THERMICS OF THE TUNDRA UNDERLIER AND ITS CONDITIONING BY THE ENERGY BALANCE AT BARENTSBURG AND REINDALEN (SPITSBERGEN ISLAND, SVALBARD) IN THE SUMMER SEASONS OF 1988 AND 1990

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SUMMARY

The thermics of the tundra underlier is analysed, as well as its link-up with the components of the energy balance of the active surface at selected localities at Barentsburg (measurements on 21 June to 20 Aug., 1988) and in Reindalen Valley (measurements on 7 July - 9 Aug., 1990) at Spitsbergen Island (Svalbard). Substratum temperatures are presented by thermoisopleth graphs and the mean vertical temperature profiles in synoptical terms. The established differences are conditioned by the properties of the substratum, such as its moisture and the character of the active surface and its immediate underlier. Considerable differences were documented between the vegetation free centre and the vegetation covered margin of the sorted circle. On days with the prevalence of the radiation weather temperatures immediately below the active surface and at the depth of 10 cm are statistically significantly dependent on the values of the radiation balance and the soil heat flux, advection effects obscuring this link-up. Differences in the thickness of the active layer of permafrost are documented for different parts of the sorted circle.

KEY WORDS

Barentsburg - Reindalen - thermics of the tundra underlier - components of energy balance

INTRODUCTION

In context with the measurements of components of energy balance of the active surface which were part of the scientific programme of expeditions of the Department of Geography, Masaryk University, to Svalbard in the years 1988 and 1990, profile temperature measurements of the tundra underlier were carried out in the tundra near Barentsburg and in the upper part of Reindalen Valley (see Figs. 2, 3 in Prošek, Brázdil, 1994) in the periods of 21 June - 20 Aug., 1988 and 7 July - 9 Aug., 1990. Their objective was finding the impacts of the energy economy of the active surface and its regime on the thermics of the substrate and/or the development of the surface active layer of permafrost (further ALP).

A detailed description of the character of the active surface and its underlier at the two localities is given in the paper quoted above. The subsurface temperature measurements were carried out at

Barentsburg at the depths of 1, 5, 10, 20, 30 and 50 cm (below that level there occurred only slope debris consisting of rough angular material) with platinum resistance thermometers PT 100 attached to a recording millivoltmeter, type 28/SK 120/6 (VEB Messgerätenwerk E. Weinert, Magdeburg). At Reindalen a similar method was used for temperature measurements at the depths of 35, 55 and 65 cm (at lower levels there was again slope debris). For measurements near the active surface at this station classical mercury soil thermometers were used in two profiles: below the centre of the selected sorted circle without vegetation (1, 5, 10, 15, 20 and 30 cm) and below its margin covered with tundra vegetation with a prevalence of mosses with an admixture of grasses and the polar willow. Detailed information about the structure of that circle is given in Fig. 1. Doubled measurement of the subsurface temperature at smaller depths was targeted at finding different properties of the active layer including the substrate on its thermics at a typical morphological unit of sorted soil.

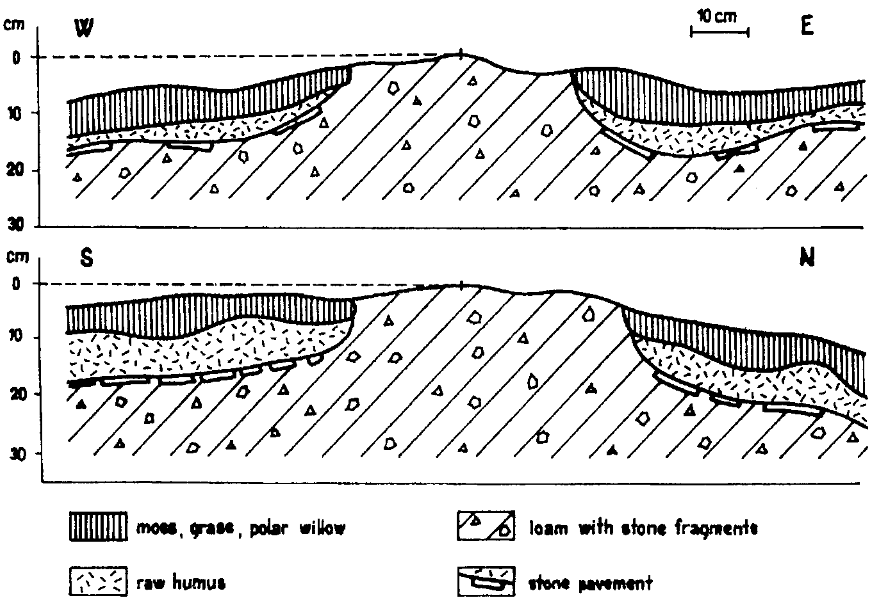


Fig. 1. Vertical sections of the underlier of the sorted circle in Reindalen Valley in whose central part and on the margin temperature measurements of the active surface underlier were performed

SOIL THERMICS

The basis of evaluating temperature conditions of the underlier of the active surface in the two cases were graphs of isopletes (Figs. 2, 3) of mean daily temperatures. Their profiles at the two stations document the effects of irregular warming from above, and in the case of Barentsburg it hints a cooling from both above and below at the end of the period. From complementary information of Figs. 2 and 3 (mean daily cloudiness and mean daily air temperature) it is evident that the temperature

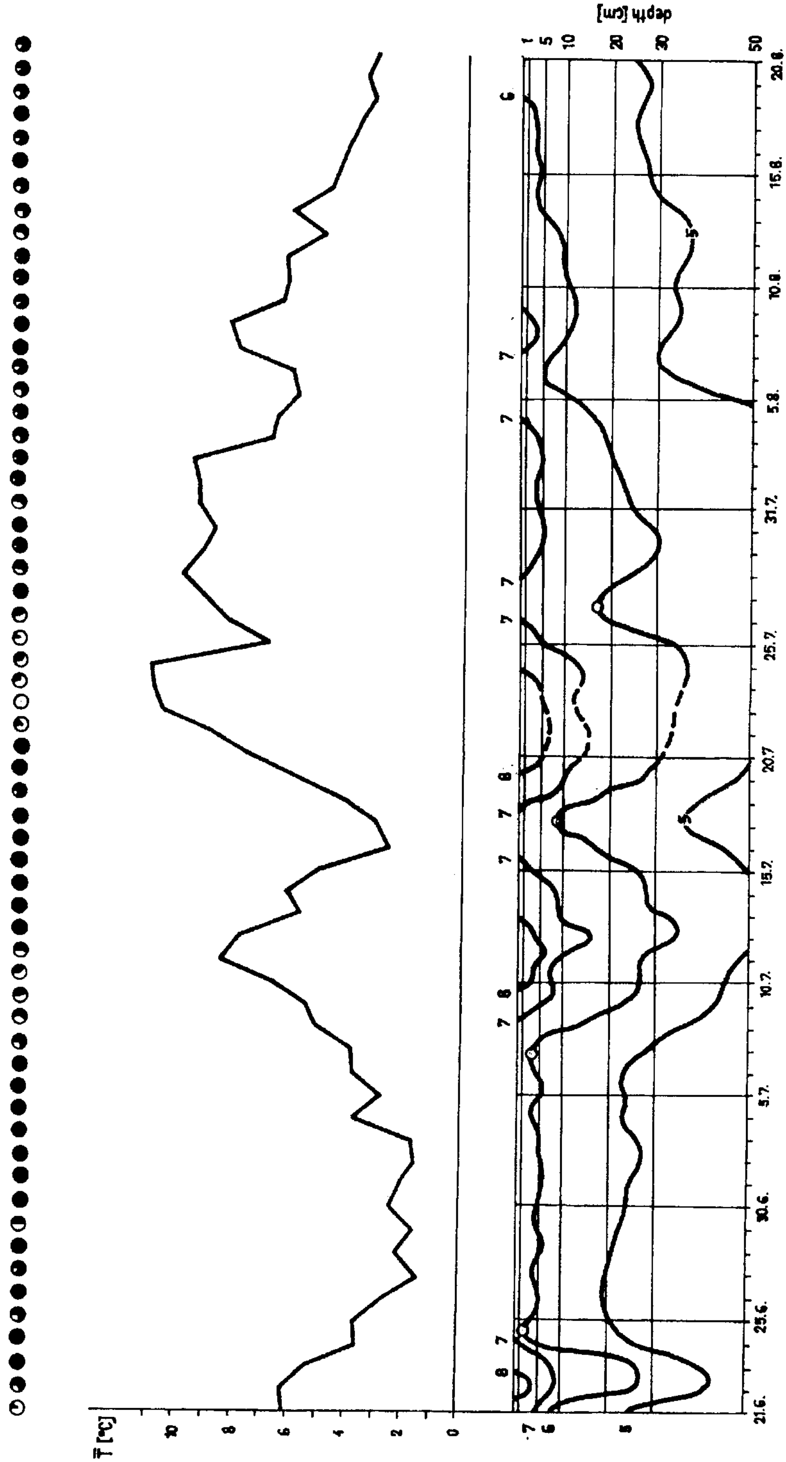


Fig. 2. Thermoisopleths of mean daily temperatures [°C] of the active surface underlier at the station of Barentsburg in the period of 21 June - 20 Aug., 1988 (on 21 and 22 July there was a break of registration), completed by mean daily air temperatures (T̄) in a meteorological screen and the mean daily cloudiness (in tenths of the sky cover)

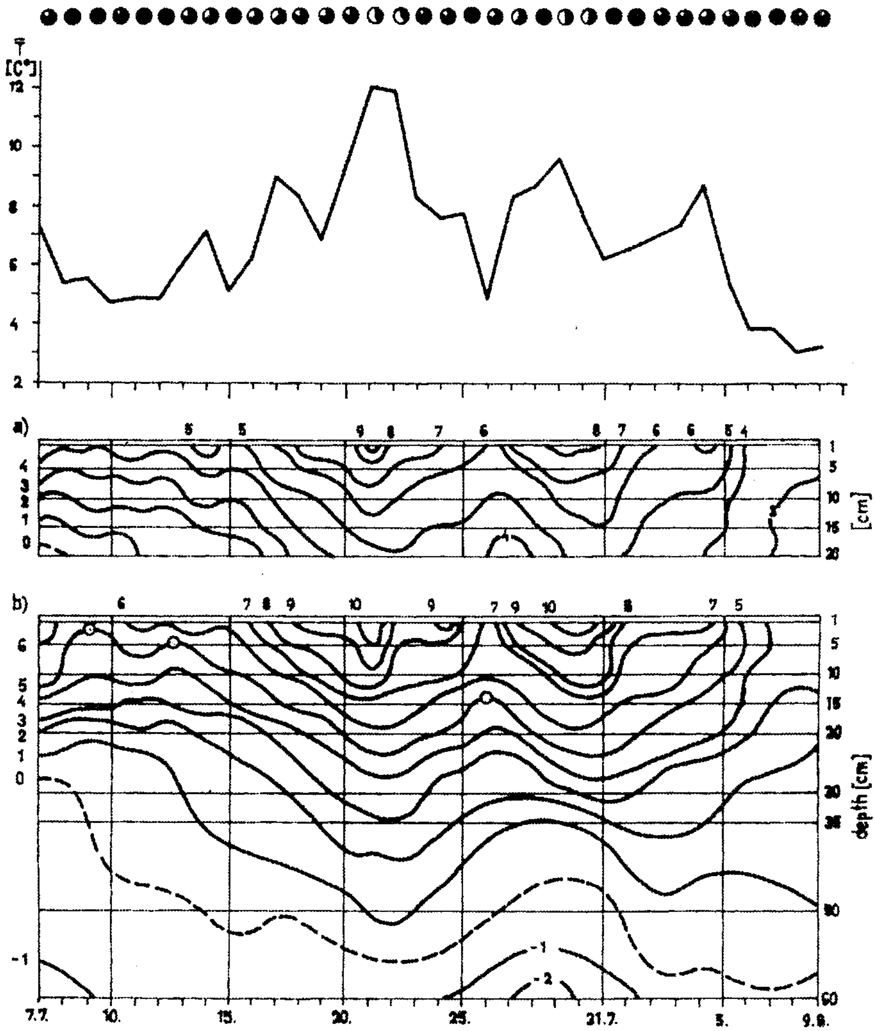


Fig. 3. Text see Fig. 2 - at the station of Reindalen in the period of 7 July - 9 Aug., 1990 (a - the margin, b - the centre of the circle)

regime of immediately subsurface layers at both stations is, unlike air temperature, clearly more continuous, being closely associated with the cloudiness, i.e. with the sunshine duration and thus evidently with the daily sums of radiation absorbed by the surface (thus, at Barentsburg the surface temperature maxima correspond well with cloudiness minima on 21 and 22 June, 9 to 11, 21-23 and 29-31 July, at Reindalen on 21-22 July and 29-30 July). Radiation effects on air temperature are, on the contrary, more free as a consequence of the fact that it is more subject to the character of advection (at Barentsburg e.g. 29 June and 12-13 Aug., less conspicuously in the period of 26-31 July, at Reindalen 22, 29, 30 July and 4 Aug.). In both graphical supplements there is a clear lagging of the radiation conditioned warming and advection influenced cooling with depth.

At the two stations it is evident that temporary more or less episodic intervals of radiation conditioned warming are interrupted by periods of cooling from below, reflected in the approach of the isopletes to the surface (Barentsburg 25 June - 6 July, 17-18 July and 26-27 July, at Reindalen 25-31 Aug.), taking into consideration the fact that due to the summer warming of the substrate with the progressing date they do not reach their previous level in a single case (see e.g. the encircled values of the isoplete of 5.0 °C at Barentsburg up to 27 July, at Reindalen up to 26 July). The rise of isopletes at the end of the period of measurement is an evident consequence of the prevalence of the cooling effect from the underlier of the ALP at the end of summer.

Typical of the station of Reindalen, unlike Barentsburg, is a greater density of isopletes, i.e. a more conspicuous vertical temperature profile (see also Figs. 6 and 7). It is evidently the consequence of a reduced thermal conductivity at this station in contrast with the effect of high thermal capacity of water in exceptionally moist to water saturated underlier of the active surface at Barentsburg, reflected at Reindalen also by a lower thickness of ALP (see the depth of the isoplete of 0 °C, which at Barentsburg was not at all registered and which at Reindalen - again with delay - corresponds with the warming and cooling of the surface).

The double active surface underlier temperature measurement at Reindalen (the centre and the margin of the sorted circle) proved a considerable spatial variability of temperature conditions of this type of sorted soils (Fig. 3). Although the course of isopletes in the two profiles is similar, which is due to the same regime of radiation and advection causes, at the same time it documents the overwarming of the centre of the circle (roughly by 1 - 2 °C), reaching up to the greatest depth of measurement. It is unambiguously the consequence of the insulating effect of the tundra vegetation at the margin of the circle and a thin layer of rough humus in its underlier (Fig. 1) which, as stated below, has its consequences in the defreezing of the ALP.

As documented by examples in Figs. 4 and 5, at the two localities there are significant differences also in the daily temperature regime and in its changes with the depth. Whereas the daily periodicity of temperature changes is reflected in on the whole lower amplitudes at Barentsburg more conspicuously only to the depth of about 10 cm, at Reindalen it can be well followed even at the depth of 30 cm. Also from these graphical supplements the phase shift of the daily temperature wave with depth can well be seen.

The differences in the temperature regime of the surface layers of the substratum also appear in vertical profiles as temperatures whose mean daily regime is graphically documented in Figs. 6 and 7. Even with the awareness of a different interval of averaging the soil temperatures between the two stations, the two figures materialise the idea about the different temperature regime at both localities. The mean daily variability of surface layer temperature is at Barentsburg, where it is 1.1 °C, substantially lower than at Reindalen (with the mean amplitude of the centre and the margin of the circle of 4.2 and 2.5 °C, respectively). Whereas at the former station in all terms a more or less continuous cooling with depth is typical (its intensity decreasing logically in the direction to the underlier), the much more intense drop in temperature in the surface layers at Reindalen is less continuous (particularly below the centre of the circle at the terms of 22, 01 and 04 h CET). At all terms of night measurement it is an evident effect of active surface cooling penetrating to the depth of roughly 10 cm, whereas at greater depths the dropping trend of temperature from daily hours is preserved.

A relatively conspicuous daily temperature regime of immediately subsurface levels decreases quickly with the depth due to a relative dryness of the substrate, disappearing practically at the depth of 25-30 cm.

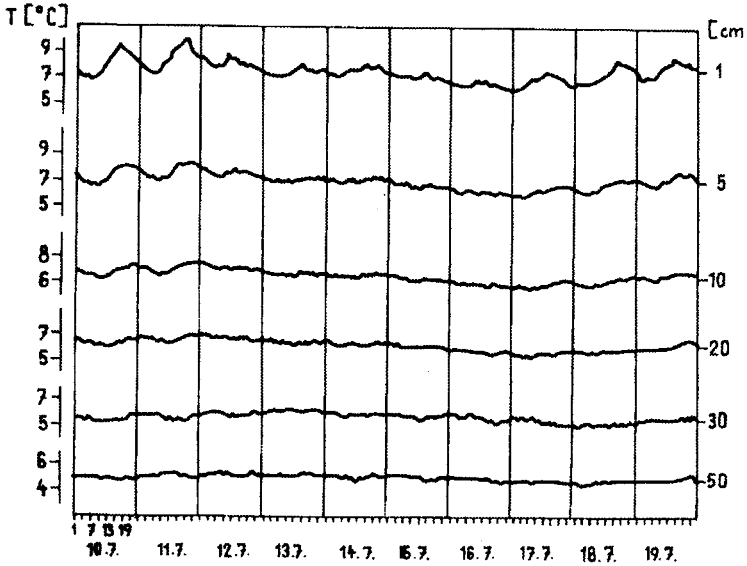


Fig. 4. Temporal changes in the temperature of the active surface underlier at the depths of 1, 5, 10, 20, 30 and 50 cm in synoptical terms at the station of Barentsburg in the period of 10-19 July, 1988

The slowing down of the temperature drop with depth from the level of about 30 cm is most probably linked up with the increase in thermal conductivity in deeper and moister substrate layers on the one hand and with a small vertical heat flow at those depths on the other hand.

A very marked drop in the daily temperature amplitude at the margin of the circle is the consequence of the heat insulating properties of the thin layer of the tundra vegetation, appearing already in the first centimetre of depth, and having a consequence in the overall lower temperature level of this part of circle, observable up to the depth of measurement (20 cm).

The fanlike opening of the profile lines in immediately subsurface layers is typical of neither locality, but, on the other hand, it is typical of the daily regime of soil temperature on the moraine and more or less naked sorted circles in the region of Werenskiold (Brázdil et al., 1988). Even that fact documents the consequences of the thermal insulating properties of the tundra vegetation and rough humus in its underlier, due to which thermal losses are limited by the heat flow from the substrate to the active surface night. The consequence of it is the diminution of energy losses by means of effective radiation and thus also a lower cooling of the surface layers. A certain role here is no doubt that of increased soil humidity, decreasing - thanks to the high volume thermal capacity of water - the night cooling (conspicuous chiefly at Barentsburg).

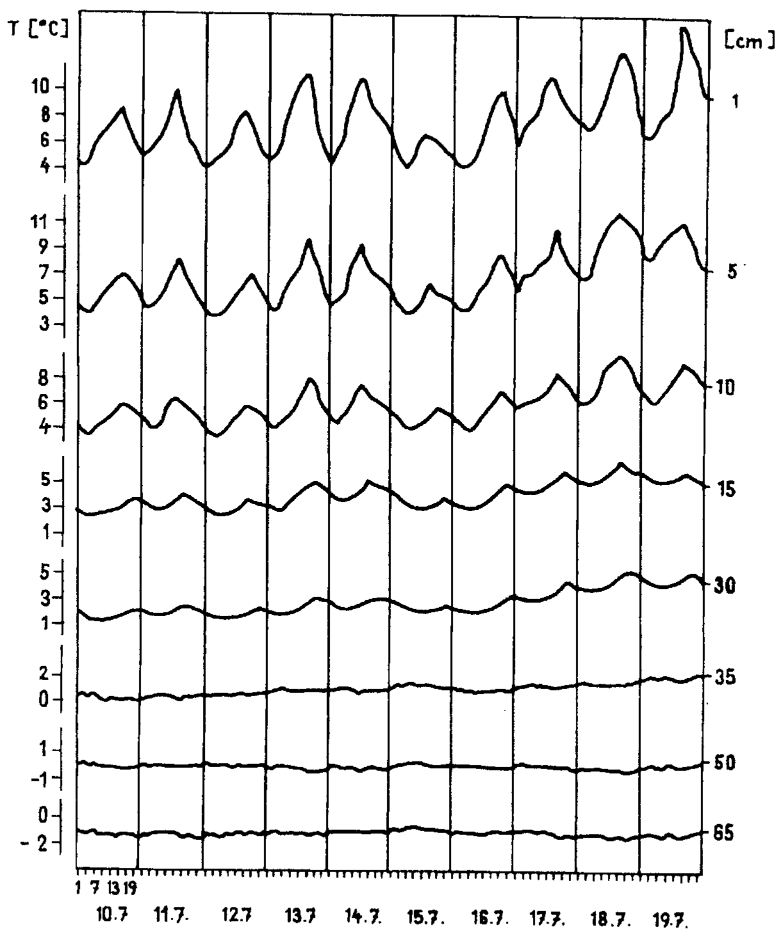


Fig. 5. Text see Fig. 4 - at the depths of 1, 5, 10, 15, 30, 35, 50 and 65 cm at the station of Reindalen in the period of 10-19 July, 1990

THE RELATION OF THE THERMICS OF TUNDRA UNDERLIER AND COMPONENTS OF THE ACTIVE SURFACE ENERGY BALANCE

Already in the analysis of active surface energy balance components at both localities statistically significant effects of the radiation balance on the heat flow into the underlier of the active surface were found (Prošek, Brázdil, 1994). Therefore also the consequences of the energy economy of the active surface on the temperature conditions of the substrate were evaluated from two viewpoints: the recognition of influences of R and influences of G on the subsurface temperatures. Another step was then the monitoring of the ALP development at Reindalen as a consequence of heat accumulation in the active surface underlier. The implementation of a similar intention at Barentsburg was impossible due to the occurrence of coarse stone debris under the layer of rough humus in the tundra underlier, making probes impossible.

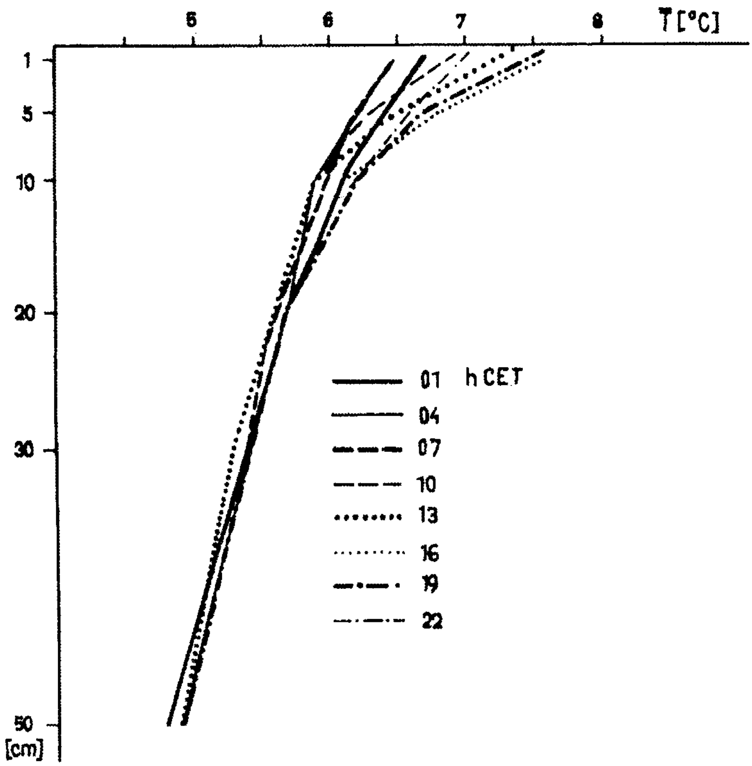


Fig. 6. Mean vertical profiles of the active surface underlier temperature at the station of Barentsburg in synoptical terms in the period of 21 June - 21 Aug., 1988

The idea about the regime of daily sums of the radiation balance (ΣR), the soil heat flux (ΣG) and the mean daily temperatures at the depths of 1 and 10 cm ($\overline{T}_1$, $\overline{T}_{10}$) is given in Figs. 8 and 9. Particularly at the station of Barentsburg (Fig. 8) a relatively good agreement of temperature regimes at the two depths and regime ΣG is evident. In verifying the dependence of temperature changes on changes in ΣR by the calculation of the correlation coefficients it was found that the visual agreement of the regime of the two pairs of variables was not so close as would seen at first sight. Although globally it is possible to state that the total character of temperature rises and drops follows the increase and decrease of the ΣR values, in detail these changes need not correspond to each other. In correlating the corresponding pairs of the sets ΣR and $\overline{T}_1$ or $\overline{T}_{10}$, respectively, it was reflected at both stations by low and statistically insignificant values of correlation coefficients. On the basis of experience with the analysis of a similar problem in processing the results of measurements from the region of Werenskiold in 1985 (Brázdil et al., 1988) attention was therefore paid to seeking the relation between the cause of temperature changes of the substrate (ΣR) and its consequence on days with prevailing radiation regime of weather (Figs. 10-12). Those days are marked in Figs. 8 and 9 by encircling the respective values of ΣR.

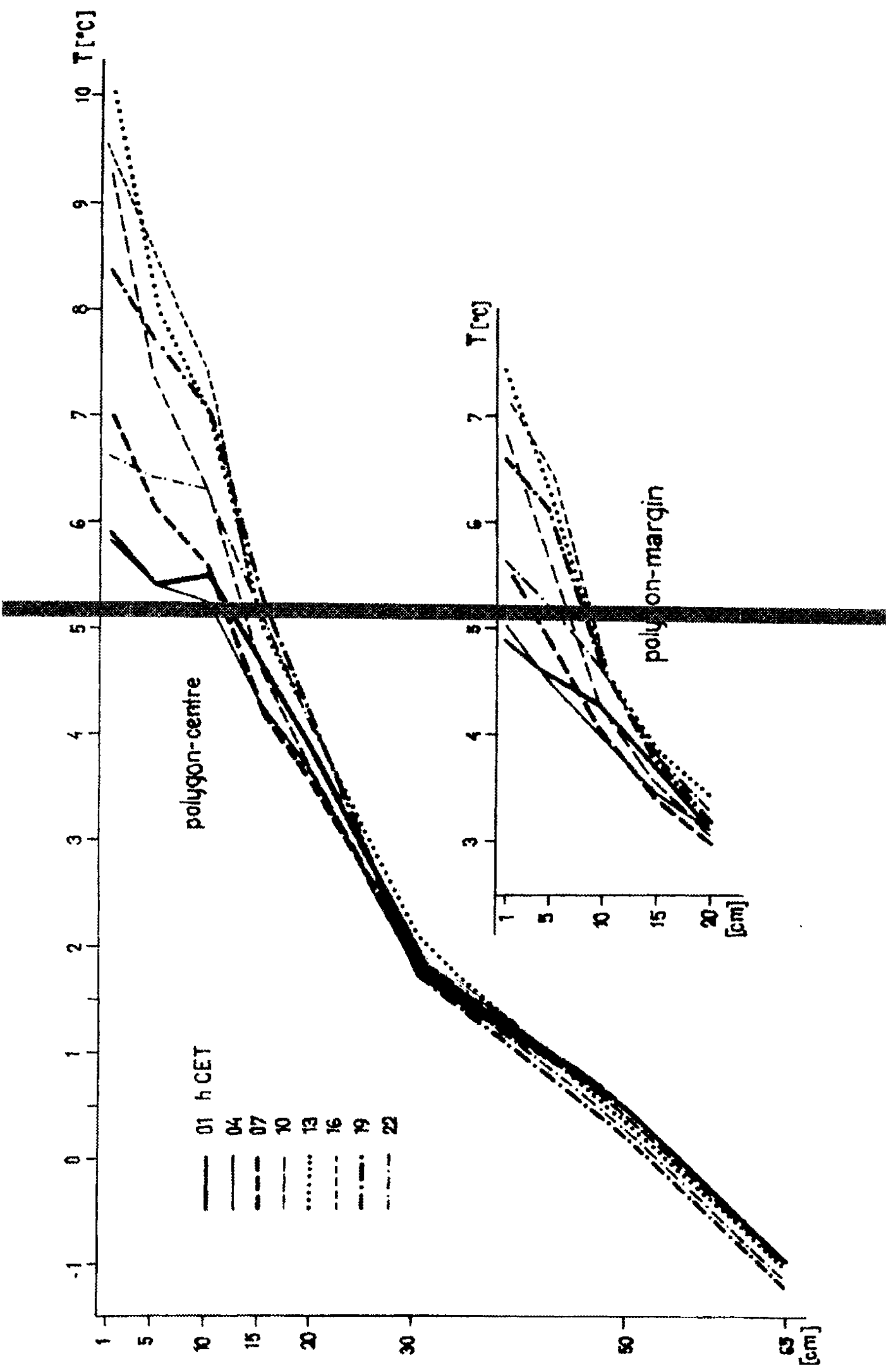


Fig. 7. Text see Fig. 6 - at the station of Reindalen (margin and centre of the sorted circle) in the period of 7 July - 9 Aug., 1990

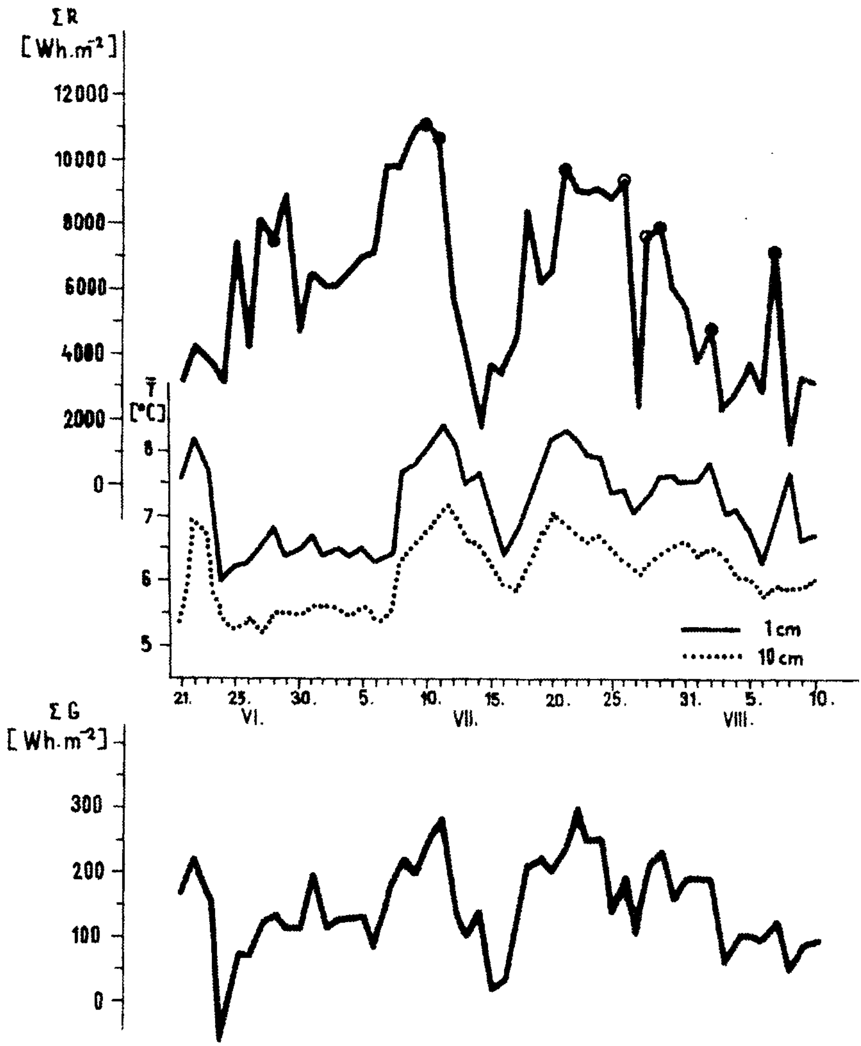


Fig. 8. Temporal changes in daily sums of the radiation balance (ΣR), the soil heat flux (ΣG) and the mean daily temperature of the active surface underlier ($\overline{T}$) at the depths of 1 and 10 cm at the station of Barentsburg in the period of 21 June - 10 Aug., 1988

Even in this case, like in the region of Werenskiold, the disturbing role of the character of advection on the studied relation was confirmed and by the level of values of the respective correlation coefficients (also given in Figs. 10-12, including the significance levels used for testing) the significance of effects of ΣR on soil temperatures at the above type of weather was documented.

At the same time, from the correlation graphs and the level of correlation coefficients there follows an increased closeness of the relation of the two variables in a greater depth, which is evidently the consequence of an increased operation of advection effects on the surface. In view of

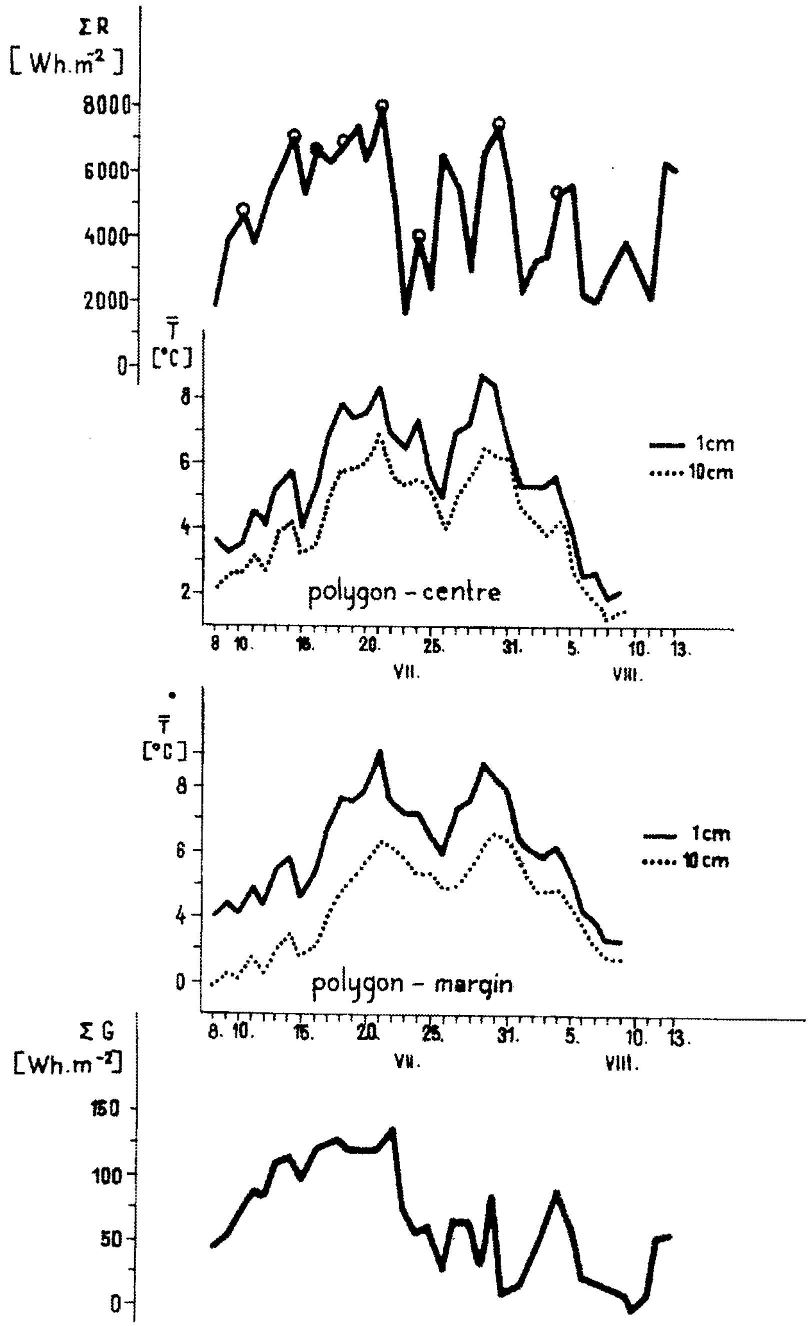


Fig. 9. Text see Fig. 8 - at the station of Reindalen in the period of 8 July to 13 Aug., 1990

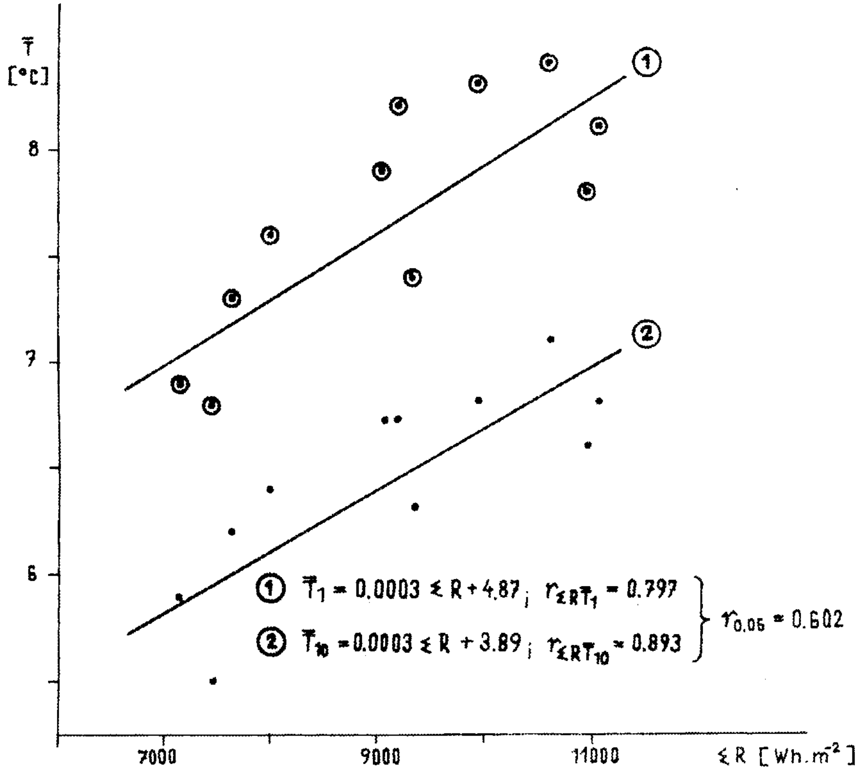


Fig. 10. Regression dependence of the mean daily active surface underlier temperature at the depths of 1 cm ($\overline{T}_1$) and 10 cm ($\overline{T}_{10}$) on daily sums of the radiation balance (ΣR) on days with the prevalence of radiation weather at the station of Barentsburg (period of 21 June-10 Aug., 1988); $r_{\Sigma RT}$ - correlation coefficient, $r_{0.05}$ - the critical value of the correlation coefficient at the level of significance 0.05

the exposed position of Svalbard Archipelago as a whole, they play a certain role even under the prevailing radiation regime of weather. They are then reflected by an increased dispersion of temperature values immediately below the active surface, whereas at a greater depth the temporal changes in temperature are more smoothed, corresponding better to the radiation effects.

Despite the fact that the ΣR maxima achieve higher values at Barentsburg, soil temperatures are affected by the ΣR regime under the radiation weather thanks to considerable humidity of the substrate on a much lower scale than at Reindalen. The high humidity of the active surface underlier at the former locality plays a certain balancing role in the sense of a lower variance of values $\overline{T}_1$ and $\overline{T}_{10}$, respectively, corresponding to the respective ΣR. That is expressed by higher values of the correlation coefficients in comparison with Reindalen.

From Figs. 10-12, including the respective correlation coefficients there follows at the same time a similar balancing effect of the tundra vegetation (Barentsburg, Reindalen - margin of the circle), whereas for the underlier of the active surface constituted by inorganic material (Reindalen - centre

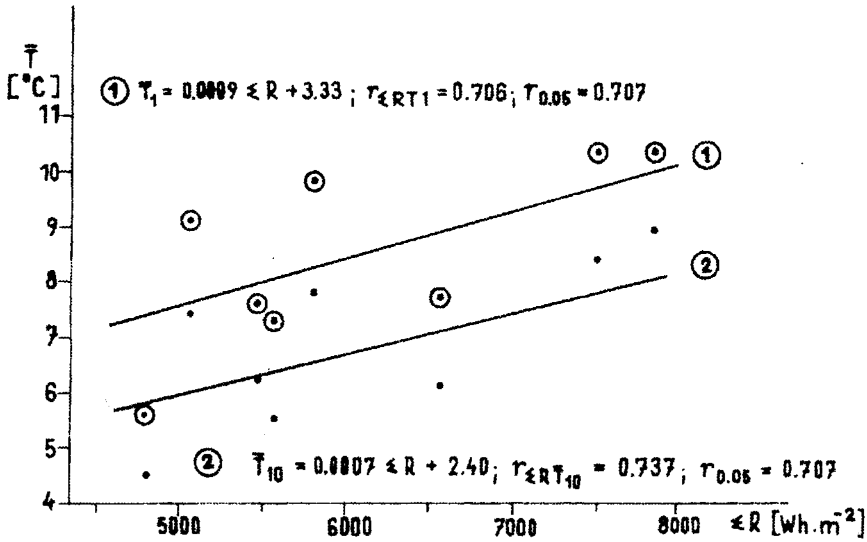


Fig. 11. Text see Fig. 10 - at the station of Reindalen - centre of the sorted circle (period of 8 July - 9 Aug., 1990)

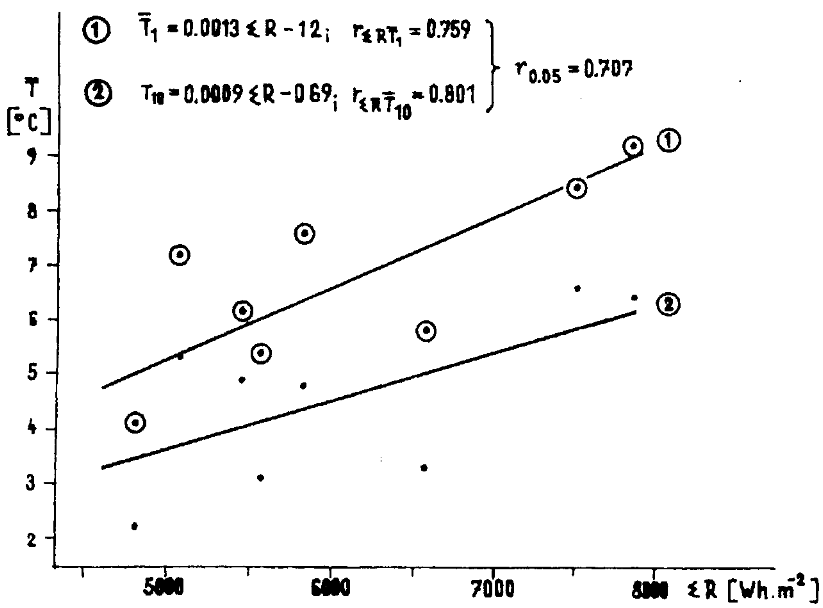


Fig. 12. Text see Fig. 11 - margin of the sorted circle

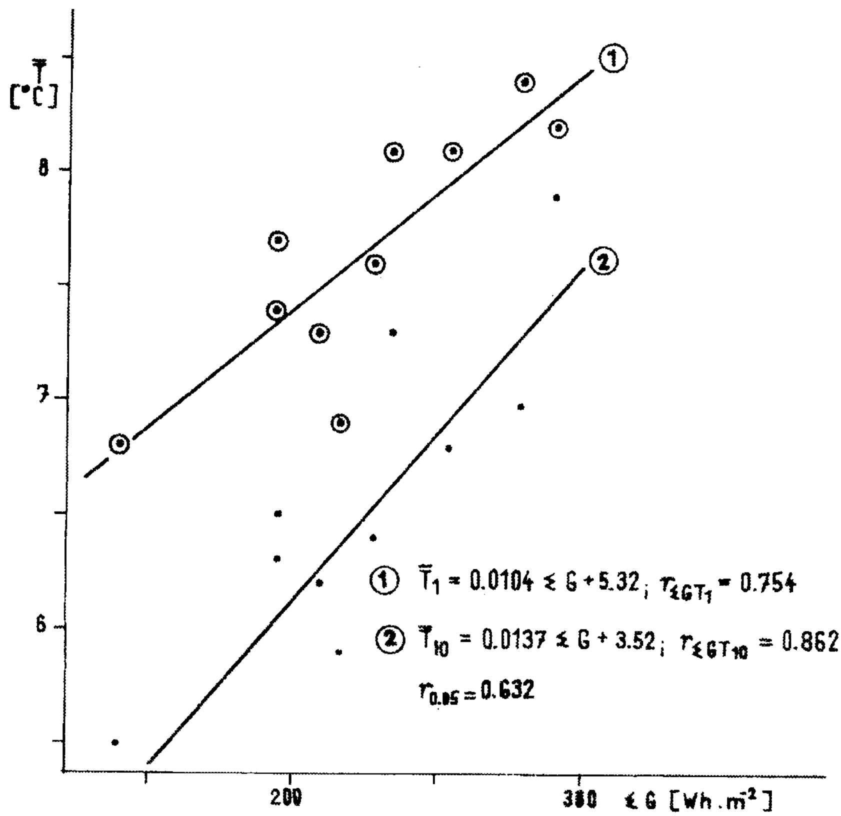
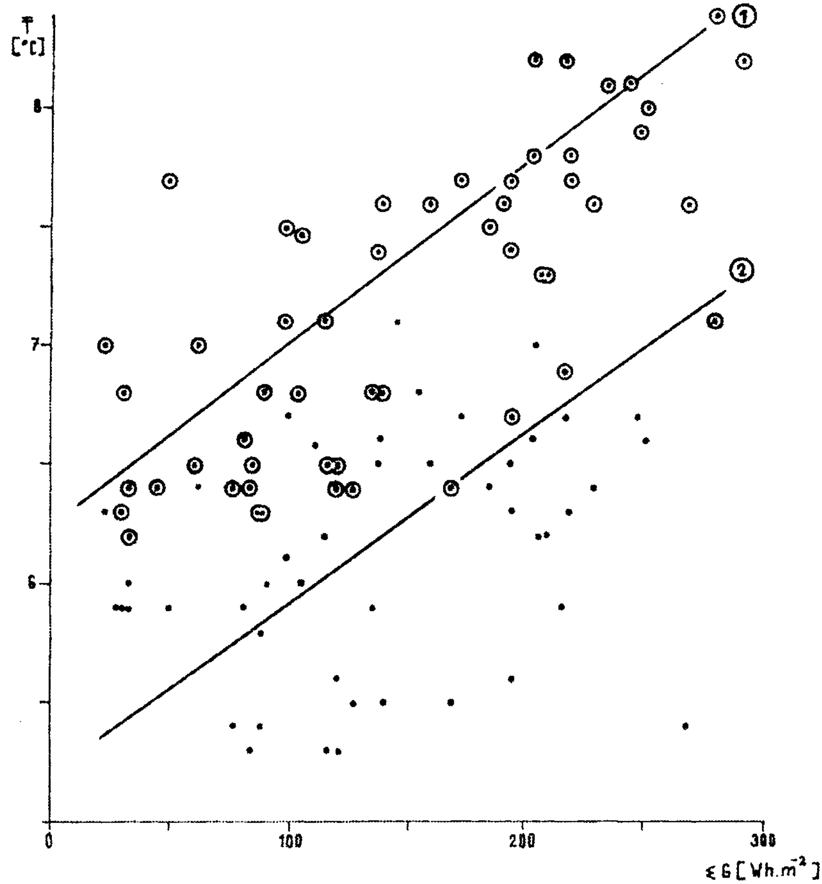


Fig. 13. Regression dependence of the mean daily temperature of the active surface underlier at the depths of 1 cm ($\overline{T}_1$) and 10 cm ($\overline{T}_{10}$) on the daily sums of the soil heat flux (ΣG) on days with the prevalence of radiation weather at the station of Barentsburg (period of 21 June - 10 Aug., 1988)

of the circle) the variance of the sets of values $\overline{T}_1$ and $\overline{T}_{10}$, corresponding to the respective ΣR is higher (see lower values of the correlation coefficients).

The dependence of $\overline{T}_1$ and $\overline{T}_{10}$ on ΣR corresponds in all three cases best to the linear one. The effect of the character of the active surface and its underlier is evident from the mutual relation of the course of pairs of regression straight lines. While at Barentsburg and at the centre of the naked sorted circle at Reindalen their course is practically parallel (thus documenting a very close temperature effect of the surface gain of radiation energy with depth), on the tundra margin of the circle the differences of the slopes of both lines (Fig. 12) are a document of differences in temperature consequences of ΣR, conditioning the drop in the magnitude of substrate warming with depth.

It can be assumed that the similarity of the dependence of $\overline{T}_1$ ($\overline{T}_{10}$) on ΣR is affected in the positive sense by a good thermal conductivity of the substrate. That can be conditioned either by its density, by an increased share of well conductive inorganic soil material, or by an increased content of water. From the reasons here stated, at Barentsburg the main role is played by the third one, whereas at Reindalen (centre of the circle) the second reason, to a lesser extent the third one. The underlier of



① $\overline{T}_1 = 0.0076 \cdot \Sigma G + 6.25;\ r_{\Sigma G \overline{T}_1} = 0.612$

② $\overline{T}_{10} = 0.0071\ \Sigma G + 5.22;\ r_{\Sigma G \overline{T}_1} = 0.609$

$r_{0.05} = 0.264$

Fig. 14. Text see Fig. 13. - for the whole period of 21 June - 10 Aug., 1988

the sorted circle at Reindalen has - in view of its composition (tundra vegetation, rough humus) - at relative dryness, on the other hand a very good insulation ability which results, particularly at high ΣR, in the increase of the temperature difference in comparison with the lower levels.

The linear character of the dependence of $\overline{T}_1$ and $\overline{T}_{10}$ on ΣR, typical of the localities evaluated, differs considerably from the results of the analysis of a similar dependence in the region of Werenskiold (Brázdil et al., 1988), where a nonlinear dependence was stated between the two variables, documenting an increasing intensity of the warming of the substratum with the increase in ΣR (particularly in the case of a relatively dry material of the moraine). Also this difference falls evidently at the cost of the good thermal conductivity of the moist underlier of the active surface of the tundra at Barentsburg and Reindalen.

The next step was looking in a similar way for consequences of the daily sums of the soil heat flux (ΣG) on the subsurface temperatures. Whereas at the locality of Reindalen (like at the Werenskiold station) the statistically significant effect of the heat transport in the substrate on its temperature was not stated, even during the prevalence of the radiation regime of weather, at Barentsburg a statistically significant dependence of $\overline{T}_1$ and $\overline{T}_{10}$ on ΣG was found not only in the selection of radiation days (Fig. 13), but also in the whole sample of the processed soil temperatures and their appurtenant ΣG (Fig. 14). This fact again documents the balancing effect of the high content of soil moisture on temperature consequences of the heat transport in the substratum via G.

The significance of influencing the substrate temperature by ΣG values is in the whole set of values, due to advection effects, somewhat lower than in the selection of radiation days and, like in the case of correlating the sets ΣR and $\overline{T}_1$ (and/or $\overline{T}_{10}$) it documents a closer bond between ΣG and the mean daily temperature at the depth of 10 cm ($\overline{T}_{10}$) during the radiation weather.

The character of the dependence of both subsurface temperatures on ΣG is, like in Figs. 10-12, linear, and the course of the regression lines for the whole period studied is practically parallel (Fig. 14). This statement, however, does no longer hold for days with the prevalence of the radiation weather factors (Fig. 13). A steeper course of the dependence of $\overline{T}_{10}$ on ΣG documents, besides the already mentioned high values of the correlation coefficient, more significant effects of ΣG on mean daily temperature at greater depth. Also in this case it is necessary to look for the reason of the described fact in the specific properties of the active tundra surface underlier at Barentsburg (high content of soil moisture). The flows of both radiation and heat energy, oriented from the atmosphere to the active surface and absorbed by it, are partly, via the molecular conduction, transported to its underlier (G). In our case, however, this energy is absorbed in the immediately subsurface layers for evaporation (see Prošek, Brázdil, 1994). The consequence thereof is a less steep dependence of soil temperature on ΣG at the depth of 1 cm. At a greater depth the effects of evaporation are no longer reflected. Due to evaporation and partial heat absorption at higher levels G is naturally smaller here (to which also the overall temperature level at the depth of 10 cm corresponds), but at the same time it is the only energy factor affecting temperature. Its consequence is also a steeper dependence of $\overline{T}_{10}$ on ΣG.

RELATION BETWEEN THE THAWING OF THE ACTIVE LAYER OF PERMAFROST AND ENERGY BALANCE

The temperature consequences of the energy balance of the active surface are naturally also reflected in the dynamics of the development of ALP in summer. For verifying this dependence measurements of the vertical dimension of this surface layer (d) were carried out at Reindalen and relations between its changes, the soil heat flux and its temperature were looked for. With respect to the fact that the probing of the ALP was done in only 6 terms (on 6, 19, 24 and 29 July, 3 and 10 Aug.), in evaluating the effect of ΣG on substrate temperatures and the development of the ALP, besides the measurement of the thickness of this layer also cumulated daily sums of the soil heat flux (ΣG_c) were used, as well as cumulated daily mean temperatures ($\Sigma\overline{T}_{10}$) in the intervals between the probing, which are graphically represented in Fig. 15.

From the development of the values of d it follows that the thickness of the ALP is affected by the character of the active surface to such extent that its value reflects changes in the distance of 20-25 cm (vegetation free centre of the sorted circle - the tundra cover) (Fig. 1). The insulation effect of the vegetation then conditions a drop in the course of thawing of the ALP by 10 cm (at the beginning) to 5 cm (at the end), and it was significantly reflected at the end of summer in the refreezing of the ALP from below (10 Aug. by 13 cm). A document of the sensitive connection of

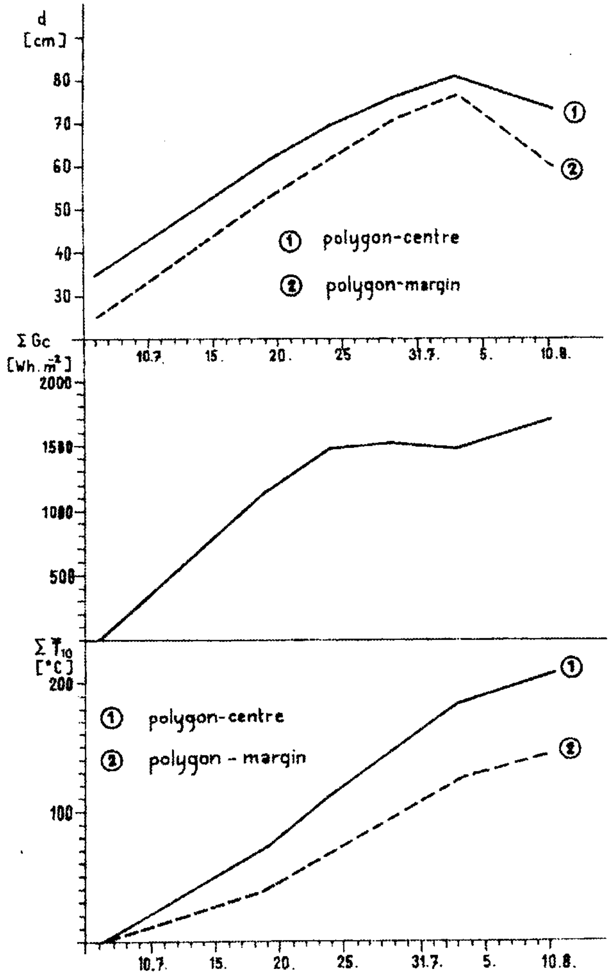


Fig. 15. The development of the thickness of the ALP (d), the cumulated sum of the soil heat flux (ΣG_c) and the cumulated daily mean temperature at the depth of 10 cm ($\Sigma \overline{T}_{10}$) at the station of Reindalen in the period of 6 June - 10 Aug., 1990

the values of d on the character of the surface layers of the active surface underlier are also the results of detailed probing of the thickness of the ALP at two crossing sections through the circle, presented in Fig. 16.

The described development (i.e. the increase in the value of d and subsequent drop) continues with some delayed action also for the period with practically zero heat accumulation in the active surface underlier (24 July - 3 Aug.), which documents the consequences of heat accumulation in the underlier of the active surface in the preceding period. The subsequent rise in G can no longer balance the consumption of energy for the defreezing of the soil water and there is a drop in the value of d due to freezing from below.

The time development of the values of $\overline{T}_{10}$ at first sight does not correspond to the development of the values of ΣG_c. With intense heat accumulation in the substrate at the beginning of the period studied (before 19 July) is in contrast a less conspicuous rise in cumulated temperature sums, reaching

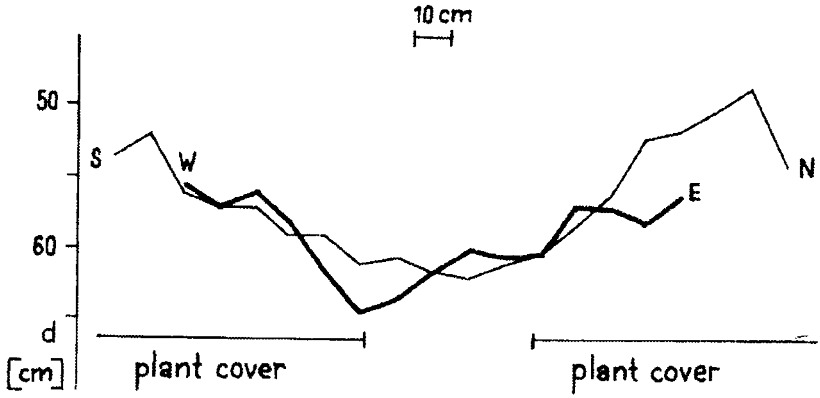


Fig. 16. The thickness of the ALP (d) in the underlier of the sorted circle and its immediate surroundings covered with the tundra vegetation, measured at the basic station of Reindalen on 19 July, 1990

its maximum as late as between 19 July and 3 Aug., during which the rise in ΣG_c slows down to the practically zero value. The described differences in the development of $\overline{T}_{10}$ and ΣG_c reflect here the well known fact of delaying the maximum of the soil temperature as against the maximum of the soil heat flux (see e.g. Prošek, Rein, 1982).

CONCLUSION

The present paper links up with the results of the study of the active surface underlier thermics in the region of Werenskiold glacier in the course of summer, 1985 (Brázdil et al., 1988), thus completing the overall picture of investigations oriented in this way during the three summer expeditions to different parts of Spitsbergen Island. In contrast to numerous papers devoted to the soil thermics and the dynamics of the development of the ALP (see e.g. the list of papers in Brázdil et al., 1988), it stresses to a greater extent the connection with the components of the energy balance of the active surface, the most important of them being the effect of the radiation balance and the heat flow into the substrate. The obtained results, despite the short time of measurements, document the more general effects of different types of the active surface, substrate moisture and meteorological conditions on the thermics of the underlier and the dynamics of the ALP.

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