POLISH POLAR RESEARCH
vol. 29, no. 3, pp. 261–278, 2008

Changes in thermal structure of permafrost active layer in a dry polar climate, Petuniabukta, Svalbard

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Abstract: The relationships between meteorological conditions, permafrost active layer thickness and thermal structure were studied for a dry, polar climate site, next to Petuniabukta (central Spitsbergen), during four successive summer seasons (2000–2003). In addition to determination of the ground sedimentological and mineralogical properties, the following parameters were measured: air temperature, air humidity (both at 2 m and 0.05 m above the ground), wind direction and velocity (at 2 m), precipitation, cloudiness, thickness of the permafrost active layer and ground temperature at 0.05, 0.1, 0.25, 0.5 and 0.75 m below the surface. The permafrost level was lowered 0.7 to 1.1 cm day^{-1} during days with temperature above freezing, reaching a maximum depth of 1.2 m. The temperature of the top 0.1 m of the ground reacted within one to two days to changes in air temperature. The reaction period of the ground temperature at 0.5 m was several days. Rainfall events were of minor importance to thermal ground structure, in contrast to sites with a more marine climate. Other meteorological factors had a very small influence on the ground temperature. During summer, a well developed thermal gradient reaching over 12°C m^{-1} was observed, followed by isothermal conditions with temperature of 0°C at the beginning of fall, and reversal of the thermal gradient (-6.7°C m^{-1}) in late fall. The interannual variations were mainly due to changes in summer temperature and to the length of period with snow cover in spring, which limited the beginning of thawing. The thermal structure of active layer is governed by seasonal conditions, regardless of overall climatic change.

Key words: Arctic, Svalbard, permafrost, active layer, ground temperature, meteorological conditions.

Introduction

Arctic environments are being particularly altered by recent global warming (*e.g.* Overpeck *et al.* 1997; Richter-Menge *et al.* 2006). Existing climate models also predict that the greatest future change will occur in the Polar Regions. Among the most sensitive components of the Arctic system, besides glaciers and biota (*e.g.* Wlodarska-Kowalczuk and Weslawski 2001; Hagen *et al.* 2003; Ziaja 2004; Rachlewicz *et al.* 2007), is permafrost. It has been observed that climate warming has severe consequences for the permafrost on regional and global scales (*e.g.* Kane *et al.* 1991; Anisimov *et al.* 1997; Brown *et al.* 2000; Humlum *et al.* 2003; Zamolodchikov *et al.* 2004). The thermal structure of the permafrost active layer and its reactions to climate changes are of particular importance because they directly influence biogeochemical reactions and the basic geotechnical properties of the ground. The former are believed to influence the atmospheric greenhouse gas (CO_2 and CH_4) balance (*e.g.* Oechel *et al.* 1993) and the latter are important in areas occupied by people – for example on Spitsbergen in the European Arctic (Nelson *et al.* 2001; Humlum *et al.* 2003).

In the context of projected warming, changes in meteorological conditions during the thawing season and site-specific ground properties are particularly important, where these are responsible for depth and temperature structure of permafrost active layer development. Radiation balance, air temperature, presence of snow cover, precipitation, humidity, ground physical properties and distance to water bodies are among the most significant influences on permafrost active layer development (*e.g.* Karczewski 1988; Kane *et al.* 1991; Romanovsky and Osterkamp 1995; Boike *et al.* 1998; Putkonen 1998; Beltrami 2001; Migała *et al.* 2004). However, their impacts vary in relation to their duration and magnitude of influence, as well as with specific local conditions.

The Svalbard region has been the subject of many permafrost-related studies, covering various aspects (*e.g.* Jahn and Walker 1983; Grześ 1990; Etzelmüller 2000; Humlum *et al.* 2003; Repelewska-Pękalowa and Pękala 2004; Gibas *et al.* 2005). These studies also measured time series of active layer temperature collected from several sites, mostly along the relatively warmer and more humid western coast of Spitsbergen (*e.g.* Czeppe 1966; Jahn 1982; Głowicki 1985; Marciniak *et al.* 1988; Miętus 1988; Kejna 1991; Migała 1991; Putkonen 1998; Roth and Boike 2001; Araźny 2002; Leszkiewicz and Caputa 2004; Migała *et al.* 2004). Most of the data are one season or one year series, so comparison of different meteorological scenarios for the same site are limited to a few locations along the western coast of Spitsbergen, for example: Hornsund Polar Station – 77°00.1'N 15°32.6'E (Baranowski 1968; Głowicki 1985; Miętus 1988; Migała 1991; Araźny 2002; Leszkiewicz and Caputa 2004; Migała *et al.* 2004), Calypsostranda – 77°33.5'N 14°30.6'E (Repelewska-Pękalowa and Pękala 2004), Kaffiøyra – 78°40.4'N 11°50.5'E (Marciniak *et al.* 1988; Kejna 1991) and Ny Ålesund – 78°55.4'N°11°55.4'E (Putkonen 1998; Roth and Boike 2001). From the central part of Spitsbergen, which is characterized by a more continental climate with lower precipitation (Kostrzewski *et al.* 1989; Przybylak *et al.* 2007), only data from Adventdalen and the vicinity of Longyearbyen, where the Circumpolar Active Layer Monitoring (CALM) site is lo-

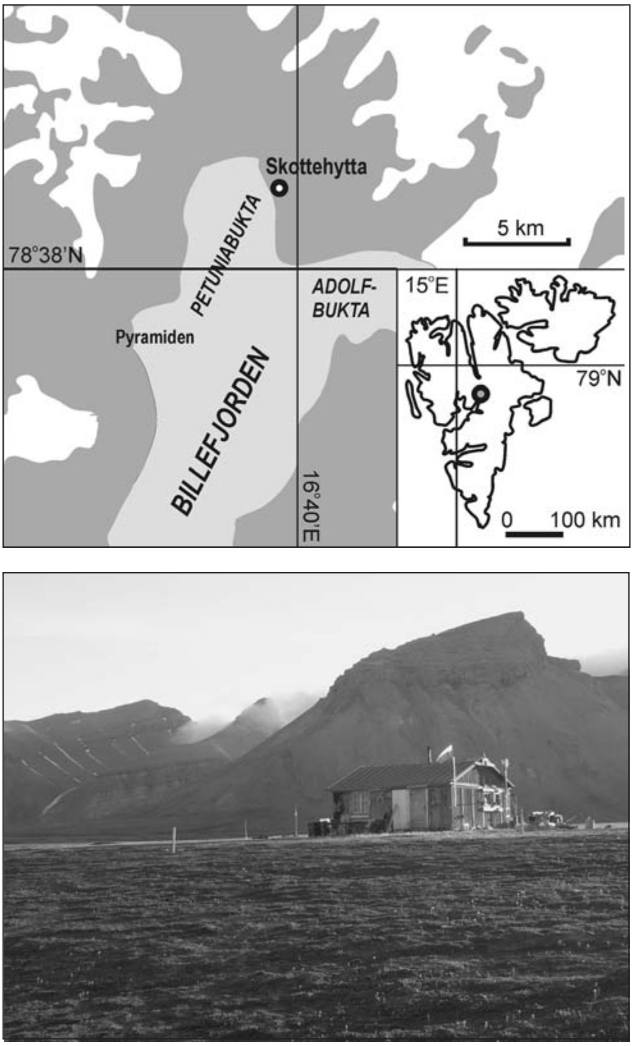

Fig. 1. Location of the study site showing fjord waters (light grey), glacier covered (white) and non-glacier covered areas (dark grey). Photo presents the relief of raised marine terrace (5 m a.s.l.) near Skottehytta and the meteorological station on its left hand side. The ground temperatures were measured 20 m away from the station.

cated (Christiansen and Humlum 2003; Christiansen 2005), and one-season measuring series by Karczewski (1988) and Kostrzewski *et al.* (1989) from the vicinity of Petuniabukta have been published.

In the present study, variations in the thickness of the permafrost active (thawing) layer and its thermal structure are documented in relation to meteorological conditions at a site next to Petuniabukta, central Spitsbergen. The measurements were conducted during four summer expeditions (2000–2003). They allowed observations of different cases of ground temperature reactions to changes in air temperature, humidity, precipitation, wind speed and other meteorological parameters. The main objectives of the present paper are threefold: 1) to document changes in the summer ground thermal structure in relation to changing meteorological conditions for the little-studied central part of Spitsbergen, 2) to determine the relative significance of influencing factors and 3) to assess the importance of interannual changes in climate on permafrost thaw depth and ground temperature structure.

Study site

The investigated site is located in the central part of Spitsbergen – the largest island of the Svalbard archipelago, on the eastern coast of Petuniabukta – next to an old wooden hut called *Skottehytta* (Fig. 1), located at geographical coordinates 78°41.98' N and 16°36.69' E. The study site is the same one used for measurements of ground temperature and meteorological conditions in July 1985 by Kostrzewski *et al.* (1989). It is situated on the Holocene marine terrace, formed during glacioisostatic uplift. The site is covered with poorly-developed sandy soil, covered with heath vegetation composed of *Salix polaris*, *Saxifraga oppositifolia*, *Saxifraga cernua*, *Polygonum viviparum* and *Cassiope tetragona* (Gulińska *et al.* 2003). The average annual air temperature is about -6.5°C. The warmest months are July and August (usually 5–6°C but recently even above 7°C – Rachlewicz 2003a). Precipitation is very low, about 200 mm annually (Hagen *et al.* 1993). The period of air temperatures above 0°C starts in June and lasts until the end of August or middle of September (Hansen-Bauer *et al.* 1990). As shown by Kostrzewski *et al.* (1989) and Rachlewicz (2003a), the weather conditions in this part of Spitsbergen differ from the well-studied western coast of the island, particularly with regard to precipitation, which is much lower at the site described here (Przybylak *et al.* 2007). Snow cover is usually thin, and due to strong local winds the snow often drifts away from the study site. The permafrost active layer thickness in the region of Petuniabukta varies between 0.5 and 2.5 m (Gibas *et al.* 2005).

Methods

The ground temperature and meteorological conditions were measured during the 2000 (11.07–09.08), 2001 (07.07–18.09), 2002 (11.07–30.09) and 2003 (21.06–14.08) summer season at the same site, four times per day (at 0:00, 6:00, 12:00, and 18:00 GMT). The ground temperature was measured at 0.05, 0.1, 0.2, 0.5 and 0.75 m below the ground surface with thermistors installed in early July 2000. The accuracy of the thermometers was 0.1°C. They were inserted in the wall of a pit, which was dug down to permafrost layer with significant amount of interstitial ice, and then carefully covered with the material previously taken out. The surface soil cover was previously cut and, after the thermometer installation, was replaced. The active layer thickness (thaw depth) was determined mechanically with a graduated rod, which was inserted into the ground to the point of resistance. These measurements were taken weekly, near the temperature measuring site.

Meteorological measurements were based on the automatic weather station WMR 900 H by HUGER. The following parameters were recorded hourly: atmospheric pressure (reduced to sea level), air temperature and humidity (both at 0.05 m and 2 m above the ground surface), wind speed and direction (2 m above the ground surface), and precipitation (1 m above the ground surface). Cloud coverage on a nine-element scale (0 – clear sky, 8 – total coverage) was recorded four times per day. Collected data were averaged daily except for precipitation, which is presented as a daily sum.

To determine the ground properties, samples of major sediment types were collected from the profile where the thermometers were installed. The samples were analyzed for grain size distribution by sieving. Results are presented on a [phi] scale. Conversion of size from millimeters into [phi] values is based on the relationship: Φ [phi] = - $\log_2 D$, where D is the size in millimeters. The mineralogy of the gravel fraction was determined by macroscopic investigations. The clay fraction (<2 µm) was analyzed by X-ray diffraction (CuKα-radiation). Samples were investigated as oriented, glycolised and heated at 550°C. Mineral identification followed Moore and Reynolds (1989).

Results

Ground properties. — The ground is composed mostly of gravel and sand of marine origin. Detailed grain size analysis for representative layers shows the uppermost soil layer (0–0.1 m) to be a poorly sorted gravelly muddy sand. The deposit below, down to a depth of 0.5 m, is composed of poorly sorted sandy gravel, which is underlain by moderately sorted gravel (Fig. 2). The deposits are stratified, except for the top soil layer. The gravels are composed mainly of local limestone and dolomite. The clay fraction in the top sample is composed mainly of illite with a minor contribution of chlorite.

Meteorological conditions. — The meteorological conditions in Petuniabukta were partially presented for the years 2000 and 2001 by Rachlewicz (2003a) and for 2002 by Rachlewicz (2003b). Observations of basic meteorological components show distinct differences between successive summer seasons (Figs 3–6). The highest temperatures were observed in August (monthly average between 6.5°C and 8.5°C), and the next highest in July (monthly average between 6.5°C and 7.0°C). This is opposite to the relation between July and August in Longyearbyen, which is more affected by maritime climatic conditions (Rachlewicz and Styszyńska 2007). The melting season had already begun by the beginning of July

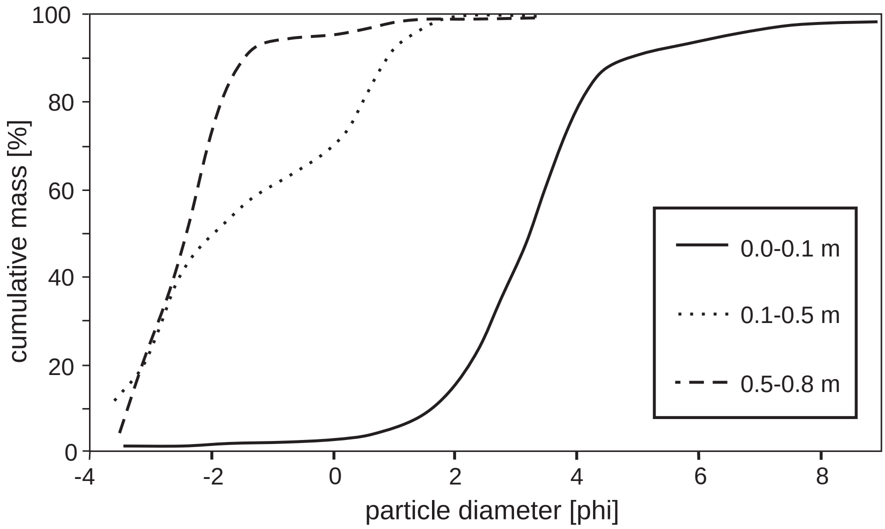

Fig. 2. Cumulative grain size distribution curves for three representative samples from the study site.

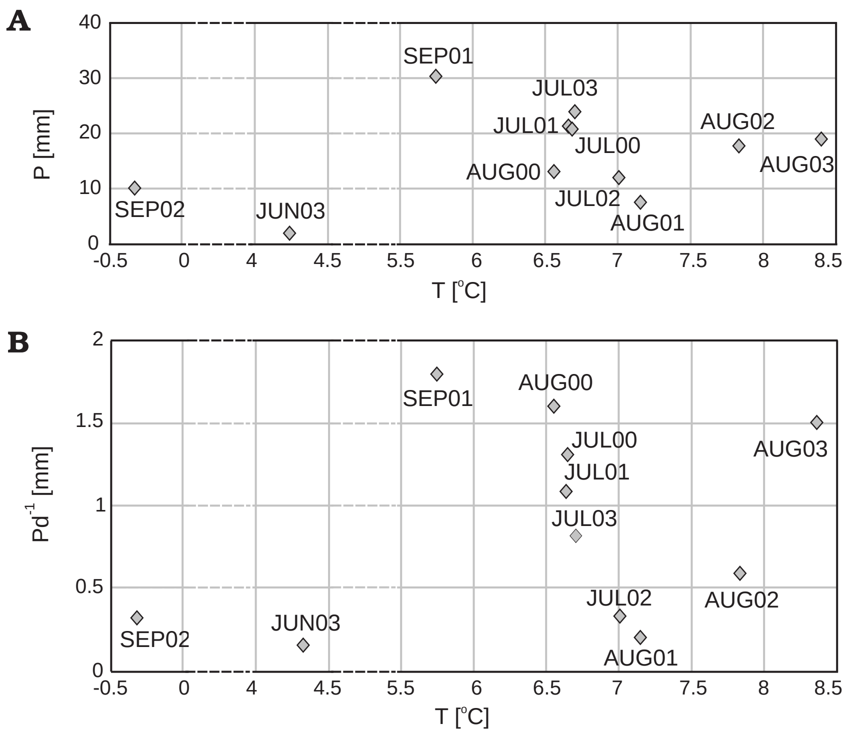

Fig. 3. Average air temperature (T) plotted vs. (**A**) sums of precipitation during these days (P) and (**B**) average daily precipitation (Pd^{-1}). For June 2003; July 2000, 2001 and 2002; August 2000 and 2003; and September 2001, the average is based on the available record of observation periods shorter than a month.

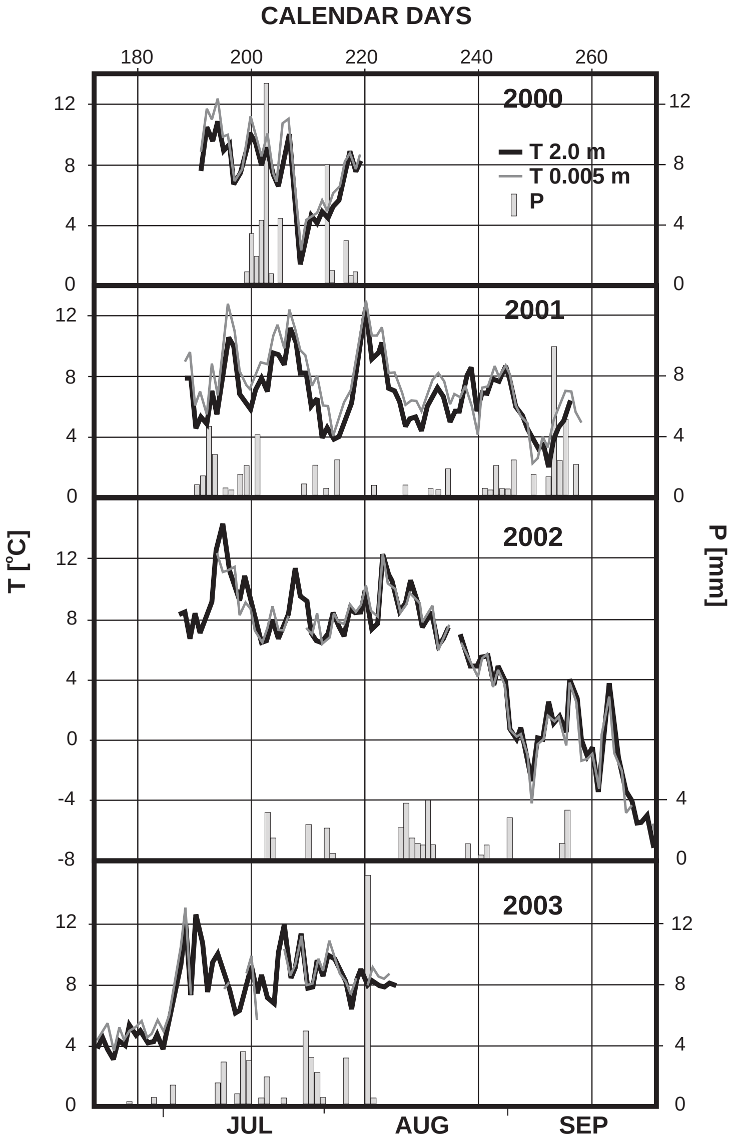

Fig. 4. Time series of daily mean air temperatures (T) 2 m and 0.05 m above the ground surface, and daily sums of precipitation (P).

when observations started each year, except in 2003, when a distinct rise in temperature (more than 5°C) was observed at the beginning of July, initiating intensive melting processes (Fig. 4). The termination of positive temperature periods was observed at the beginning of September or at the beginning of October. In 2001, after a relatively cool and very dry August, no drop below 0°C was observed until the end of September, while in 2002 temperatures reached the freezing point in the first days of September.

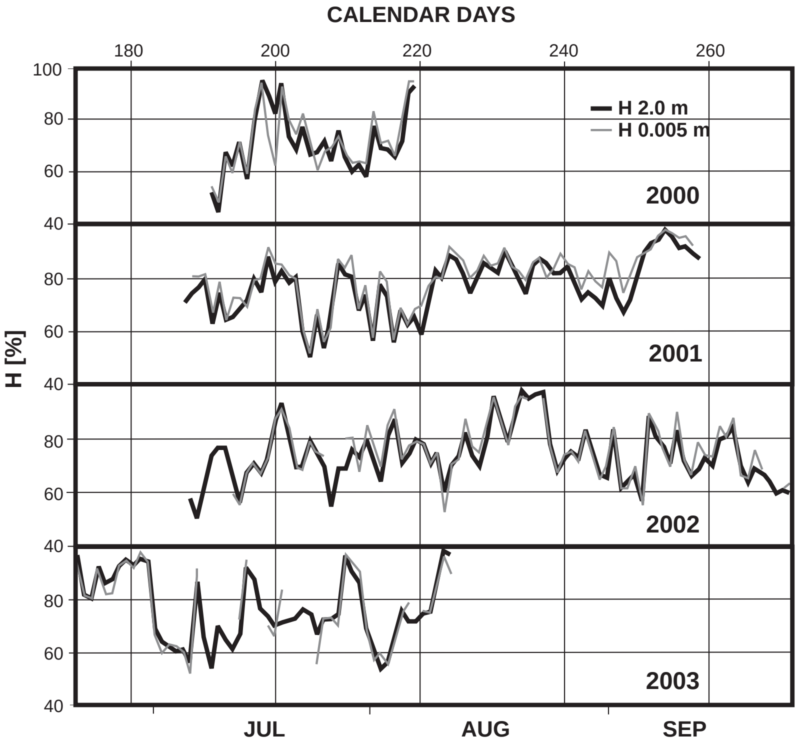

Fig. 5. Time series of daily mean relative air humidity (H) 2 m and 0.05 m above the ground.

The measurements of air temperature performed at two levels (2 and 0.05 m) were very well correlated (Fig. 4). On average, the air temperature near the ground was about 0.5°C higher in summer. In fall, when air temperatures were below 0°C, the near-ground surface air layer was colder than at 2 m.

Precipitation was distributed unevenly over the summer months (Figs 3 and 4). Sums of precipitation were usually higher in July than in August. During the longest period of measurements in 2002, the total sum of precipitation was the lowest (33 mm). The highest precipitation was in 2001 (59 mm). The seasons 2000 and 2003 were between those previously described in terms of precipitation, with rainfall of 41 and 47 mm, respectively. The most frequent daily sum of precipitation was in the range between 0.5 and 4 mm, exceeding that level three to four times per season. The maximum daily precipitation amounts for the years of investigation were: 13.7 (20.07.2000), 11.1 (13.09.2001), 4.1 (23.08.2002) and 14.8 mm (11.08.2003). Precipitation occurred as rainfall, except on 10.09 and 21.09.2002, when the snowfall generated a few centimeters of snow cover, which melted away within a single day.

The relative air humidity was measured continuously at 2 m above the ground and at 0.05 m above the ground, with some gaps (Fig. 5). Comparison of these measurements showed that the average seasonal values varied between 72 and

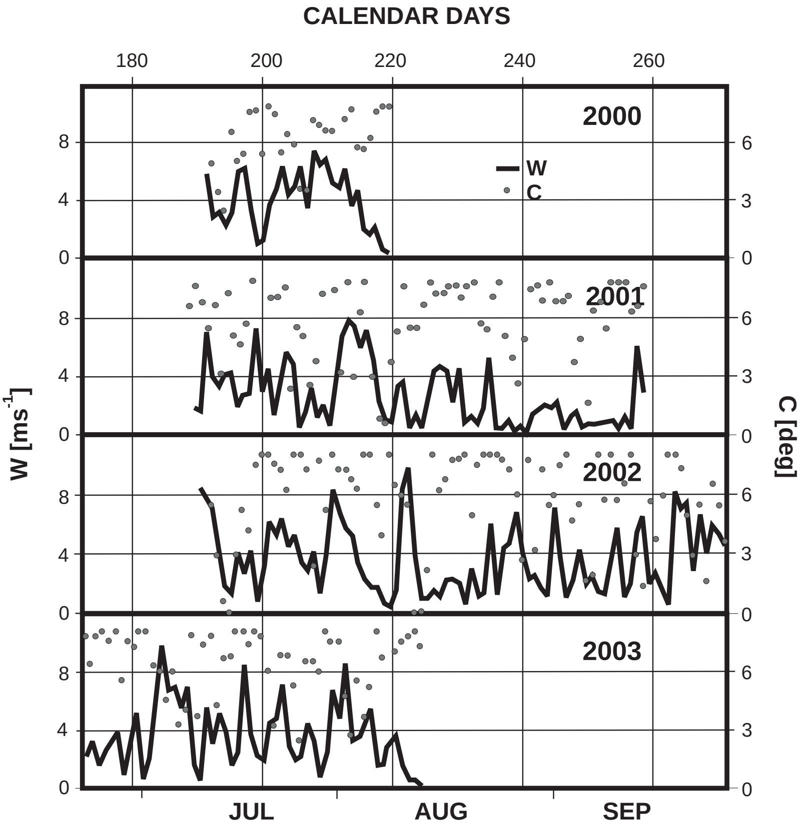

Fig. 6. Time series of daily mean wind velocities (W) 2 m above the ground surface, and daily mean cloudiness (C) on a scale from 0 to 8.

80%, and were slightly higher near the ground. Differences usually did not exceed 5%, but reached 20% when temperature increased rapidly. Daily average relative humidity varied between 44 and 99%. Humidity values are negatively correlated with the air temperature.

Prevailing wind directions observed in the study area were from the south and east, and followed the main morphological features: a fjord and valleys (Rachlewicz 2003a). However, the strongest winds reflected *föhn* conditions and blew from the north (Rachlewicz 2007). Average daily wind velocities did not exceed 8 m s^{-1}, frequently oscillating about 4 m s^{-1} (Fig. 6). Periods of stillness, with the percentage of no-wind conditions reaching 15%, were separated with events of wind gusts with velocities up to 17.7 m s^{-1}. There was a weak negative correlation between wind speed and relative air humidity, matching best when wind velocities were between 2 and 4 m s^{-1}.

The average cloudiness (Fig. 6) was above 5.7, and rose during the fall (by 0.4 unit) due to long-term periods of total sky coverage. Average seasonal values varied between years of observations from 5.7 to 6.4.

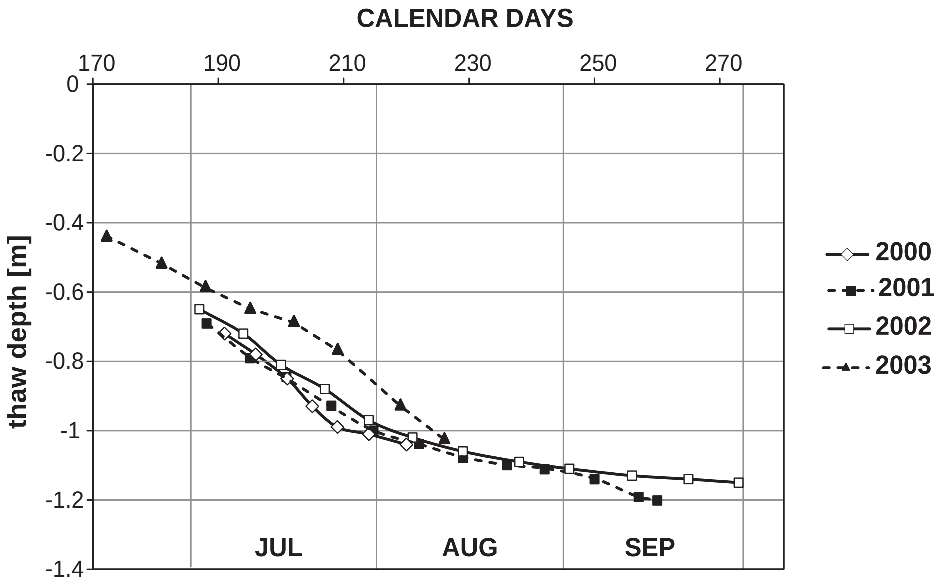

Fig. 7. Active layer thickness changes during the monitoring periods.

Table 1

Minimum and maximum thaw depth, and rate of its change in subsequent summer seasons 2000–2003

Year	Thaw depth thickness at the beginning of the survey season (date) [m]	Thaw depth thickness at the end of the survey season (date) [m]	Average rate of increase of the active layer thickness [m day^{-1}]	Average rate of increase of the active layer thickness during positive degree days only [m day^{-1}]
2000	0.72 (11.07)	1.04 (08.08)	0.011	0.011
2001	0.69 (07.07)	1.20 (17.09)	0.007	0.007
2002	0.65 (06.07)	1.14 (30.09)	0.006	0.008
2003	0.45 (21.06)	1.03 (14.08)	0.011	0.011

Thaw depth. — Changes in the active layer thickness were similar during all the studied years, except 2003 when the process of permafrost level lowering was delayed. At the end of June, the thaw depth was usually at about 0.5–0.6 m, and at the end of the summer season it reached up to 1.2 m (Table 1, Fig. 7). The average rate of permafrost melting during the summer (positive degree days) was between 0.007 and 0.011 m day^{-1} (Table 1). During the fall (as exemplified by September 2002), the permafrost table was stabilized at a maximum depth of 1.14 m. In the warmer years (2001), when positive air temperatures extended through September, thawing proceeded down to 1.2 m until the middle of September. The intensity of the thaw rate and the record of air temperatures allowed a prediction of May for the beginning of the thaw for the last decade.

Changes in ground temperature. — Temporal sequences of ground temperature changes in a vertical profile for consecutive years are presented in Fig. 8. The largest changes in the ground temperature were observed for the near-surface level. At depths of 0.1, 0.2, 0.5 and 0.75 m below the ground surface, the recorded tempera-

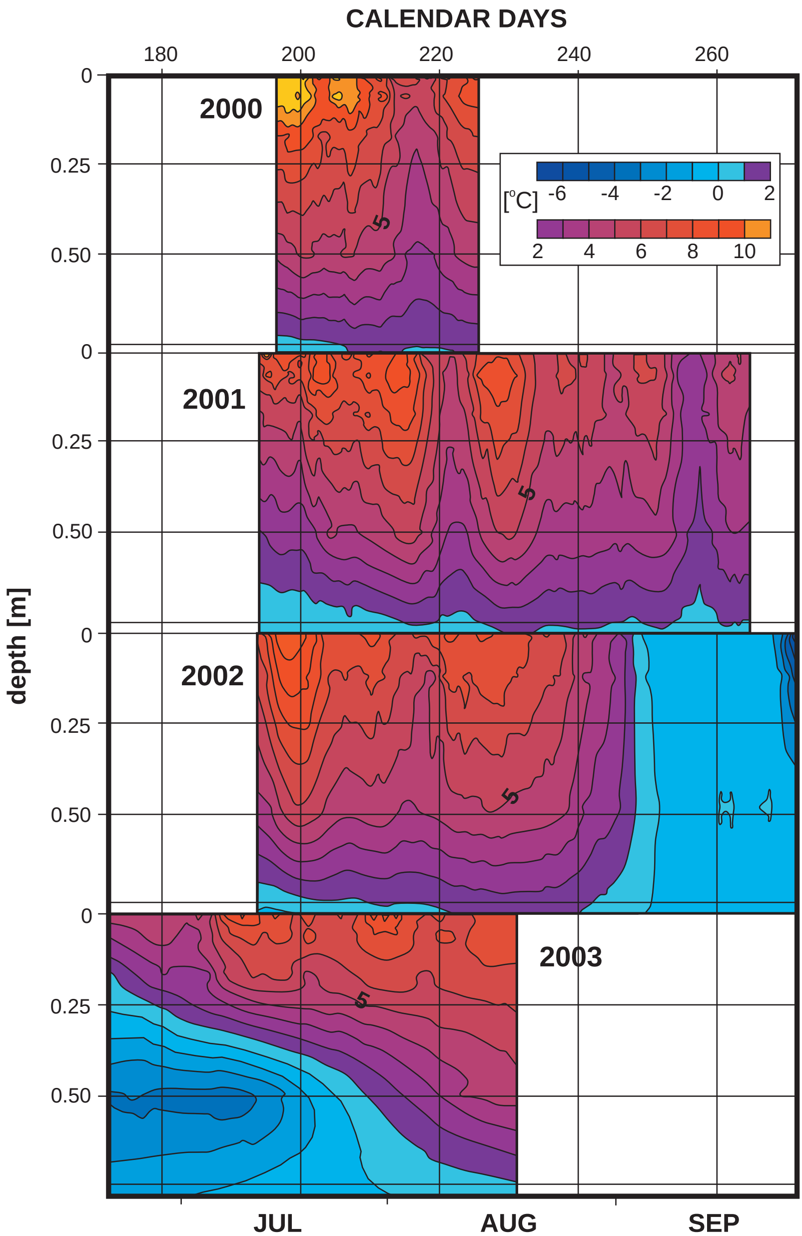

Fig. 8. Temporal changes of ground temperature with depth below ground surface for the summer seasons 2000–2003.

ture amplitudes for the individual measurements throughout the observation period were 20, 14.5, 9.5 and 4°C, respectively. The beginning of the summer season (the end of June 2003) is reflected by the thawing front penetration, with the lowering of the 0°C isotherm from the depth of 0.25 m, to more than 1 m in August. At the beginning of each summer, within the first decade of July, thermal gradients exceeded 9°C m^{-1}. The full warm season, observed in 2001 until the end of measurements, and in 2002 until the end of August, showed a "nested" temperature profile. Maximum day-to-day changes recorded at the shallowest depths were in the range of 4 degrees. Oscillations adjusted to longer periods of weather changes, on the order of 5–7 days, were reflected down to the depth of 0.5 m. The maximum ground temperature of 15.3°C was noted near the surface on 25.07.2003. Within these warmer periods, short cooling intervals are marked with a distinct decrease of ground temperature amplitude in the whole profile, down to 4 or even 3°C. At the end of the summer, the tendency of decreasing temperature amplitude within the ground profile leads to isothermal conditions, called zero-curtain effect (Outcalt *et al*. 1990), with a temperature of 0°C lasting almost 20 days, followed by gradual cooling from the top of the profile. The minimum ground temperature of -7.0°C was recorded at the depth of 0.1 m (30.09.2002).

Discussion

The presented results of changes in the active layer thawing rates, ground thermal structure and meteorological conditions make it possible to assess the relative significance of particular climatic factors on the permafrost active layer development.

The ground temperature in the surface layer (0.05–0.1 m), as shown in Figures 4 and 8, followed the changes in air temperature immediately. The reaction period at 0.2 m depth was slightly delayed and tempered. However, correlation between temperature time series of air and ground at that depth were still very high (even >0.9). For deeper parts, only changes of longer duration were observed. Rainfall had a very limited impact on the thermal structure – likely in part because precipitation amounts were low. The relation between humidity, cloudiness, wind velocity and ground temperature were also of minor significance.

The correlation between air temperature and ground temperature is weak only during fall, when air temperature drop below freezing point. At that time active layer was characterized by persistence of nearly constant temperature close to 0°C for 19 days. Such a situation of maintained stable temperature is explained by the role of latent heat released during water freezing and is commonly referenced as zero-curtain effect (Outcalt *et al*. 1990). It suggest also considerable amount of water in the active layer despite generally dry conditions.

If the ground temperature is controlled during the summer primary by changes in air temperature the conductive heat transfer model should predict the observed changes. This model applies the Fourier's Law, where thermal conductivity of the material and thermal gradient are the most important variables. However, as demonstrated by many studies, processes of non-conductive heat transfer may be also significant (*e.g.* Karczewski 1988; Kane *et al.* 2001; Putkonen and Roe 2003). As listed by Kane *et al.* (2001), among these processes are those related to non-thermal gradients (gravitational, pore water pressure, osmotic, density, vapor pressure), to boundary conditions and phase change, which was already exemplified by zero-curtain effect. The non-thermal gradients are related mostly to the presence of water and its movement (infiltration from snowmelt or rainfalls) in soils. It is hypothesized that non-conductive thermal effects of very small rainfalls (generally below 5 mm per day) are mostly limited to the uppermost soil portion (less than 5 cm deep), however because our uppermost thermometer was at depth of 5 cm it was not possible to investigated it in detail in the present study. It maybe interesting to extend the future studies of active layer thermal structure to include small scale thermal changes in the near surface zone.

The next factor to be considered is the influence of air temperature trends, in particular whether the ground temperature reacts faster to a warming trend or to a cooling trend. The reactions to both warming and cooling, based on daily averaged temperatures, were of the same magnitude, and showed strong correlation between air and ground temperatures. During periods with oscillating air temperatures, their correlations to ground temperature were weaker.

Long-term series are necessary to assess the importance of interannual changes of climate on permafrost thaw depth and ground temperature structure. However, the only available data for the study site are from 1985 (Kostrzewski *et al.* 1989). They revealed the same range of active layer thickness, with its lowering at a rate of 0.011 m day^{-1} (28.06–26.07.1985) and a similar range of ground temperatures. In fact, temperature changes, as well as correlation of air temperature changes with the air temperature, were very similar to those observed in the year 2000. Climatic data for the period 1985–2003 reveals a steady increase in average annual air temperature (Førland and Hanssen-Bauer 2003), which is also reflected in ice core proxy data (Isaksson *et al.* 2001) and the retreat of many glaciers (Rachlewicz *et al.* 2007). The similarity between data from 1985 and the results presented here suggests that seasonal conditions may be more important for the active layer thickness and thermal structure than long term decadal trends.

Considering the interannual variability among the collected data, the summer 2003 is distinctly different from the previous years and showed a relative delay in active layer development (Figs 7 and 8). As observed by previous researchers (*e.g.* Ling and Zhang 2003; Guglielmin 2006), interannual differences in active layer thickness can be relatively large and mainly related to differing snow accumulations. Indeed, the spring of 2003 was characterized by much higher snow accumulation than previous years (unpublished data from Svalbard Lufthavn, Longyearbyen). This probably caused a delay in the thawing of the ground at the study site.

Alternative explanation would be an exceptional amount of ground ice, which would cause delay in the ground warming.

The major difference between the investigated location and the well-studied western coast of Svalbard is related to about two times smaller amount of precipitation in Petuniabukta. Miętus and Filipiak (2004), in their analysis of ground temperature changes in Hornsund for the period 1978–2000, identified air temperature, and to a lesser extent cloudiness, thickness and density of snow cover, as major factors controlling heat flow and consequently ground temperature. The correlation between summer ground temperature and air temperature for Hornsund in that period was high; however, the correlation indexes are at the lower limit of those observed in the present study. One of the important factors influencing this relation may be meltwater infiltration, which is often overlooked in the energy budget. The infiltration causes abrupt warming events and delivers considerable energy to the soil in late spring (Putkonen 1998). Putkonen and Roe (2003) considered rainfall on snow events as very important for the heat budget. Since snow cover is thin and is subjected to sublimation in central Spitsbergen, the summer thermal structure of the active layer is mainly related to air temperature and phase change effects during freezing and thawing of water.

Conclusions

The presented results lead to the following conclusions:

- The permafrost level decreases during accumulations of days with positive temperature at the study site in central Spitsbergen between 0.007 and 0.011 m day^{-1}, reaching a maximum depth of 1.2 m.
- The ground temperature of the upper 0.1 m reacts within one to two days to changes in air temperature.
- The reaction period of the ground at 0.5 m is up to several days.
- Rainfall events were of minor importance to thermal ground structure during the period of measurement, in contrast to sites with a more maritime climate. Because of the local conditions, a “quasi-continental” climate sub-type of the inner-fjord part of Spitsbergen, only one major meteorological factor – air temperature – correlated closely with ground temperature and permafrost active layer thaw depth.
- During summer seasons, thermal gradients are up to 12°C m^{-1}, followed by a well-developed zero-curtain effect at the beginning of fall, when latent heat released during water freezing plays major role, and reversed thermal gradients developing in winter.
- Interannual variations are mainly due to changes in seasonal (summer) temperature and to the length of period with snow cover in spring, limiting the beginning of thawing.
- The existing data do not reflect climate warming in the last two decades.

Acknowledgments. — This study was supported by grants no. 6 PO4E 041 21 and PBZ-KBN 108/P04/2004 from the Polish Ministry of Science and Higher Education. Witold Szczuciński was supported by a Foundation for Polish Science (FNP) fellowship. Field support provided by members of the Adam Mickiewicz University expeditions to Svalbard in the years 2001–2003 is greatly acknowledged. Michał Kubiak helped in XRD measurements. Helpful comments were provided by anonymous reviewer.

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Received 2 June 2008
Accepted 22 August 2008