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Author: Jan Leszkiewicz, Zbigniew Caputa

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The thermal condition of the active layer in the permafrost at Hornsund, Spitsbergen

Jan LESZKIEWICZ and Zbigniew CAPUTA

Wydział Nauk o Ziemi, Uniwersytet Śląski, ul. Będzińska 60, 41-200 Sosnowiec, Poland
<leszkiew@us.edu.pl>, <caputa@us.edu.pl>

ABSTRACT: Ground temperature variations have been analysed to the depth of 160 cm, with respect to meteorological elements and short-wave radiation balance. The database of the ground temperature covers a thirteen month-long period (May 1992 – June 1993), which included both the seasons of complete freezing of the ground and thaw. Special attention has been given to the development of perennial permafrost and its spatial distribution. In summer, the depth of thawing ground varied in different types of ground — at the Polish Polar Station, this was ca. 130 cm. The ground froze completely in the first week of October. Its thawing started in June. The snow cover restrained heat penetration in the ground, which hindered the ground thawing process. Cross-correlation shows a significant influence of the radiation balance (K*) on the values of near-surface ground temperatures ($r^2 = 0.62$ for summer).

Key words: Arctic, Spitsbergen, ground temperature, short-wave radiation, meteorological seasons.

Introduction

The objective of the research was to identify any pattern in the temperature changes in the near-surface ground layer to a depth of 160 cm during full summer and winter seasons. The present study also aims to determine the more important meteorological elements and components of the solar radiation balance, which influence ground temperature variations in the vicinity of the Polish Polar Station at Hornsund, Spitsbergen. Ground temperature is an important indicator of the nature of the perennial permafrost and the active layer. It strongly influences geomorphological, hydrological, and other phenomena, which are manifested mainly in the active layer and are almost completely restrained by the total freezing of the ground below. To date, investigations of thermal conditions of the active layer of the permafrost in Spitsbergen (Czeppe 1966; Baranowski 1968; Głowicki 1985a; Migała 1990, 1991; Niedźwiedź 1992) include few full-year measuring series. Some investigations have been carried out in summer periods (*e.g.* Leszkiewicz

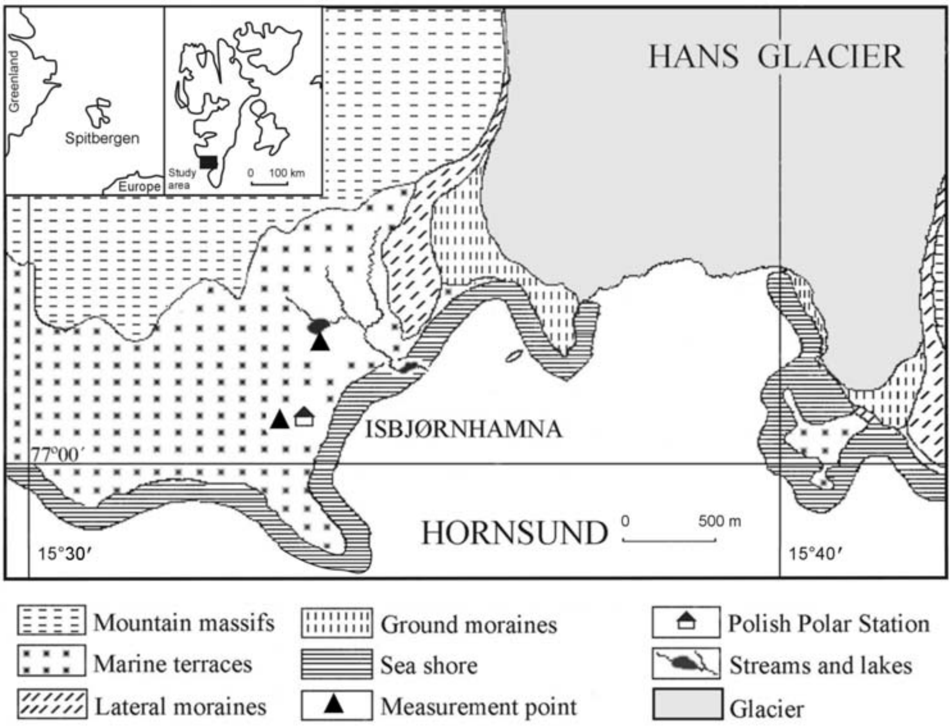


Fig. 1. Locations where ground temperature and radiation balance were measured.

1977; Grześ 1984; Szmyrka *et al*. 1986; Wójcik and Przybylak 1987; Wójcik and Marciniak 1987; Repelewska-Pękalowa and Magierski 1989; Angiel 1993, 1994) but there are very few winter investigations (Kamiński and Wach 1993).

Routine measurements of ground temperature at the Polish Polar Station in Hornsund have been carried on since July 1978. Ground temperatures have been usually measured every 3 hours at depths of 5, 10, 20, and 50 cm in 1978–1986 and, additionally, at the depths of 80 and 100 cm in 1980–1986 (Miętus 1988a, 1988b; Miętus and Filipiak 2001). The application of automatic measuring equipment in 1988–1998 was an important supplement to this programme (Caputa and Głowacki 1999). Since January 2001, the measurements have been conducted automatically every 10 minutes using a set of thermometers placed at the depths of 5, 10, 20, and 50 cm (http://hornsund.igf.edu.pl/meteo.html).

Actinometric observations, other than measuring solar radiation, have been carried out only rarely, and then almost exclusively in summer periods (Baranowski 1977; Pereyma and Piasecki 1986; Pereyma and Lucerska 1988; Angiel 1996). Annual measuring programmes were carried out since 1957/1958 (Baranowski 1977), 1980/1981 (Niewiadomski 1982; Głowicki 1985b), and 1989/1990 (Niedźwiedź 1993); however, they have not always been related to other meteorological elements. The total influx of solar radiation to surfaces of various inclinations and exposures has been calculated by Styszyńska (1995, 1997).

A long, perennial series of data, regarding the thickness of the permafrost active layer, allows us to investigate the influence of the absorbed flux of radiation on its dynamics (Caputa and Głowacki 2002). However, there are also other factors, which influence the thermal conditions of the ground, *e.g.* melt water production and cryochemical processes in non-glaciated areas (Pulina 1984, 1990; Głowacki *et al.* 1999).

List of symbols used in this paper

f – function,
G – downward ground heat flux [W/m^2],
K_i – elements of short-wave radiation balance [W/m^2],
K^* – balance of the short-wave radiation [W/m^2],
$K\uparrow$ – reflected short-wave radiation [W/m^2],
$K\downarrow$ – total incoming short-wave radiation [W/m^2],
p – significance level,
P – precipitation [mm/d],
r – Pearson's correlation coefficient,
r^2 – determination coefficient,
Sn – thickness of snow cover [cm],
ta – air temperature [°C],
tg_d – ground temperature at the depths "d" equal to 0, 5, 10, 20, 50, 75, 100, 120 and 160 cm [°C],
V – wind velocity [m/s],
X_i – meteorological elements different in particular seasons,
α – albedo [% or part of 1.00].

Data and methods

Databases of ground temperature and short-wave radiation, collected in the vicinity of the Polish Polar Station in Hornsund (Table 1), are stored in the Laboratory of the Polar Environment, Department of Geomorphology, University of Silesia. The database of ground temperature, as measured by ground thermometers in the period of 20. 06. 1992 – 4. 06. 1993 at the site of Polish Polar Station, constitutes the basis for this work. As the measuring period did not cover the beginning of the thawing season in May and June 1992 and in June 1993, above data were supplemented by the database of ground temperature measured by an automatic station located in the Fuglebekken (Fugle) catchment basin. The measuring points referred to were located close to each other (500 m) and they were also close to the sea, on raised marine terraces — a typical physiographic unit along the western coast of South Spitsbergen. The depth of measurements was 160 (the Station) and

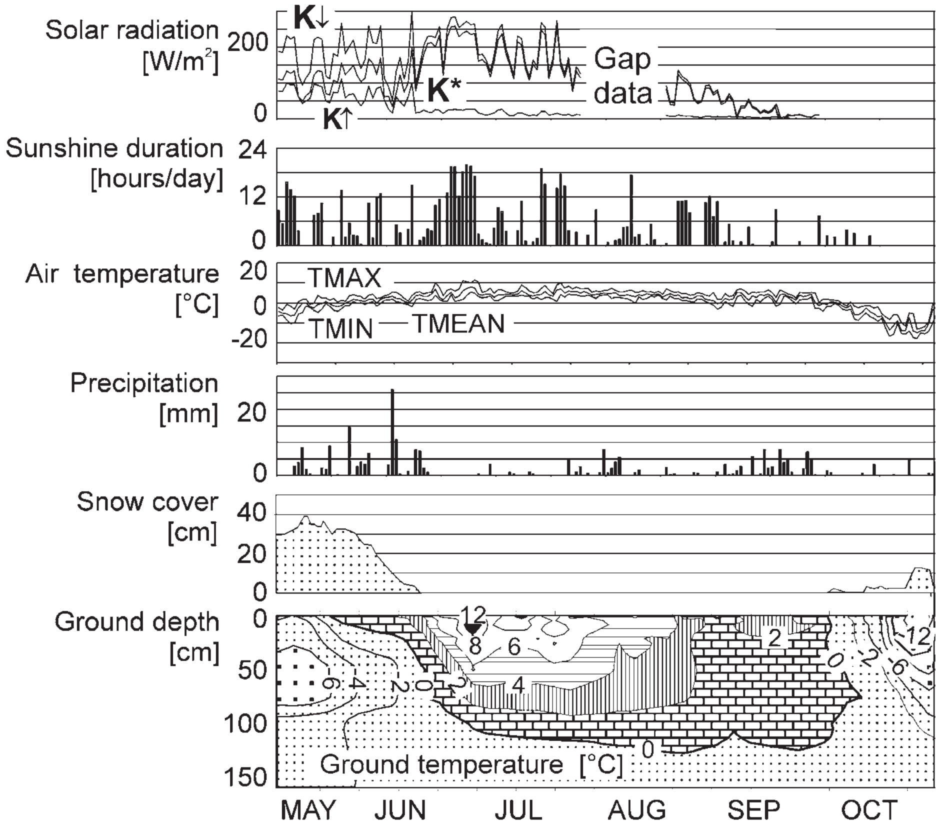
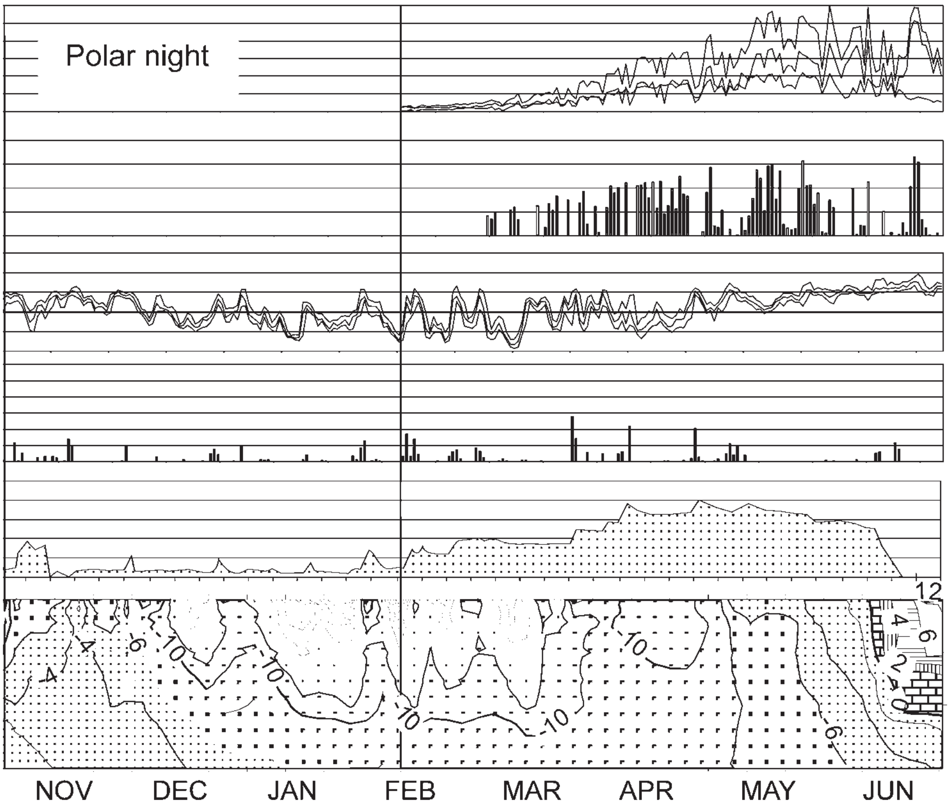


Fig. 2. Ground temperature against solar radiation, sunlight altitude, air temperature, precipitation, →

200 cm (the Fugle); both span the active layer to the top of the permafrost. Short-wave radiation: total, reflected, and the balance were registered at the Fugle site. Meteorological data were provided by the Polish Polar Station in Hornsund (Fig. 1).

The automatic station for measuring ground temperature at the Fuglebekken site was installed in summer 1989. It was equipped with platinum resistant thermometers (Pt-100), placed in the ground at the depths of 200, 150, 100, 75, 50, 20, 10, 5 cm, on the surface of the ground, 5 cm above ground level, and in a meteorological screen at 200 cm. Further, two pyranometers at the Station recorded short-wave radiation: MW-81 — the flux of total radiation (K↓) and MW-91 — reflected radiation (K↑). The pyranometers were located at a distance of 25 m from the laboratory and 1.5 m above the tundra level. The sensitivity of both sensors was 10 W/m^2, and the measuring range was from 1 to 2000 W/m^2 for the wave lengths from 300 to 2600 nm. More detailed description of the method is included in the paper written by Caputa and Głowacki (2002).



and thickness of the snow cover. Ground temperature distribution down to the depth of 160 cm.

Table 1

Databases on ground temperature and short-wave radiation stored at the Department of Geomorphology, Faculty of Earth Sciences, University of Silesia.

Database	Measuring point	Measuring period	Measuring time step	Depth (height) of measurements [cm]
Database on ground temperature measured by ground thermometers	Polish Polar Station (Station) 8 m a.s.l.	June 20, 1992 – June 4, 1993	3 hours	0, 5, 10, 20, 50, 75, 100, 120, 160
Database on ground temperature measured at the automatic station	Fuglebekken Catchment Basin (Fugle) 5 m a.s.l.	1986–1996	10 minutes	0, 5, 10, 20, 50, 75, 100, 150, 200
The database on short-wave radiation from the automatic station	Fuglebekken Catchment Basin (Fugle) 5 m a.s.l.	1986–1996	10 minutes	150

The automatically-registered data were binned into observation periods and presented in Fig. 2. The Program Statistica was used to carry out statistical modelling, whereby mean daily values were obtained.

Thermal seasons

As in the case of the thermal regime of the ground, air temperature could be one of the basic criteria by which the thermal seasons of the year might be distinguished (Tables 2 and 3). Normally, several meteorological elements, mainly the course of isopleths and the state of the snow cover, are the basis by which the thermal seasons are distinguished (Fig. 2). In the research reported here, six thermal seasons have been distinguished: pre-winter, winter, pre-spring, spring, summer, and autumn. Their classification is related to hydrological criteria of Leszkiewicz (1987). The seasons: pre-winter, winter, and pre-spring are associated with "winter" in the general sense, whereas spring, summer, and autumn represent "summer". In particular seasons (data from pre-spring and pre-winter seasons are insufficient to attempt a proper analysis), special attention was paid to statistical correlation between selected meteorological elements, the elements of the radiation balance, and ground temperature. Multiple regression analysis was applied to determine the coefficients of regression (see the attached list for symbols, p. 225):

$$tg_d = f\,(ta, K_i, X_i)\ .$$

After the winter season of 1991/1992, pre-spring started on May 25, 1992, when snow started to thaw mainly in low-lying areas in the vicinity of the Polish Polar Station. The water equivalent of the snow cover in the vicinity of the station was 600–1000 mm on the Hans Glacier, ca. 200 mm in the lowlands, and 150 mm at the Station (Leszkiewicz and Pulina 1999). During the thaw, the temperature of the permafrost rose slowly from negative 4–6°C to 0°C; however, the thaw did not begin until the snow-cover had completely melted. At the Polar Station, the snow cover lasted until June 18, 1992, but the time of complete thawing of snow in the direct neighbourhood of the Station was variable and depended on local conditions, mainly the physiography.

Owing to the thawing of the snow cover, the albedo was reduced from 50 to 15%. The reflected radiation decreased from 63.8 (the average value for pre-spring) to 22.0 W/m^2 (the average value for spring). This also caused a large increase of the heat flux into the ground (G flux). The ground without the snow cover in the spring season quickly thawed down to the depth of 50–95 cm. Locally, large patches of snow thawed, creating nival runoff. The ground surface was first moist then damp.

The beginning of summer is determined by the formation of the summer thermal and humid regime in the ground. A large heat flux caused drying of the ground and an increase of its temperature up to 8°C. Unlike previous seasons, further thawing of the ground was slow — from 100 cm at the beginning of July to 130 cm in the last week of August; this represents the maximum depth of thawing.

Significantly, during the summer period, the ground temperature depended on air temperature, radiation, and solar altitude (Fig. 3). The determination coefficient (r^2) between the values of absorbed radiation (K*) and the ground temperature equals 0.45 ($p < 0.05$). A negative correlation ($r^2 = 0.42$, $p < 0.05$) between the

Table 2

Thermal characteristics of seasons and criteria of determination of their beginnings (* – terms explained in the text).

Season	Characteristics of the season	Determination of the beginning of the season (first day)
Pre-winter	Air temperature around 0°C, temporary snow cover, freezing of the ground downwards from the surface	Occurrence of air temperature close to 0°C
Winter	Winter thermal regime of the ground *, permanent snow cover	Permanent drop of ground temperature below 0°C
Pre-spring	Thaws at lowlands	Beginning of thaws
Spring	Thawing of isolated snow patches at the lowlands, fast thawing of the ground	First day without a snow cover
Summer	Summer thermal regime of the ground *	Beginning of the thermal and humidity regime in the ground *
Autumn	Autumn thermal regime of the ground *	Permanent drop of the ground surface temperature below 3°C

Table 3

Thermal seasons of the year in Hornsund (in the period of October 1991– June 1993) considering meteorological and radiation elements.

Season	Beginning	End	Duration [days]	Depth of the isotherm 0°C [cm]	Ground temperature in the layer 0–160 cm [°C]			Air temperature [°C]			Elements of short-wave radiation balance [W/m^2]		
					tg av	tg max	tg min	ta av	ta max	ta min	K↓	K↑	K*
Pre-winter 1991	2.10	7.10	6	–	–	–	–	–	–	–	–	–	–
Winter 1991/1992	8.10	24.05	230	*	–	–	–	–	–	–	–	–	–
Pre-spring 1992	25.05	18.06	25	0–50	–2.1	2.4	–7.1	0.9	5.5	–4.7	177.9	63.8	114.1
Spring 1992	19.06	30.06	12	50–95	0.9	11	–1.4	3.7	10.0	0.5	216.6	22.0	194.6
Summer 1992	1.07	28.08	59	95–125	2.7	16.1	–1.1	4.5	11.4	–0.2	169.8	14.5	155.3
Autumn 1992	29.08	29.09	32	125	0.8	4.3	–0.6	2.8	7.1	–3.2	35.1	4.2	30.9
Pre-winter 1992	30.09	8.10	9	125–0	0	1.4	–2.5	–0.8	2.0	–4.2	11.0	0.0	11.0
Winter 1992/1993	9.10	12.06	247	*	–8.2	0.5	–27.3	–9.4	5.1	–28.6	• 0.0 ⊗ 116.6	• 0.0 ⊗ 50.6	• 0.0 ⊗ 66.1
Pre-spring 1993	13.06	20.06	8	–	–	–	–	2.2	7.2	–0.6	147.3	59.6	87.8

*	isotherm 0°C does not exist in the ground in winter,
–	no data or data under processing,
•	the period of the polar night,
⊗	the period after the polar night.

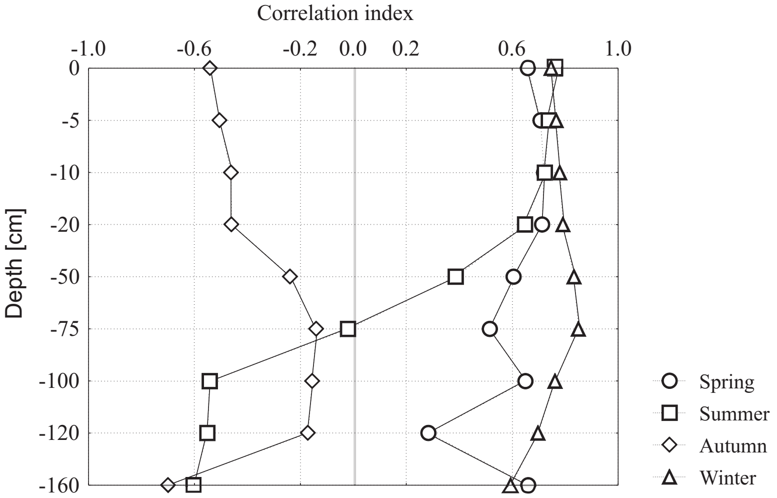


Fig. 3. Correlation between the balance of radiation K* and the ground temperature at the depths of 0, 5, 10, 20, 50, 75, 100, 120, and 160 cm in particular seasons. Due to the lack of solar radiation, the period of the polar night was neglected in the calculations.

wind velocity and the ground temperature was proved. Significant statistical relations have enabled the establishment of a reliable model of multiple regression, which illustrates the statistical dependence between meteorological and radiation elements and the ground temperature measured at particular depths (see the attached list for symbols, p. 225):

$$tg_0 = 0.163 + 0.404ta_{max} + 0.748ta_{min} + 0.0239K^* - 0.209P - 0.283V \qquad (r^2 = 0.93, p < 0.05)$$

$$tg_5 = 0.991 + 0.225ta_{max} + 0.832ta_{min} + 0.0220K^* - 0.156P - 0.235V \qquad (r^2 = 0.90, p < 0.05)$$

$$tg_{10} = 1.33 + 0.256ta_{max} + 0.847ta_{min} + 0.0214K^* - 0.183P - 0.204V \qquad (r^2 = 0.86, p < 0.05)$$

$$tg_{20} = 0.835 + 0.170ta_{max} + 0.852ta_{min} + 0.0167K^* - 0.105P - 0.122V \qquad (r^2 = 0.78, p < 0.05)$$

$$tg_{50} = 2.38 - 0.0242ta_{max} + 0.546ta_{min} + 0.00660K^* + 0.0306P - 0.0138V \qquad (r^2 = 0.48, p < 0.05)$$

$$tg_{75} = 2.51 - 0.0648ta_{max} + 0.257ta_{min} + 0.00106K^* + 0.0658P + 0.0105V \qquad (r^2 = 0.23, p < 0.11)$$

$$tg_{100} = 1.39 - 0.0230ta_{max} + 0.00118ta_{min} - 0.00304K^* + 0.0589P + 0.0257V \qquad (r^2 = 0.35, p < 0.05)$$

$$tg_{120} = 0.188 - 0.00978ta_{max} - 0.0863ta_{min} - 0.00218K^* - 0.0107P + 0.0144V \qquad (r^2 = 0.50, p < 0.05)$$

$$tg_{160} = -0.394 + 0.00250ta_{max} - 0.0460ta_{min} - 0.00176K^* + 0.0102P + 0.00956V \qquad (r^2 = 0.46, p < 0.05)$$

A high, statistical dependence ($r^2 = 0.78 - 0.93$, $p < 0.05$) occurred to a depth of 20 cm. At 75 cm, it decreased to $r^2 = 0.23$, $p < 0.11$. At lower depths (100, 120, and 160 cm), the increase of the statistical dependence up to $r^2 = 0.50$ appears to relate to a slight fluctuation of the ground temperature during that season. The results of the multiple regression for selected depths of the ground are presented in diagrams of the dispersion of the measured values against those predicted (Fig. 4).

The highest ground temperatures occurred in July during hot sunny weather, when the flux of heat in the ground was the greatest. The mean temperature of the ground in July was 8.7°C; it was 5.2°C at a depth of 50 cm, whereas –0.8°C at 160 cm. The mean depth of the permafrost, which in summer was 112 cm, was

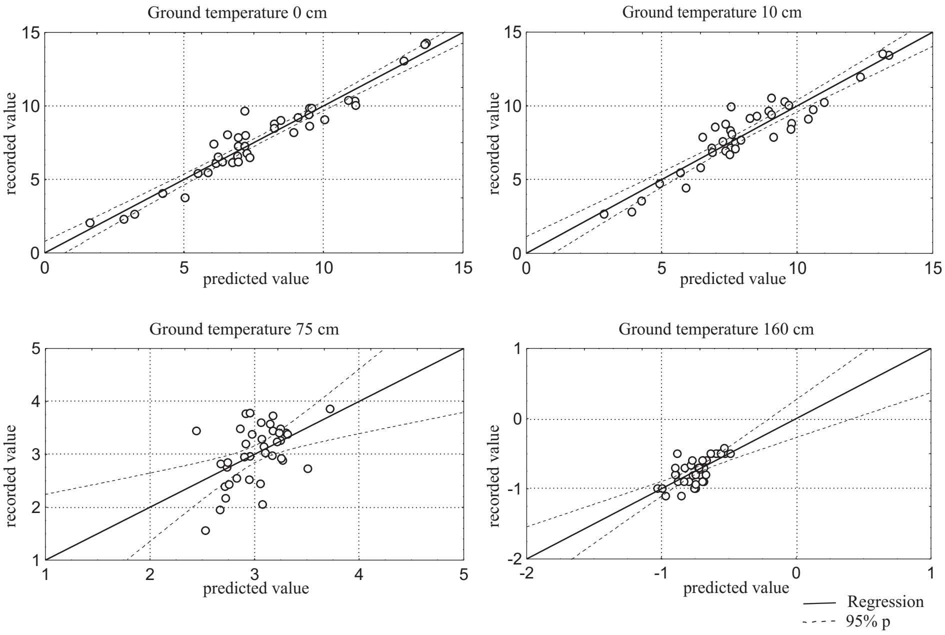


Fig. 4. The results of multiple regression for summer. Dispersion of the measured values against the predicted ones at the depths of 0, 10, 75, and 160 cm.

identified by the course of the zero isopleth. The highest mean daily temperature on the ground surface (14.3°C) was recorded on 3 June, which was an extremely warm, sunny day with intensive radiation. The 24 hours mean temperature reached 8.0°C on that day, total radiation 263 W/m^2, and the sum of 24 hours solar exposure was equal to 19.6 hours.

A decrease of the ground temperature down to 1–2°C in the first week of September marks the beginning of the thermal autumn. Owing to the variable autumn weather conditions (Fig. 2), several consecutive periods of warming (up to 4.7°C — September 7) and cooling of the ground (to –0.3°C — September 19) occurred, and, as a result of these conditions, the heat flux was low and it was ineffective at depths below ca. 30 cm. Their depth of thawing in autumn thermal regime was similar to that of the summer. However, as distinct from the summer, the vertical temperature gradient of the ground temperature was low; 2°C at the surface and 0°C at a depth of 125 cm. Autumn was a period of considerable fluctuation of the ground surface temperature close to 0°C. This was pronounced during night hours (2, 3, 4, 6, 8, 13, 19, 20, 29 September). Further cooling of the active layer occurred in the pre-winter seasons, with the ground temperature falling to 0°C. Also, a direction of the heat flux changed, resulting in a cooling of the ground surface to as low as –5.0°C, due to a lack of a snow cover.

At the beginning of winter, the snow cover began to form. Its average thickness was 8 cm. Later (November 10 – February 11), its thickness was reduced to

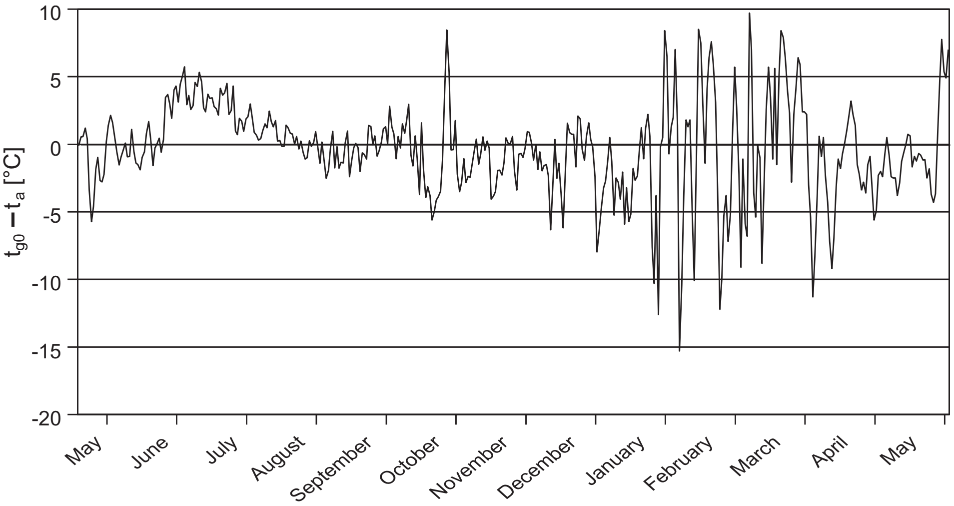


Fig. 5. The difference between ground surface temperature and air temperature (the daily values).

4 cm, due to snow ablation. Aeolian modification of a snow cover has been discussed by Leszkiewicz and Pulina (1999). Relatively high maximum air temperatures, as much as 3.0°C, caused an increase of the ground temperature from –16°C to –2°C. Further cooling of the ground started from the first week of December. Significantly, owing to the very thin snow cover (5 cm), the ground temperature related directly to air temperature. Advection of warm and cold air masses influenced the ground temperature only after an appreciable time delay, which resulted in less variability (Fig. 5). In the second half of the winter, the snow cover became permanent. Its mean thickness was 26 and its maximum thickness was 40 cm. The lowest ground temperature (24 hours mean –27°C) occurred on February 10. Cooling of the ground gradually progressed into the deeper layers. At a depth of approximately 120 cm, the temperature was ca. –10°C from February to May. The winter of 1992/1993 ended late (June 12). The following model of multiple regression was the result of the statistical analysis. The model applied the following mean 24 hours values: maximum and minimum air temperature (ta_{max}, ta_{min}), total radiation (K↓), thickness of the snow cover (Sn), and wind velocity (V).

$$tg_{0} = -9.40 + 0.222ta_{max} + 0.241ta_{min} + 0.0205K\downarrow - 0.0567Sn - 0.0314V \qquad (r^2 = 0.86, p < 0.05)$$

$$tg_{5} = -9.68 + 0.178ta_{max} + 0.227ta_{min} + 0.0215K\downarrow - 0.0531Sn - 0.0471V \qquad (r^2 = 0.85, p < 0.05)$$

$$tg_{10} = -9.51 + 0.121ta_{max} + 0.241ta_{min} + 0.0236K\downarrow - 0.0410Sn - 0.0714V \qquad (r^2 = 0.82, p < 0.05)$$

$$tg_{20} = -10.6 + 0.0856ta_{max} + 0.225ta_{min} + 0.0243K\downarrow + 0.0355Sn - 0.0827V \qquad (r^2 = 0.80, p < 0.05)$$

$$tg_{50} = -10.4 - 0.00510ta_{max} + 0.150ta_{min} + 0.0246K\downarrow + 0.00940Sn - 0.105V \qquad (r^2 = 0.77, p<0.05)$$

$$tg_{75} = -9.88 - 0.0226ta_{max} + 0.102ta_{min} + 0.0222K\downarrow - 0.0896Sn - 0.0880V \qquad (r^2 = 0.76, p<0.05)$$

$$tg_{100} = -9.68 - 0.0236ta_{max} + 0.0724ta_{min} + 0.0186K\downarrow - 0.0197Sn - 0.0661V \qquad (r^2 = 0.75, p<0.05)$$

$$tg_{120} = -8.36 - 0.0143ta_{max} + 0.0475ta_{min} + 0.0129K\downarrow - 0.0283Sn - 0.0491V \qquad (r^2 = 0.73, p < 0.05)$$

$$tg_{160} = -7.50 - 0.00952ta_{max} + 0.0338ta_{min} + 0.00809K\downarrow - 0.0323Sn - 0.0338V \qquad (r^2 = 0.65, p < 0.05)$$

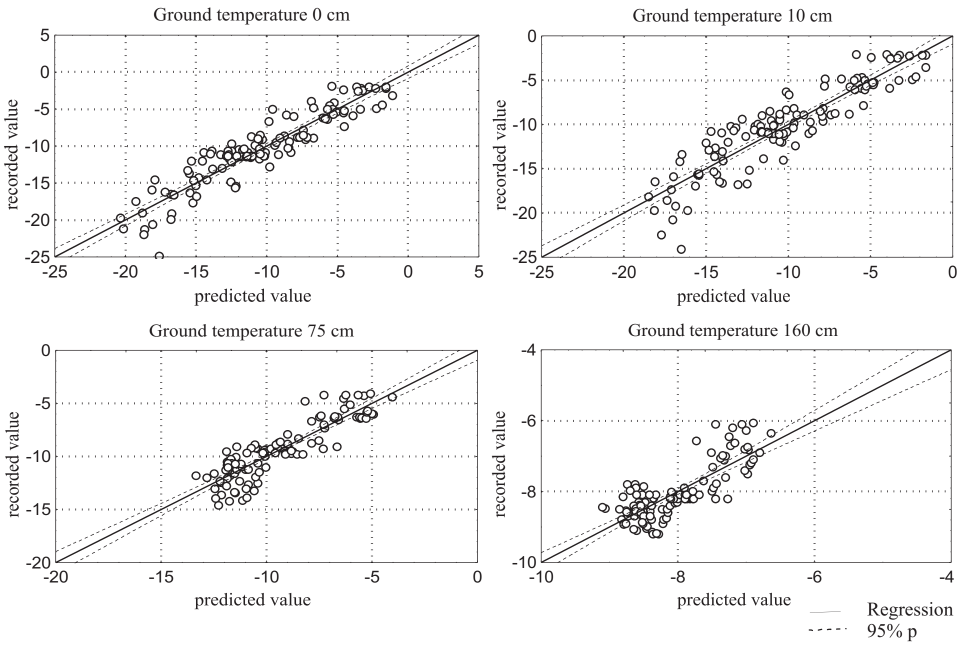


Fig. 6. The results of multiple regression for winter. Dispersion of the measured values against the predicted ones at the depths of 0, 10, 75, and 160 cm.

As distinct from the results from the summer season, high statistical dependencies were observed ($r^2 = 0.65–0.86$, $p < 0.05$) throughout the entire measuring profile (Fig. 6).

Characteristics of the radiation season 1992/1993

The greatest intensity of the flux of total radiation were 750 $\mathrm{W/m^2}$ in May 1992 and 690 $\mathrm{W/m^2}$ in July 1993. The highest monthly totals of $K\downarrow$ were registered in May (422–498 $\mathrm{MJ/m^2}$), June (473–596 $\mathrm{MJ/m^2}$), and July (502–642 $\mathrm{MJ/m^2}$) in 1990–1995. The total annual radiation $K\downarrow$ was 2064 $\mathrm{MJ/m^2}$ in 1992, with similar values in 1991 and 1993, 2349 $\mathrm{MJ/m^2}$ and 2397 $\mathrm{MJ/m^2}$ respectively. Owing to technical limitations, measurements of the maximum radiation may contain significant errors.

The radiation absorbed by the surface of the ground (K^*) is a part of the flux $K\downarrow$ and is expressed by the following equation:

$$K^* = K\downarrow - K\uparrow = K\downarrow \cdot (1-\alpha), \text{ where } \alpha \text{ – albedo (0–1.00)}$$

This is an important element of exchange of energy between the atmosphere and the ground. Radiation K^* warms up upper parts of the ground and any water contained in it. Concurrently, the flux of heat directed into the ground (G) caused gradual warming of deeper layers. The thermal effect of the flux K↓ may thus be reflected in the vertical temperature profile.

With the exception of the polar night and the winter periods, when there is a thick snow cover, the total radiation strongly affects the thermal condition of the ground. The polar night lasts 104 days in Hornsund (October 31 – February 11), when the ground surface receives no solar heat. On the other hand, the polar day lasts for 117 days (April 24 – August 18). Part of the flux K↓ is reflected from the ground surface. Its intensity depends on the ground surface structure, where such factors as colour, humidity, and porosity are important. The degree of reflection is usually expressed by the albedo of the surface (α). The value of albedo is usually between 70–80% in spring (snow cover) and 10–20% in summer (tundra). The values are similar to the results obtained by Głowicki (1985b) in the summer of 1980 and Niedźwiedź (1993) in the winter of 1989/1990.

As previously stated, the direction of a heat flux in the ground changes during the year. Disappearing snow cover and albedo (30–60%), apart from the flux K↓, are the main elements determining changes of direction of the flux G from negative during winter to positive in pre-spring. In summer, when K↓ and K* values are high, an intensive flux is directed into the ground. In autumn, 24 hour changes of direction of the flux G were observed (1) into the ground during the day — despite low values of the flux K↓ and the surface temperature and (2) emission of heat from the ground, resulted from lack of snow cover, low temperature of the ground, and small 24 hour totals of radiation K↓. In winter, when the air temperature is low and there is no radiation K↓, the surface emits heat to the atmosphere. The exchange of heat between atmosphere and ground governs the thermal conditions of the ground and the temporal pattern of ground temperature change in the vertical profile reflects this process (Fig. 2).

The snow cover may significantly modify this exchange of heat. The thermo-insulative role of a snow cover is confirmed by the present results. Further, it is clear that the snow, protects the permafrost from degradation during ablation periods (Jahn 1982) and reduces cooling of the ground in winter (Migała 1988, 1994).

In the area investigated, the typical surface was covered with gravel and tundra vegetation in summer and snow in winter. The low values of albedo (10–20%) show, indirectly, a strong absorption of radiation by the surface during summer season (Figs 7 and 8). After thawing of the snow cover (June 18, 1992) the value of the flux K* increased from about 100 to 250 W/m^2. In the summer, the intensity of that flux influenced the flux G and, below the depth of 100 cm, temperature rose to above 0°C. In that period, only a heavy cloud cover could strongly restrained the flux K↓. However, a cloud cover influenced the flux K↑ to a much smaller degree and values of K↑ in summer were reduced to ca. 50 W/m^2.

Owing to low values of albedo, 80–90% of the flux K↓ was absorbed in summer, which formed ground thermal conditions in that season. The presence of snow cover decreased absorption to 10%. In the case of a thick snow cover, K* was

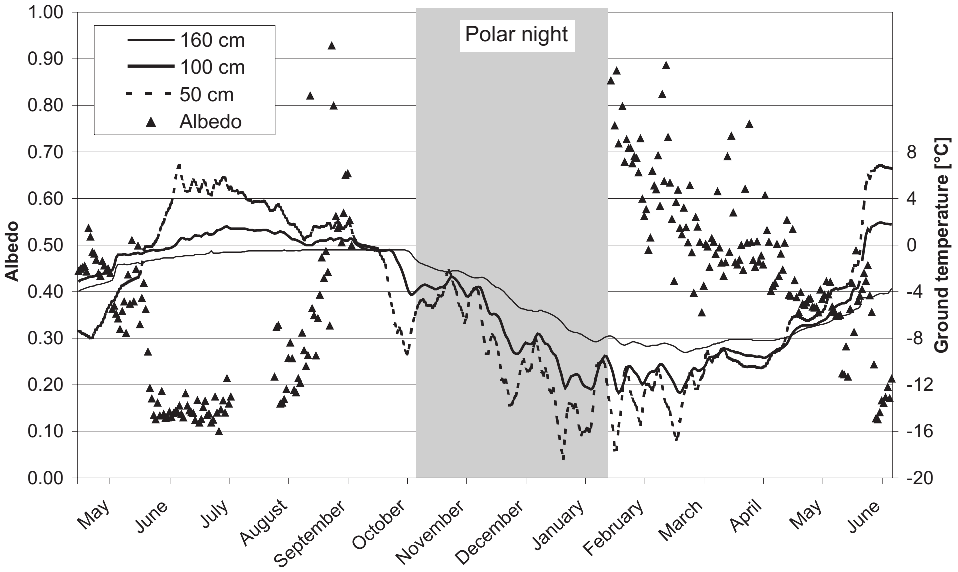


Fig. 7. Ground temperature at the depths of 50, 100, and 160 cm against the albedo.

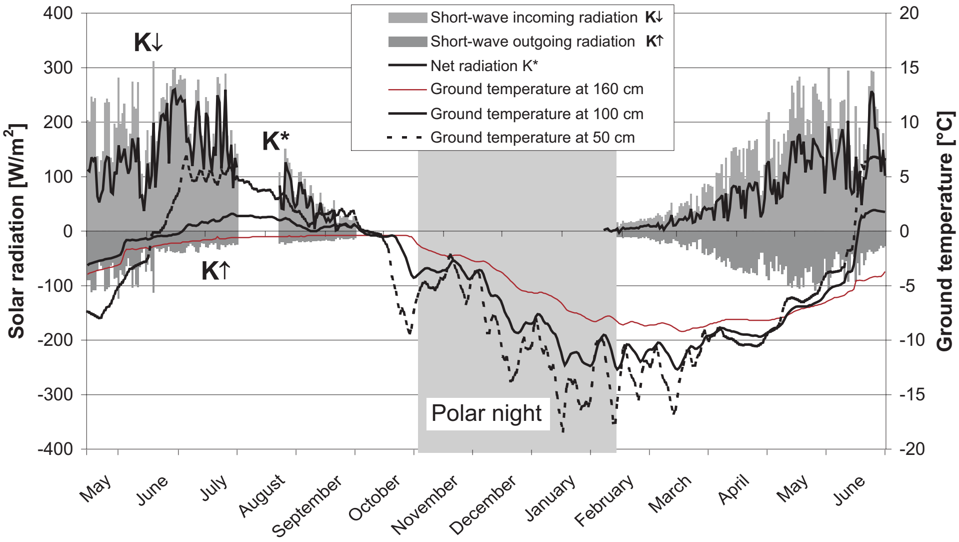


Fig. 8. Ground temperature at the depths of 50, 100, and 160 cm against the balance of radiation (K*).

completely absorbed. In consecutive months after the polar night, relatively low values of albedo (15–40%) of the snow surface, were accompanied by changes of colour and the structure of the snow, known as a "wearing off" process. Fresh snow produced high values of albedo (80–95%).

Correlation, between the radiation balance K* and the ground temperature in the vertical profile from the surface down to the depth of 160 cm, changed in consecutive seasons according to the cycle reflecting direction of the flux G (Fig. 3). In a winter season, after the end of the polar night, a significant positive correlation was observed in the whole vertical profile ($r \geq 0.7$), due to the lack of solar radiation, the period of the polar night was neglected in the calculations. In the spring and summer seasons, the correlation was similar to that of winter season only to the depth of 20 cm. However, at lower depths, significant differences were observed. In spring, correlation values were lower than in winter. At the depth of 120 cm, the correlation coefficient was only 0.28. By contrast, in the summer, at the depth of 75 cm, there occurred a passage of correlation coefficient, from positive value, through zero, to approriate negative value, beginning at the depth of 100 cm. As a result of a slight flux G in the autumn, negative correlations occurred in the whole vertical profile; however, the values of the correlation coefficient were variable. Good correlations ($r \geq -0.6 - -0.5$) were observed from the surface to 20 cm and at 160 cm. However, between 50 and 120 cm, the correlations were poor or insignificant. The seasonal cycle of thermal relationships, as outlined here, needs to be confirmed by a much longer-term investigation.

Conclusions

Active layer temperatures in the vicinity of the Polish Polar Station in Hornsund suggest that six seasons (pre-winter, winter, pre-spring, spring, summer, and autumn) may be recognised. These variations are closely matched by air temperature variations.

With regard to the results from the whole investigation period, the following thermal layers may be distinguished:

- 0–20 cm layer; where ground temperatures are strongly influenced by solar radiation, air temperature, wind velocity, and precipitation. Significant daily changes occur. Such a layer was also distinguished by Miętus and Filipiak (2001);
- 20–50 cm layer; several diurnal changes of the ground temperature occur;
- 50–130 cm layer; seasonal changes of the ground temperature occur;
- below 130 cm layer; permafrost (no thawing was observed).

These depths are deriven from the measurements at the Polish Polar Station. Locally, other thickness of the layers were observed, *e.g.* places where snow patches and watercourses occur.

A long-term series of measurements has enabled us to determine the dynamics of the thermal changes in the whole active layer in the raised marine terrace regime. Statistical analysis has proved a strong correlation between ground temperature and the fluxes K↓ and K*, which has enabled us to form equations of multiple regression regarding particular depths and seasons. In winter, during the polar night, changes of temperature did not occur in a daily cycle but over longer periods. This was presumably due to the lack, or minimal influence of total radiation and solar altitude, which control the diurnal temperature patterns, of the ground and the air. During the polar night, changes in the thermal conditions of both the ground and the air are due to air circulation.

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