural boundaries are defined by the Aavatsmarkbreen flowing into the Hornbækbukta in the north, and the Dahlbreen terminating in a bay of the same name in the south (Fig. 1). The eastern boundary is provided by the following six glaciers: Waldemarbreen, Irenebreen, Elisebreen, Eivindbreen, Andreasbreen and Oliverbreen, and the mountain massifs of Prince Heinrich and Jacobson (Sobota 2013).

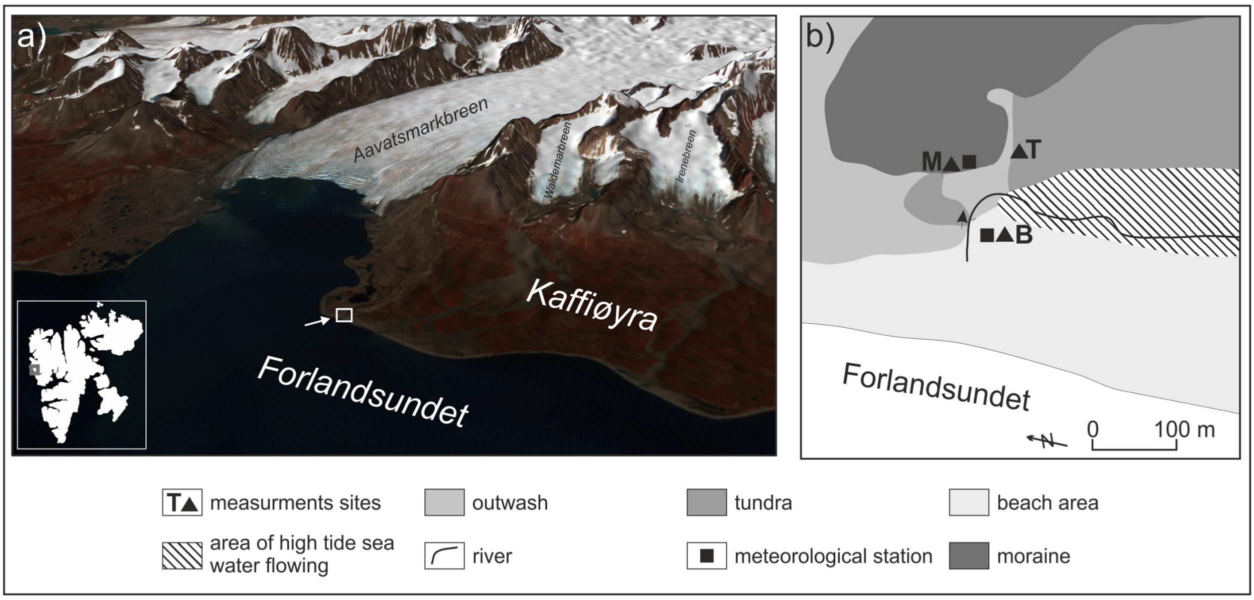

Fig. 1. Study area (a) and location of the active layer thickness and temperature measurement points (b), M – Moraine, B – Beach, T - Tundra (Sobota and Nowak 2014)

The main pedogenetic processes in that area consist in the accumulation of organic material, braunification, gleying and decarbonation. A slowed-down mineralisation process, due to unfavourable hydrothermal conditions, contributes to a high humus content despite a limited supply of organic remains. The chemical composition of the Kaffiøyra soils is mainly shaped by the parent rocks, pedogenetic processes and external influences (e.g. from sea spray aerosol). Cryogenic processes, overlapping the pedogenetic processes, also play an important role in the genesis of the soils there. Substantial moisture content of the surface layers and stagnant waters result in a shallow reach of permafrost (Plichta 2005).

Climate research in the area of Kaffiøyra has been carried out since 1975, mainly in the summer (Przybylak et al. 2012). General trends of the climate change observed on the Kaffiøyra are the same as in the entire Svalbard. This is particularly evident in the gradual increase of air temperature, which has a major effect on contemporary changes in the cryosphere in that area (Sobota 2013). In the years 1997–2015, the mean air temperature during the summer season reached there 5.4^{o}C (Sobota et al. 2016).

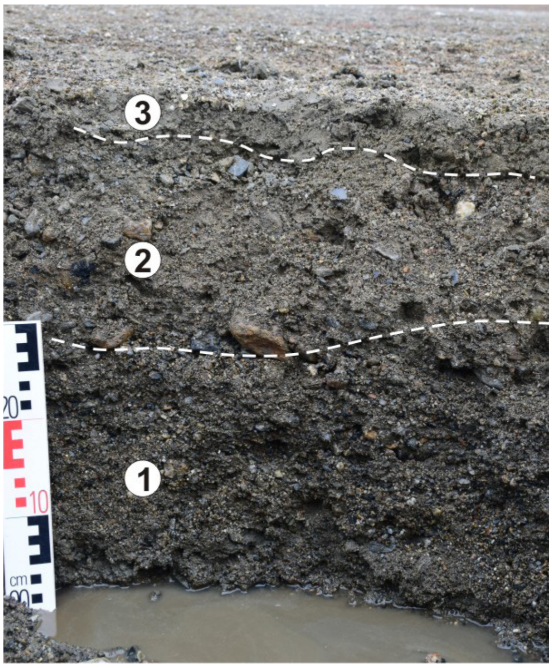

Fig. 2. Lithological profile of a measurement point on tundra (photo by P. Weckwerth). 1 – coarse-grained sands mixed with gravel and remnants of mollusc shells (coastal depositional environment); 2 – poorly sorted sands and gravels with boulders (fluvioglacial depositional environment); 3 – sands and silts (deposited in ephemeral pools on the tundra surface)

The climate changes clearly contribute to the negative glacier mass balance in the area of Kaffiøyra (Sobota 2009, 2010, 2011, 2013). The valley glaciers have shrunk by approximately 43% since the time of their maximum reach at the turn of the 20th century (Sobota et al. 2016).

In the years 1996-2012, the thawing of the active layer in the Kaffiøyra region demonstrated a considerable variability in individual summer seasons. Its greatest thickness, which was 212 cm at the time, was recorded at a place located at the terminal moraine of the Aavatsmarkbreen, and was mainly caused by the blowing away of the sun and the fact that the thaw began earlier. A much lower mean value was recorded on the beach (124 cm). On the other hand, the active layer in the tundra reached 148 cm on average. The mean temperature of the ground in 2007-2011 was more than 1^{o}C higher than in the 1970s (Sobota and Nowak 2014).

The 1 ha test area in the tundra, where observations were carried out, comprised 36 measurement points. One of these was a permanent measurement point, determined by the following coordinates: 78^{o} 40’ 31.2” N, 11^{o} 49’ 46.5”E, which has been a part of the Circumpolar Active Layer Monitoring programme (CALM) since 1996 (Sobota and Nowak 2014). That point is situated at about 3 m a.s.l., in an old outwash plain, in the forefield of the Aavatsmarkbreen’s moraine ridge. Its geologic structure mainly comprises gravels and local impurities of sand and silt fractions with occasional boulders (Figs 1, 2). The surface of the outwash plain is covered by a relatively shallow dry tundra with moss and lichens of such plant communities as Saxifraga opositifolia - Scorpidium Revolvens, Salix Polaris-Sanionia uncinata, and Luzula arcuata ssp. confuse - Centrariella delisei (Sobota and Nowak 2014).

Within the test field in the tundra, Gleic Regosols were encountered, which are very wet most of the time in the summer. Another typical feature is the occurrence of a layer of water (Sobota 2013) above the permafrost table, as shown in Figure 2. The morphological properties of this kind of soil, related to soil-formation processes, were hardly expressed. The surface section of the profile incorporates a non-continuous organic level of a few millimetres, mainly based on blue-green algae. A very thin humus level does not exceed a thickness of 5 cm. The humus observed in the surface levels is partially allochthonous. It comes from the organic matter of the tundra, carried in by the wind or redeposited by seasonal runoff. The soil has similar physical and chemical properties to those of the parent rock (Plichta 2005).

The height differences within the analysed area are not significant and do not exceed 1.6 m. The relief involves a gradual sloping of the surface from the NE to the SW, towards the periodically active tidal channel.

Metods

There are three permanent permafrost measurement points in the vicinity of the NCU Polar Station. They are located in areas which represent typical surface features of the Kaffiøyra region, i.e. a sandy beach, a moraine ridge and a tundra plain (Fig. 1) (Sobota 2013). Besides those permanent active layer monitoring points, two test fields representing the tundra and the beach are situated near the Station, as well (Fig. 3). For the purpose of this article, data obtained during observations in the tundra test field were used. The test area was 100 m by 100 m, and comprised 36 uniformly arranged measurement points (Fig. 3).

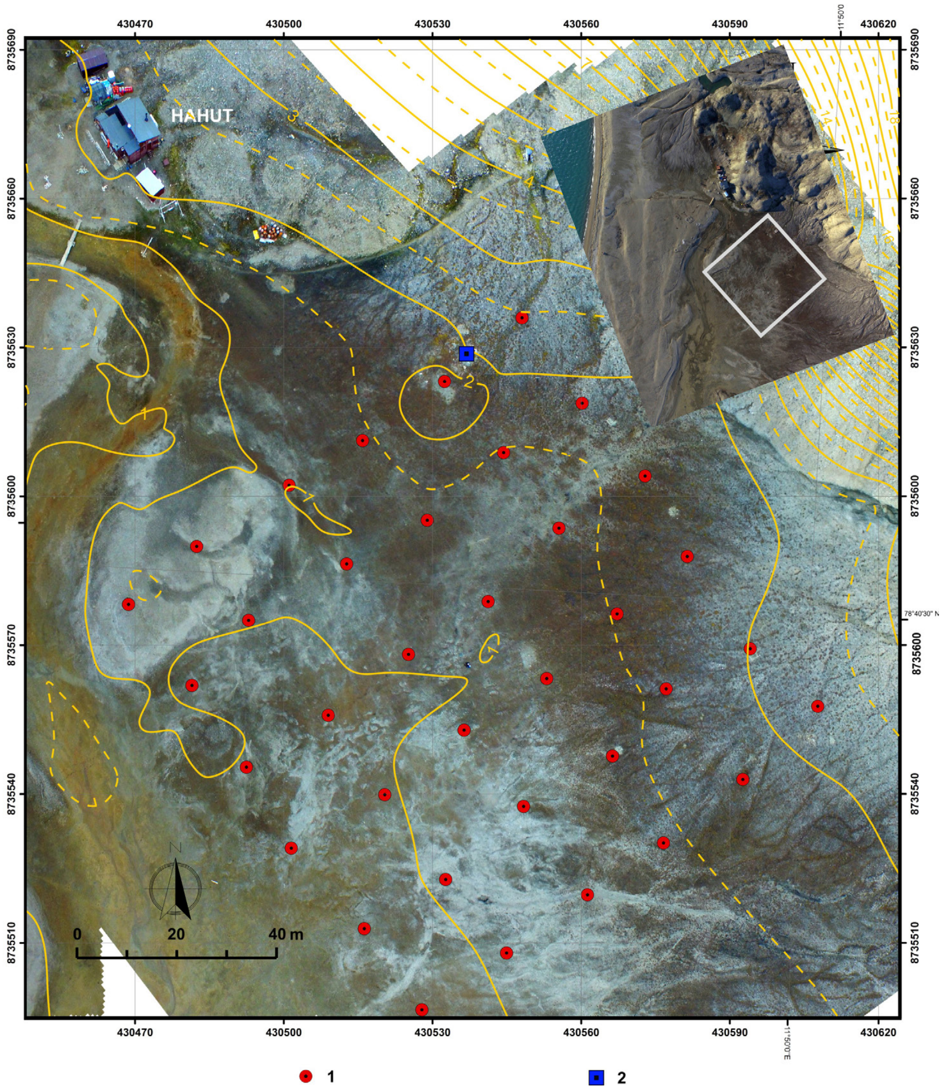

Fig. 3. Location of the test field and the measurement points in the tundra in the Kaffiøyra region. 1 – active layer thickness measurement points, 2 – ground temperature measurement point (photo by I. Sobota)

The thickness of the active layer was measured using a penetrometer at 7- to 8-day intervals during the summer season of 2015 (on 14.07, 20.07, 28.07, 4.08, 12.08, 19.08, 26.08 and 3.09). In order to eliminate errors, measurements were taken three times at each point and the result was averaged.

Mean diurnal ground temperatures at 25 cm and 75 cm below the surface and mean diurnal air temperatures were used to provide a comprehensive view on the correlation between the ground thaw dynamic and the prevailing thermal conditions. The data were obtained by means of an automatic weather station (HOBO) equipped with electronic temperature data loggers. Automatic sensors recorded ground and air temperature at hourly intervals. The accuracy of thermistors is ± 0.2°C, and the operation range is -40°C to +75°C.

In order to present the topography of the test fields, their surroundings and the location of the measurement points and any major features around the NCU Polar Station, a geodetic land survey was conducted using a Theo 010A theodolite. The polar method was used, which consists in the determination of the distance between a known point in the coordinate system and the target point, and of the angle between the sight line and the coordinate system section.

Results

The period during which the thickness and thermal conditions of the active layer were measured lasted from July 2015 until the beginning of September 2015 (Fig. 4). The mean air temperature on the Kaffiøyra from 1.07.2015 to 2.09.2015 was 6.5°C. In July, the temperature was 6.9°C, whereas in August it was 6.4°C. The highest values of air temperature were recorded in the first ten days of August, when the maximum diurnal temperature was 15.2°C and occurred on 1.08. The minimum diurnal temperature was recorded on 1.09 and 2.09 (0.2°C).

From 1.07 to 2.09 the precipitation total on the Kaffiøyra was 34.0 mm. Looking into the precipitation in July and August, the precipitation total in July was just 2.4 mm and only on 5 days its daily values ranged from 0.2 mm to 0.8 mm. August proved to be much more rainy, as the precipitation total amounted to 31.6 mm, and the highest daily value was recorded on 18 August (6.4 mm).

The results of the measurements indicate a general increase in the thickness of the active layer in the tundra in 1996–2015 (Fig. 5), however the estimated trend coefficient (+0.846 (±0.692) cm per year) at the main measurement point in the tundra proved statistically non-significant.

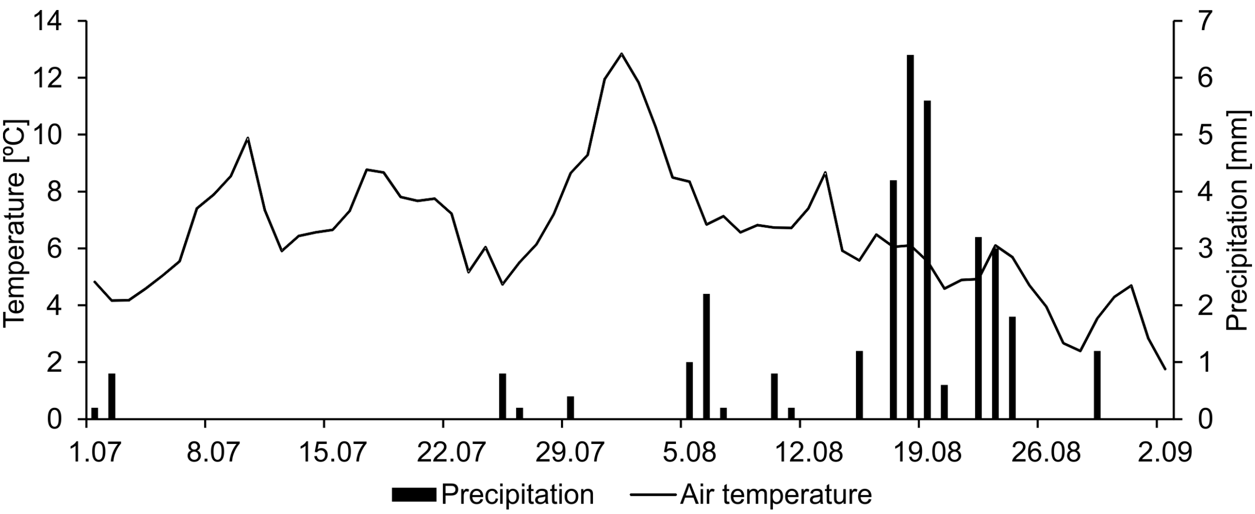

Fig. 4. Mean daily values of air temperature and the precipitation total on the Kaffiøyra in the summer season of 2015 (1st July–2nd September)

The ground temperature measurements in the tundra of the Kaffiøyra region were taken at two depths, 25 cm and 75 cm, from 1 July 2015 to 2 September 2015 (Fig. 6). The highest value of ground temperature (at 25 cm) in the summer of 2015 was recorded on 2 August (10.7°C). It coincided with the increased air temperature occurring at the same time, however it should be underlined that there is a one-day delay in the propagation of heat in the ground at the depth of the measurement. The lowest ground temperature at 25 cm was recorded on 2 September (2°C). At that time, the air temperature was 1.7°C.

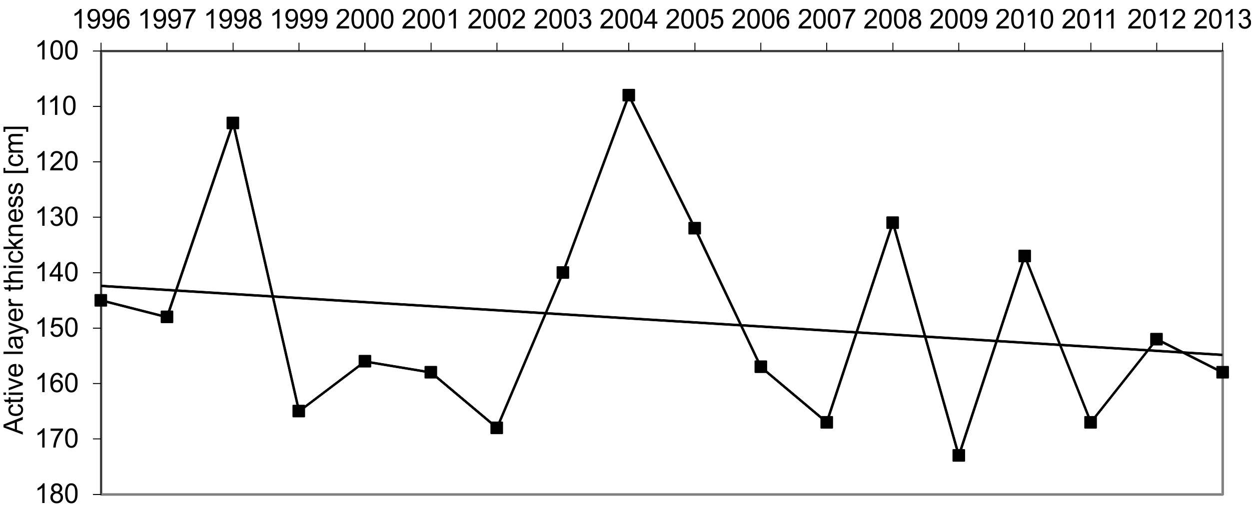

Fig. 5. Maximum active layer thickness in the tundra of the Kaffiøyra region in 1996-2015 (Sobota 2013, Sobota and Nowak 2014, modified)

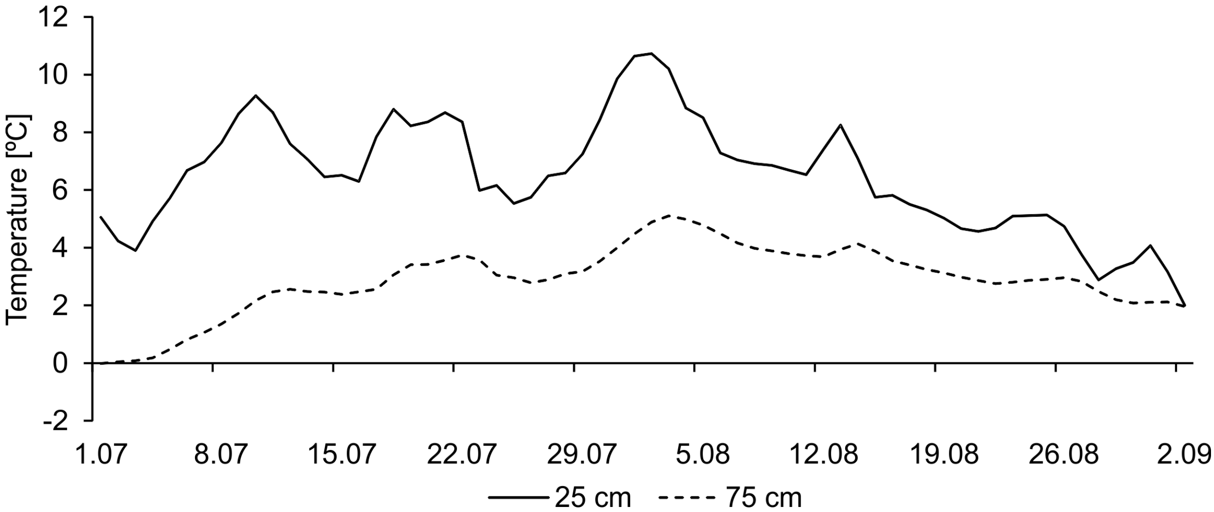

Fig. 6. Ground temperature at a depth of 25 cm and 75 cm in the tundra of the Kaffiøyra region from 1st July to 2nd September 2015

The highest value of ground temperature at a depth of 75 cm was recorded on 3 August (5.1°C). Regarding the propagation of heat into the deeper layers of the ground, a two-day delay was observed with relation to the air temperature course, as the lowest temperature at 75 cm in the analysed period occurred on 1 July (0.0°C).

A greater thickness of the active layer occurred in the eastern part of the test field (Fig. 7), whereas in the western and northern part, it was evidently smaller. Such variability of the active layer thickness of the permafrost could have been the result of the landform features of the analysed area, because a tidal channel is located to the west of it, which may influence its immediate vicinity and cause the development of the sea water infiltration zone, as well as make a base of erosion for water flowing from the higher-lying part of the test field and the terminal moraine surrounding it from the east.

As demonstrated by the results (Table 1), during the first week of observations (14.07–19.07) the active layer thickness increased the most (Table 2) and reached a maximum of 49 cm. During the last week (26.08–3.09), re-freezing of the ground was observed. This indicates that the thaw rate dropped with subsequent measurements as a result of a decreasing thermal sensitivity of the ground to the weather, which was proportional to the increasing depth of the permafrost table. Another aspect influencing the ground thaw rate, especially from mid-August onwards, was a gradual decrease in the mean diurnal air temperature. Considering the general extent of the increase in active layer thickness in the tundra test field, throughout the period of observations, i.e. from 14 July to 3 September 2015 (Fig. 8), its highest value occurred in the northern part of the test field and reached 127 cm. The smallest difference, not exceeding 50 cm, was recorded in the west and the east parts of the analysed area. In the central part of the field, where the land did not slope significantly, average values of the total increase in the active layer thickness were recorded (approximately 50 to 70 cm).

Table 1. Minimum and maximum values of active layer thickness in cm in the test field on the tundra for the selected terms

Date	14.07	20.07	28.07	4.08	12.08	19.08	26.08	3.09
Minimum	76	77	94	111	121	130	134	136
Maximum	136	147	161	168	204	205	206	212
Difference	60	70	67	57	83	75	72	76

Table 2. Minimum and maximum values of active layer thickness increase in cm in the test field on the tundra between the selected terms

Period	14.07-20.07	20.07-28.07	28.07-4.08	4.08-12.08	12.08-19.08	19.08-26.08	26.08-3.09
Minimum	1	0	6	0	1	1	-1
Maximum	49	27	19	16	17	7	6

The observations made it possible to attempt a determination of the correlation between the active layer thickness growth trend with the topography of the area (Fig. 9). The minimum value of the trend was 4.25 cm per 7 days (measurement point no. 8), whereas its maximum value was 20.93 cm per 7 days (measurement point no. 36). The spatial distribution of the obtained values does not indicate any distinct connections between the trend and the elevation. This may be due to the relatively small height differences within the analysed test area, which did not exceed 1.6 m).

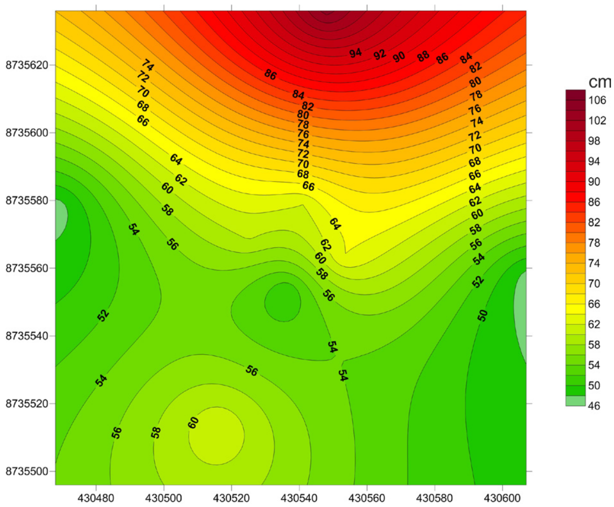

Fig. 8. The increase in the active layer thickness in the test field in the tundra of the Kaffiøyra region between the first and the last measurement (14th July to 3th September of 2015)

Summary and conclusions

The spatial variability of the occurrence of permafrost in areas situated far from the coastline depends on the presence of moss and dense vege-

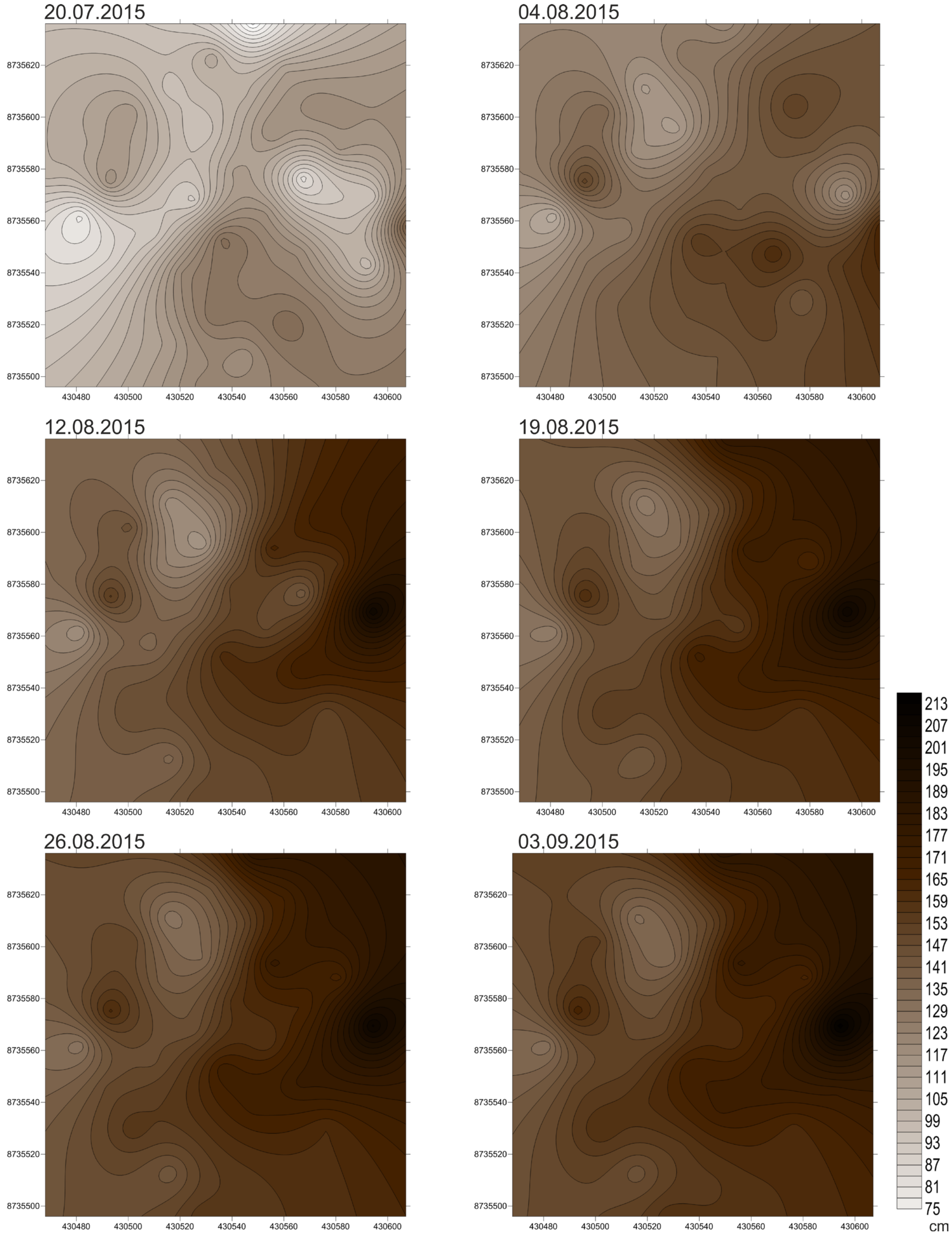

Fig. 7. Active layer thickness in the tundra on selected dates during the summer of 2015

tation, which provide thermal insulation. With such surface cover, in the case of wet tundra, the permafrost table may occur at a depth of just a few dozen centimetres. Where dry tundra prevails and in areas without vegetation, the permafrost can be found at a depth of approximately 1.5-2.0 metres (Dobiński and Leszkiewicz 2010).

According to Kejna et al. (2010), as a result of intense insolation, which takes place at the time of little cloudiness, mountainous and morainic areas in the Kaffiøyra region are warmed up. Consequently, the temperature difference between those areas and the coast affected by cooling sea water decreases. Temperature changes are largely influenced by local circulation of air in the form of glacial or foehnic winds. The amount of solar energy reaching the ground surface, which can be determined indirectly by measuring the cloud amount or insolation (Kejna et al. 1993), has a fundamental importance for the thermal conditions of the ground.

In the tundra area of the Kaffiøyra, a delay in the heat or cold transfer increasing with the depth is observed. The connection between ground temperature and air temperature weakens with the depth, which is evident in the value of the Pearson's correlation coefficient, decreasing from 0.94 for a depth of 25 cm to 0.51 for 75 cm. Observations of these correlations confirmed a delay in the changes of ground temperature relative to weather conditions. At a depth of 25 cm, the delay was about 24 hours, whereas at a depth of 75 cm, a two-day shift of changes in the thermal conditions of the ground, relative to changes in air temperature.

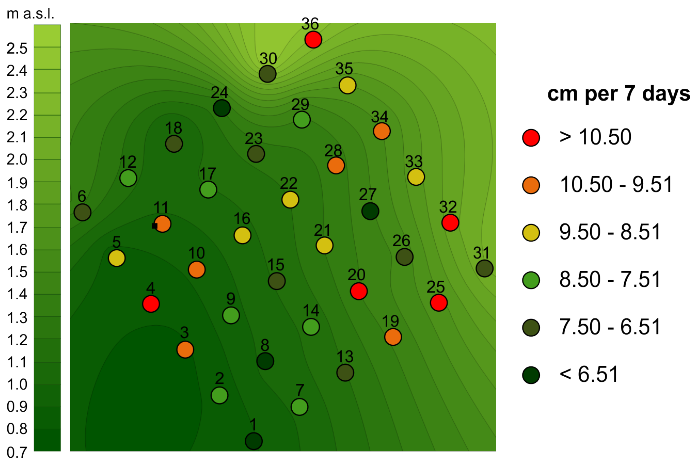

Fig. 9. Spatial distribution of trend of the active layer thickness growths for the individual measurement points in the test field in the tundra of the Kaffiøyra region, against height differences

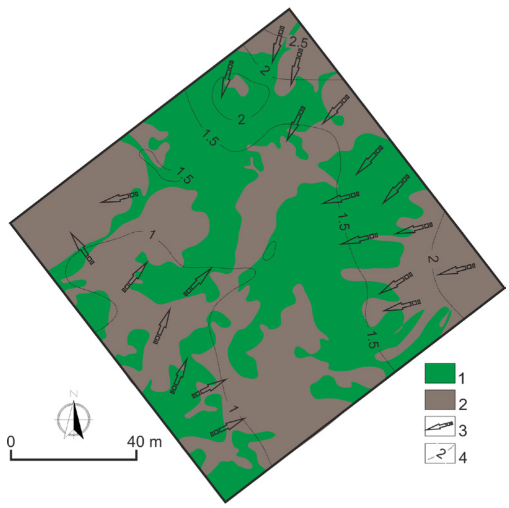

Fig. 10. Topography and plants scheme map of the test field in the tundra of the Kaffiøyra region. 1 – area with plants, 2 - area without or single plants, 3 – direction of surface water flow, 4 – contour lines

The much lesser sensitivity to weather stimuli is manifested in a decreasing variability of the diurnal temperature of the ground. As the depth increases, the temperature conditions of the ground become determined not only by the weather, but also by the growing influence of the permafrost, for which the active layer thickness at the main measurement point in the tundra was 173 cm (which is the value of the maximum thaw of the ground in the summer of 2015).

The considerable irregularity of the spatial distribution of the permafrost table depth suggests looking for reasons connected with the surface features, besides meteorological factors. The greatest thickness of the active layer (between 156 cm and 212 cm) is observed near the moraine, where the land slopes the most (Fig. 10). This can be connected with an increased surface runoff, which becomes more voluminous as a result of precipitation. Moreover, precipitable water filtrating into the ground also affects the thermal conditions and increase ground temperature (Migała et al. 1991; Sobota and Nowak 2014).

Higher values of the active layer thickness were found in the western part of the test field, adjacent to the tidal channel, and in its eastern part, bordering on the foot of the moraine. In the first case, the increased thickness could be due to sea water infiltration and decreased elevation, whereas in the latter case, the increased slope of the ground surface may be responsible for the increased thickness, causing greater surface runoff from the terminal moraine towards the tundra, which is particularly ample during rainfalls. Such increased supply of precipitable water to the tundra (local erosion base) increases its infiltration and thus raises the temperature of the active layer. This proves an indirect influence of surface features on the extent and rate of changes occurring in the active layer.

The observations demonstrated considerable changes in the temporal dynamic of ground thaw, connected with the fact that any changes in the active layer and thermal conditions of the ground are highly dependent on prevailing weather conditions.

The changes in the active layer thickness in the Kaffiøyra region are a clear reflection of fluctuations of air temperature. Nevertheless, the tendency to increase the boundary depth of ground thaw in the tundra in the years 1996-2015 is not stable and may undergo changes during subsequent seasons, depending on changes in air temperature. However, over the last few years a growing trend in the active layer thickness has been observed in the Kaffiøyra region.

The active layer is a cryosphere component which responds to environmental changes. The response can be suppressed by a number of factors with a different degree of influence. These include snow cover, the presence or absence of vegetation and moisture conditions. Observations have shown that – in recent years – seasonal (summer) ground thaw reaches deeper and deeper. This enhances morphogenetic processes, leading to intensive transformations of the surface features, which can affect other components of the polar environment.

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