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Annual variation of soil temperature at Polar Station in Hornsund, Spitsbergen

ABSTRACT: Monthly and dekadal mean soil temperatures were evaluated with a use of measurements at depths of 5, 10, 20 and 50 cm, collected during the expeditions 1978—1986 and additionally at depths of 80 and 100 cm during the expeditions 1980—1986. Fourier analysis revealed a phase shift of 1 to 2 dekads between neighboring measurement depths.

Key words: Arctic, Spitsbergen, soil temperature

Introduction

Beginning with 1957 manifold geophysic investigation has been going on, soil temperature included, in the region of Hornsund, southwestern Spitsbergen. Thermal conditions of the soil were investigated during numerous expeditions. Their surveys resulted in many papers dealing with phenomena occurring in the active soil layer, both throughout the whole year (Czeppe 1966, Baranowski 1968, Głowicki 1985) and in the summer season only (Grześ 1984, Szmyrka et al. 1986). Soils in the fiord area were extensively studied by Szerszeń (1965). Each author presented the problem using limited results of his own. This paper uses a series of several years standard daily observations and presents main characteristics of soil temperature such as monthly means on defined depths, mean thickness of active layer (i.e. soil layer which thaws in summer), range of temperatures in particular months.

Data and method

Measurements of soil temperature formed a part in standard program of meteorologic observations in Hornsund. They were made with mercury thermometers at depths of 5, 10, 20, 50, 80 and 100 cm. Measurements were started in July 1978 at first four depths whereas at 80 and 100 cm in July 1980. Thus, the series is not very long. Besides, there is no data available from the expedition 1981/82. The season 1981/82 was a cool one over Spitsbergen, and so its data seem to modify somewhat mean values of temperatures. In spite of this short measurement period of only several years, the attempt was done to perform computations needed for some generalizations and conclusions.

Results and discussion

In 1978—1986 in Hornsund there were great variations of air temperatures during successive years. This fact was also reflected in soil temperatures

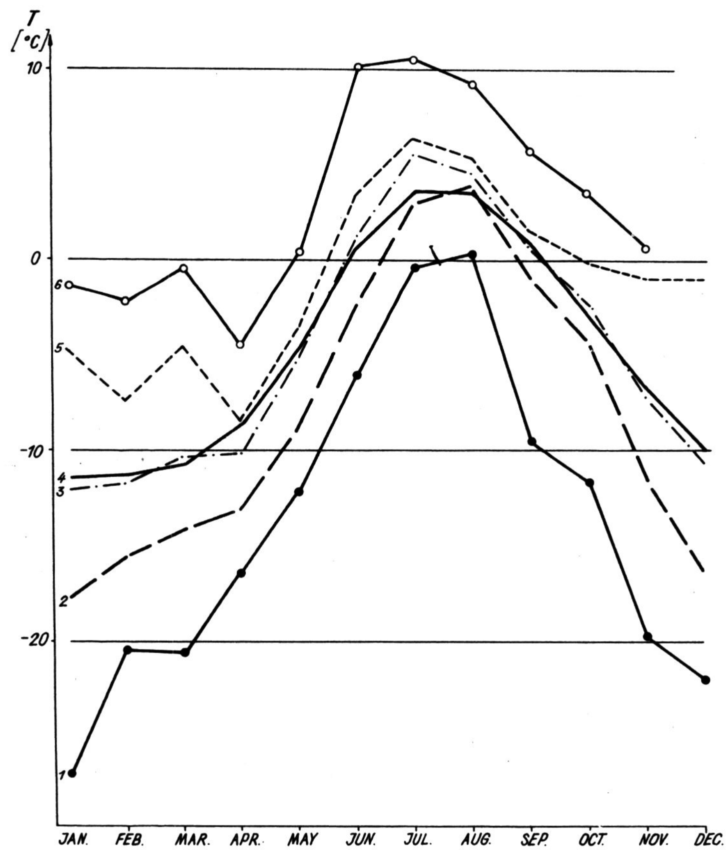

Fig. 1. Annual variation of soil temperature at depth 5 cm in Hornsund, Polar Station of Polish Academy of Sciences, July 1977 — July 1981 and September 1982 — September 1986: 1 — lowest measured values, 2 — lowest monthly means, 3 — monthly means, 4 — three-monthly overlapping means, 5 — highest monthly means, 6 — highest measured values

and could be best noted when comparying mean values of particular winter months. At depth of 5 cm, for instance, mean monthly temperatures of December oscillated between −16.2°C in 1980 and −0.9°C in 1984; January 1981 was reflected at this depth by mean temperature equal −17.8°C, and January 1985 by not lower than −4.8°C (Table 1).

Range of individual daily values was obviously much greater. For instance, with the minimum of daily temperatures in January 1981 of −26.7°C and maximum of daily temperatures in January 1985 equal −1.3°C, the temperature range exceeded 25°C in this month. Range of daily temperatures in December reached 22°C and in remaining cool months was equal about 20°C, excluding April with relatively low maximum temperatures (Fig. 1). Temperatures at other measuring depths (10 to 100 cm) behaved in a similar way, with their amplitudes dropping with increasing depth. This similarity is clearly seen in annual variation of mean values at all depths considered in relevant months (Table 2).

Mean annual variation of monthly values results in empirical curve not smooth enough to be easily used for conclusions on main climatologic characteristics of considered parameters. But only a filtering of data of monthly values by overlapping means, for instance three-monthly ones, gives an evident smoothing of existing variation (Fig. 1). Much better smoothing can be obtained by Fourier analysis and, as average annual cycle of temperature is known (with a single maximum only), its approximation is reached by the first harmonic.

On the basis of values presented in Table 2 the following relations were obtained for successive depths:

$$T(z=5,t) = -4.82 - 8.05 \cos\frac{\Pi}{\sigma}t - 2.90 \sin\frac{\Pi}{\sigma}t,$$

$$T(z=10,t) = -4.85 - 7.90 \cos\frac{\Pi}{\sigma}t - 3.03 \sin\frac{\Pi}{\sigma}t,$$

$$T(z=20,t) = -4.95 - 7.51 \cos\frac{\Pi}{\sigma}t - 3.17 \sin\frac{\Pi}{\sigma}t, \qquad (1)$$

$$T(z=50,t) = -4.86 - 6.14 \cos\frac{\Pi}{\sigma}t - 3.39 \sin\frac{\Pi}{\sigma}t,$$

$$T(z=80,t) = -4.54 - 5.27 \cos\frac{\Pi}{\sigma}t - 3.47 \sin\frac{\Pi}{\sigma}t,$$

$$T(z=100,t) = -4.19 - 4.46 \cos\frac{\Pi}{\sigma}t - 3.42 \sin\frac{\Pi}{\sigma}t, \qquad (1)$$

This allows for approximation of temperature variation at given depths (Fig. 2).

In consequence of equations (1), calculations of some annual temperature variations were possible. Thus, maximum and minimum temperatures at depth (z) are described by

Table 1

Mean monthly soil temperature at depth 5 cm in July 1978 — July 1981 and September 1982 — September 1986

Year	Mean monthly temperature (°C)											
	January	February	March	April	May	June	July	August	September	October	November	December
1978	–	–	–	–	–	–	7.4	5.2	0.0	−3.2	−7.8	−9.2
1979	−14.5	−15.6	−14.2	−13.1	−8.6	−2.2	6.1	4.2	0.9	−3.1	−5.2	−10.3
1980	−11.2	−13.5	−11.7	−9.6	−4.7	2.3	5.0	3.8	1.1	−4.3	−9.6	−16.2
1981	−17.8	−10.8	−12.0	−10.8	−6.4	−1.4	3.0	–	–	–	–	–
1982	–	–	–	–	–	–	–	–	−0.9	−3.4	−7.1	−9.8
1983	−9.3	−13.6	−9.4	−10.4	−5.0	1.2	5.8	4.0	1.3	−2.6	−11.5	−16.2
1984	−10.5	−7.4	−10.8	−8.8	−4.4	3.1	6.4	4.8	1.6	−0.1	−0.9	−0.9
1985	−4.8	−7.3	−4.5	−8.5	−4.1	1.8	6.2	4.4	1.1	−2.7	−7.4	−11.8
1986	−14.6	−13.8	−9.8	−9.9	−3.5	3.5	5.9	5.2	−0.7	–	–	–

Table 2

Mean monthly soil temperature at different depths in July 1978 — July 1981 and September 1982 — September 1986

Depth (cm)	Mean soil temperature (°C)											
	January	February	March	April	May	June	July	August	September	October	November	December
5	−12.0	−11.7	−10.3	−10.2	−5.2	1.2	5.7	4.4	0.7	−2.8	−7.1	−10.6
10	−11.9	−11.9	−10.3	−11.1	−5.4	0.8	5.4	4.3	0.8	−2.6	−6.9	−10.5
20	−11.7	−11.6	−10.4	−10.1	−5.7	0.1	4.8	3.9	0.7	−2.3	−6.7	−10.4
50	−11.0	−10.5	−9.3	−9.9	−6.2	−1.3	2.5	2.8	0.7	−1.1	−5.6	−9.6
80	−9.7	−9.6	−8.5	−8.9	−6.8	−1.6	1.4	2.4	0.8	−0.1	−4.8	−9.1
100	−9.0	−8.8	−8.0	−8.5	−6.3	−1.4	0.5	1.6	0.6	0.1	−3.5	−7.6

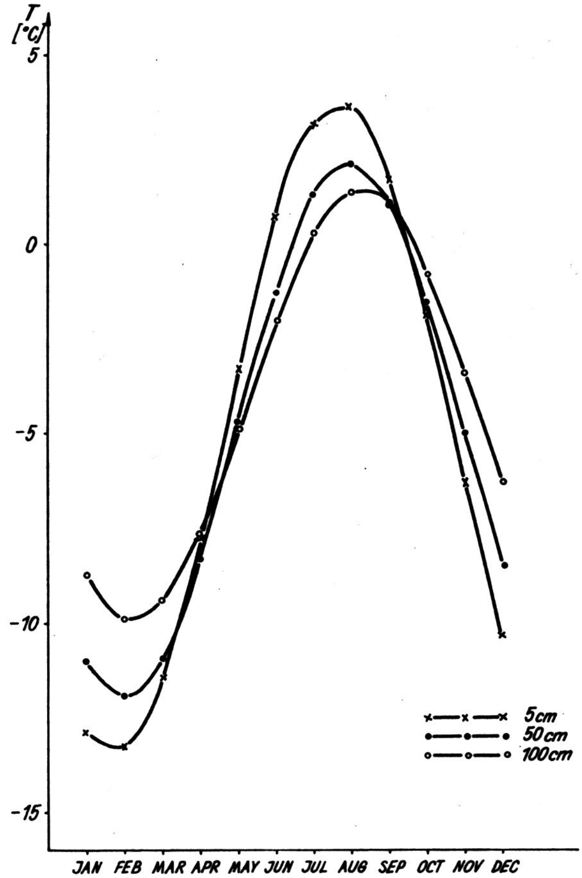

Fig. 2. Annual variation of mean monthly soil temperature in Hornsund at depths 5, 50 and 100 cm, computed by Fourier analysis

$$T_z^{min} = -13.59 + 0.036z,$$

$$T_z^{max} = 3.65 - 0.24z. \qquad (2)$$

They enable to calculate, for instance for depth 5 cm, the lowest monthly mean temperature which occurs, according to approximation, in February and is equal −13.4°C. The highest mean occurs in August and is equal 3.5°C. Annual range of temperatures ΔT is therefore equal 16.9°C. According to observation data, the annual amplitude of monthly means is very close to his value and equal 17.5°C at this depth, being the difference between mean temperatures of January and July. Extreme temperatures computed from approximation by Fourier analysis are presented in Table 3. A use of the same calculation enables to find the depth, below which maximum temperature does not exceed 0°C. This depth is equal $z^* = 152.1$ cm, with z^* as mean thickness of active layer. Further calculation reveals that annual oscillations of soil temperature do not penetrate deeper than $z_0 = 287.3$ cm and below that level a steady temperature $T_{z_0} = -3.24$°C remains. All presented values are true if assuming monthly means of soil temperature (used to calculate coefficients of Fourier series).

Fourier analysis of monthly time series has not indicated a phase shift between the considered depths: minima seemed to occur in the whole soil

Table 3

Mean annual extreme soil temperature at different depths based on Fourier analysis and monthly means

Depth (cm)	Mean annual minimum temperature (°C)	Mean annual maximum temperature (°C)
5	−13.2	3.6
10	−13.2	3.5
20	−13.0	3.1
50	−11.9	2.2
80	−10.8	1.8
100	−9.8	1.4

in February and maxima in August (Fig. 2). The phase shift could be found by re-analysis of the whole annual cycle with a use of dekadal means of temperature and approximation by the first harmonic. Following relations were obtained:

$$
\begin{aligned}
T(z=5,t) &= -4.82-7.48\cos\frac{\Pi}{18}t-4.34\sin\frac{\Pi}{18}t,\\
T(z=10,t) &= -4.85-7.31\cos\frac{\Pi}{18}t-4.43\sin\frac{\Pi}{18}t,\\
T(z=20,t) &= -4.91-6.93\cos\frac{\Pi}{18}t-4.53\sin\frac{\Pi}{18}t,\\
T(z=50,t) &= -4.84-5.52\cos\frac{\Pi}{18}t-4.57\sin\frac{\Pi}{18}t,\\
T(z=80,t) &= -4.50-4.72\cos\frac{\Pi}{18}t-4.34\sin\frac{\Pi}{18}t,\\
T(z=100,t) &= -4.23-3.73\cos\frac{\Pi}{18}t-4.24\sin\frac{\Pi}{18}t.
\end{aligned}
\qquad (3)
$$

Equations (3) state that extreme soil temperatures of the dekadal series are shifted towards growing time in comparison with the monthly values. Thus at $z = 5$, 10, 20 cm the extreme values occur during 4th and 22nd dekad.

At $z = 50$ and 80 cm temperature minima occur during 5th and maxima during 23rd dekad of the year while at 100 cm extreme values are observed during 6th and 24th dekad respectively.

Observed minimum temperatures occurred at all depths during 3rd decade of the year. Maximum temperatures were however noted at 5 cm during 20th dekad, at 10 cm during 21st dekad, at 20 cm during 20th and 21st dekads and at 50, 80 and 100 cm during 22nd dekad. Annual temperature ranges resulting from these extreme values at considered depths are presented (Table 4).

Table 4

Mean annual variation of soil temperature at different depths based on dekad means and calculated by: (a) conventional averaging, (b) Fourier analysis

Depth (cm)	(a) (°C)	(b) (°C)
5	18.5	17.3
10	18.2	17.1
20	17.5	16.5
50	14.9	14.3
80	13.2	12.8
100	11.2	11.3

Analysis of equations (1) and (3) finds annual mean values of soil temperature at all depths to vary only slightly from one another and that the depth of 20 cm was the coolest one.

Conclusions

Fourier analysis of multi-annual monthly means of soil temperature at depths of 5, 10, 20, 50, 80 and 100 cm in Hornsund does not allow to find a remarkable phase shift between temperature oscillations at considered depths.

Spliting of the time series into dekad values reveals a shift of extreme temperatures by a dekad between the depths 5 to 20 cm and 50 to 80 cm, and by another dekad more between the both latter and the depth 100 cm.

Analysis of dekad values of the annual series by the first harmonic component suggests absence of oscillations during a year.

Calculted coefficients of the Fourier series enable calculation of depth of summer thawing penetration z^* and that beneath z_o no temperature oscillations occur and steady temperature T_{z_o} is established there. These values are equal: $z^* = 152.1$ cm, $z_o = 287.3$ cm and $T_{z_o} = -3.24$°C.

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Streszczenie

Wyniki pomiarów temperatury gruntu na stacji PAN w Hornsundzie na głębokościach 5, 10, 20, 50 cm w okresie od lipca 1978 do czerwca 1986 i na głębokościach 80 i 100 cm w okresie od lipca 1980 do czerwca 1986 (z przerwą od sierpnia 1981 do sierpnia 1982 w obu przypadkach) pozwalają stwierdzić, że średnie miesięczne wartości temperatury na danej głębokości charakteryzują się znaczną amplitudą w ciągu jednego roku (fig. 1). Analogiczne wnioski można wyciągnąć na podstawie analizy wartości miesięcznych w poszczególnych sezonach (tab. 1). Świadczy to o tym, że poszczególne sezony różnią się od siebie dość istotnie pod względem niektórych parametrów meteorologicznych.

W okresie od stycznia do kwietnia i od października do grudnia temperatury gruntu wzrastają w głąb poza nielicznymi wyjątkami. Od maja do sierpnia obserwujemy stan odwrotny: najcieplej jest tuż przy powierzchni, a najchłodniej na głębokości 100 cm. We wrześniu obserwujemy swoistą izotermię (tab. 2).

W oparciu o analizę fourierowską cyklu rocznego w rozbiciu na miesiące nie można stwierdzić istnienia przesunięć pomiędzy ekstremalnymi wartościami temperatur na poszczególnych głębokościach (fig. 2). Średnia minimalna temperatura gruntu wzrasta w głąb, maksymalna natomiast maleje (tab. 3).

Średnia głębokość warstwy czynnej została oszacowana na $z = 152,1$ cm, zaś głębokość na której ustają oscylacje temperatury na $z_o = 287,3$ cm. Na tej głębokości panuje stała temperatura $T_{z_o} = -3.24°C$.

Znacznie dokładniejsze rezultaty daje analiza fourierowska cyklu rocznego w rozbiciu na dekady. Pozwala to na wychwycenie jedno- i dwu-dekadowych przesunięć pomiędzy rocznymi ekstremami. Na głębokościach 5, 10 i 20 cm ekstrema występują w 4 i 22 dekadzie, na 50 i 80 cm w 5 i 23 dekadzie, a na 100 cm w 6 i 24 dekadzie.

Porównanie amplitud drgań rocznych otrzymanych z analizy fourierowskiej z obliczonymi w oparciu o średnie wartości dekadowe wskazuje na dużą zbieżność wyników (tab. 4).