Physical Processes at the Surface of the Arctic Tundra[1]

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ABSTRACT. The results of measurements of net total radiation flux and temperatures in the air and surface layers of the tundra and snow near Barrow, Alaska, are presented for the period September 1965 to September 1966. Lowest average monthly temperatures occurred in March, the highest in July. The minimum average net total radiation occurred in January with the maximum in July. The tundra surface began to thaw by 18 June and to freeze by September.

RÉSUMÉ. *Processus physiques à la surface de la toundra arctique.* Les auteurs présentent les résultats de mesures du flux de rayonnement total net et des températures dans l'air et dans les niveaux de surface de la toundra et de la neige, près de Barrow, Alaska, pour la période de septembre 1965 à septembre 1966. Les températures mensuelles moyennes minimales se retrouvent en mars, les maximales en juillet. Le minimum de rayonnement total net moyen se produit en janvier, avec un maximum en juillet. La surface de la toundra commence à dégeler vers le 18 juin et à regeler en septembre.

РЕЗЮМЕ. *Физические процессы на поверхности тундры.* Обсуждаются результаты измерений температуры и потока общего радиационного излучения на поверхности тундры в районе Барроу (Аляска), проведенные в течение одного года. Минимальные среднемесячные температуры наблюдались в марте, максимальные — в июле. Минимальное среднее значение общего излучения было отмечено в январе, а максимальное в июле. Поверхностный слой тундры начал оттаивать 18 июня и замерзать в сентябре.

INTRODUCTION

An investigation of the temperature stratification in the surface layers of the tundra was made on a raised beach ridge near Barrow, Alaska, during 1965 and 1966, as part of a micrometeorological and atmospheric chemistry program the purpose of which was to determine the concentration variations of molecular carbon dioxide gas under the snow (Kelley *et al.* 1968). This program enabled us to observe the temperature stratification continuously throughout the year at several levels within the soil, snow, and air, as well as the radiative energy balance of the study area.

Located on an old raised beach ridge near North Meadow Lake (71°19' N., 156°36' W.) the study area (Fig. 1) is classified as well-drained upland tundra. Former investigators (Brown and Johnson 1965; Douglas and Tedrow 1960) have given detailed descriptions of the tundra soil types and associated vegetation on the raised beach area. The vegetation cover consists of grasses and sedges not exceeding 10 cm. in height, with some mosses in the more moist areas. The
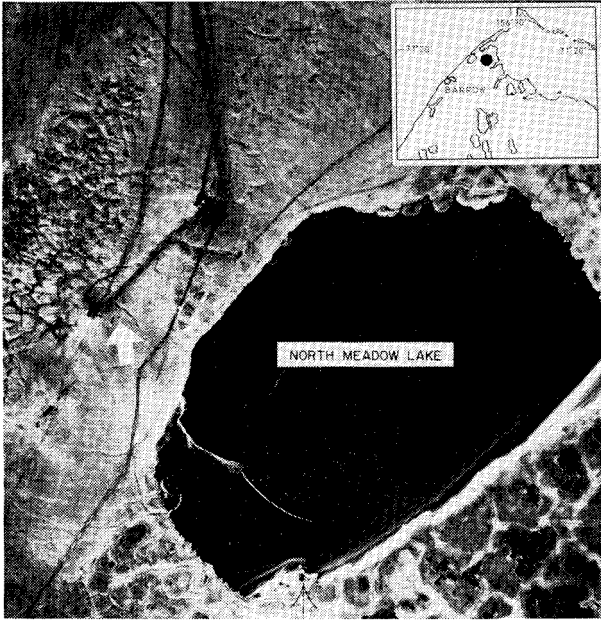
FIG. 1. North Meadow Lake field station showing thermal profile study area (white arrow). U.S. Army — CRREL photograph, 12 September 1966.

soil profile may be described as follows: the upper 8 cm. consist of a black fibrous organic matter, underlain by 25 cm. of a brown sandy loam with a small quantity of peagravel, and below this is a similar layer, but darker in colour, extending to a depth of about 60 cm. These layers constitute the active layer which lies above the permafrost and thaws during the brief polar summer.

Techniques of Observation

Temperature observations were made by means of thermocouples, located at 8, 4, and 2 cm. above the tundra surface, at the surface, and 2, 4, 8, and 16 cm. below it. The 2 and 4 cm. thermocouples were located within the grass, whereas the 8 cm. level thermocouple was usually vegetation free. Each sensor was made from No. 36 A.W.G. copper-constantan wire. The thermocouples were coated with silicone rubber and those exposed above the surface were painted flat white to reduce the solar radiation error. The output was recorded continuously on a multipoint potentiometric recorder. Data were reduced for each hour.

The radiation energy balance or net total radiation was measured about 80 m. from the thermocouple plot and over a similar tundra vegetative area. A C.S.I.R.O. net radiometer described by Funk (1959) was used. This instrument is accurate to about ±4 per cent for long wave fluxes and ±10 per cent for short-wave fluxes.

Daily thaw measurements were made by means of a steel probe. An average of 10 measurements was taken to record the thaw depth. Different observers may not handle the probe identically nor define the surface of the ground in the same way, especially when the surface is saturated with water. The average variation in sets of 10 measurements is less than 1.5 cm.

<div align="center">RESULTS</div>

Temperature Variations

Fig. 2 and Table 1 show the annual course of the ambient air temperature in a shelter 300 cm. above the ground; the ground surface temperature and soil temperature at 16 cm. below the surface. Also shown in Fig. 2 is the annual region of net total radiation and cloud cover. Lowest air temperatures for the year were recorded in February and March with highest temperatures recorded in July. The average ambient air temperature for March 1966 was 4.5 deg. C. lower than the climatic norm for that month (ESSA 1966).

The highest average hourly temperatures were recorded at the tundra surface under conditions of low wind and relatively low cloud cover during the summer solstice. Average daily maximum temperatures occurred on 15 July 1966. These were 6.1°C. at a depth of 4 cm., 5.3°C. at 8 cm. and 4.0°C. at 16 cm. On two occasions, surface temperatures exceeded 20°C. for more than one hour during the day. On 27 June 1966, the hourly average temperature at 1300 A.S.T. reached 20.9°C. under 20 per cent cloud cover and 5 knots of wind. The average
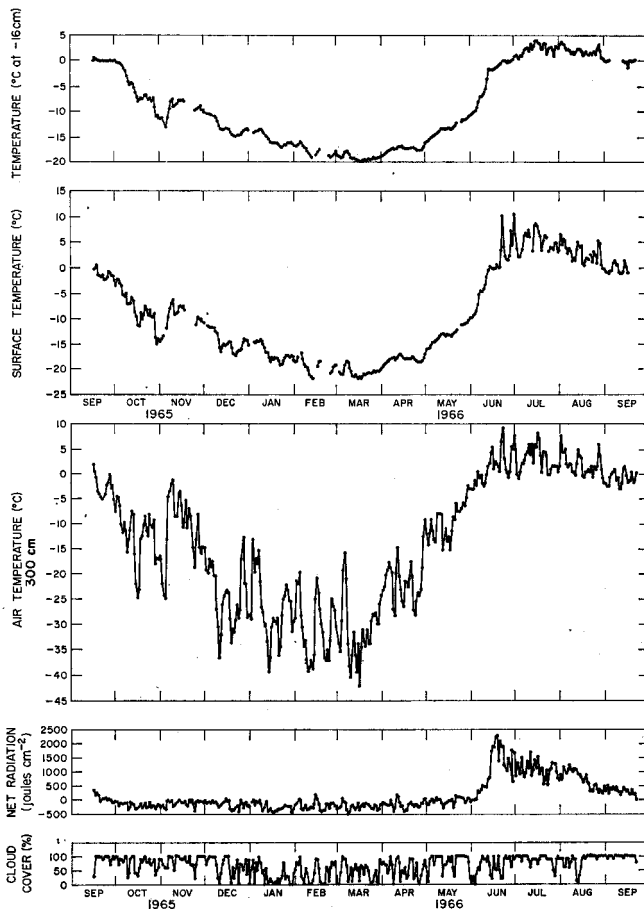

FIG. 2. The annual course of tundra temperatures at the surface and at 16 cm. levels.

TABLE 1.   Summary of average monthly soil temperatures, net radiation, and cloud cover. (M indicates missing data).

Month	Net Radiation (joules cm.⁻²)	Cloud Cover (%)	Temperature (C.)								
			−16	−8	−4	−2	0	2	4	8	300 cm.
1965											
SEP	4,900	81	0.0	− 0.1	− 0.2	− 0.3	− 1.3	− 2.9	− 3.2	− 3.3	− 1.5
OCT	−6,800	75	− 5.8	− 6.4	− 6.7	M	− 8.3	− 9.1	−10.4	−13.3	−12.6
NOV	−3,500	84	− 9.1	− 9.3	− 9.2	− 9.3	− 9.3	− 9.3	− 9.4	− 9.4	−10.7
DEC	−5,500	65	−12.9	−13.3	−13.4	−13.6	−14.3	−14.9	−15.9	−16.9	−24.7
1966											
JAN	−8,300	32	−15.4	−15.8	−16.0	−16.1	−16.8	−17.2	−17.4	−17.8	−26.5
FEB	−6,100	40	−17.6	−18.1	−18.3	−18.5	−19.3	−19.6	−19.9	−20.2	−30.2
MAR	−7,400	45	−19.0	−19.4	−19.6	−19.7	−20.4	−20.6	−20.8	−21.2	−30.5
APR	−5,200	54	−17.3	−17.4	−17.4	−17.7	−17.7	−17.8	−17.9	−18.0	−14.9
MAY	−1,000	80	−10.6	−10.4	−10.2	− 9.8	− 9.6	− 9.4	− 9.2	− 9.0	− 8.8
JUN	33,100	68	− 3.4	− 2.7	− 2.1	M	− 0.1	− 1.3	− 1.7	− 1.5	− 1.7
JUL	33,300	88	2.3	3.2	3.8	M	5.4	M	M	M	3.0
AUG	22,300	83	1.8	2.2	2.4	M	2.8	M	M	M	1.6
SEP	2,600	95	− 0.2	− 0.1	0.1	M	− 0.1	M	M	M	− 0.6

hourly tundra surface temperature on 29 June at 1100 A.S.T. was 23.1°C. with a 50 per cent cloud cover and a wind speed of 5 knots.

Table 2 summarizes the frequency distribution of maximum summer surface temperatures during any one hour of the day at the North Meadow Lake study site. The period covered extends from the time the snow left the tundra to the beginning of the freeze-up period, 19 June to 31 August 1966. Table 2 shows that during the snow-free summer period when most of the vegetative growth occurs, the surface temperatures are above −1.1°C. during part of each day.

TABLE 2.   Summer surface temperature frequency distribution.

Surface Temperature	−1.1°C. 30°F.	4.4°C. 40°F.	10.0°C. 50°F.	15.6°C. 60°F.	21.1°C. 70°F.
Frequency per cent	100	89	51	23	1

The annual cycle of soil temperatures also shows a damping of amplitude and a phase lag with depth. Throughout the winter months, the surface temperatures were colder than those at the 16 cm. level in the ground. By the end of May the situation was reversed with the surface temperatures rising above those at the 16 cm. level. However, for a period of three weeks, from 30 April to 21 May, the temperature gradient between the surface and the 16 cm. level was nearly zero. In June the net total radiation increased rapidly and the temperature at the tundra surface responded much more quickly to energy changes at the interface than did the soil below it. In early August, the 16 cm. average daily temperatures generally exceeded the temperatures at the surface.

Diurnal Temperature Variations

The diurnal variation in temperature according to the time of year is shown in Fig. 3. The greatest diurnal variations occurred from June through September
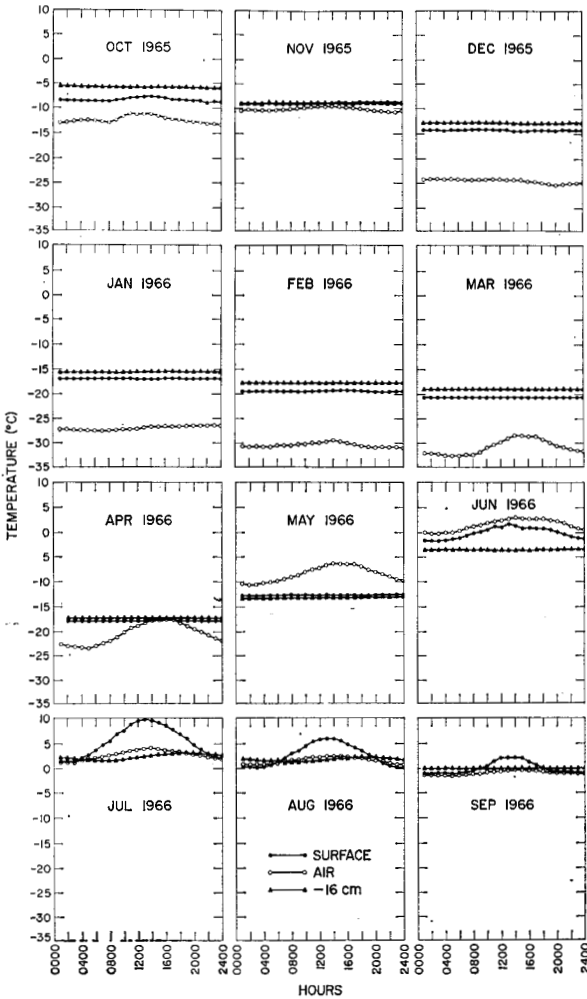
FIG. 3. The diurnal course of temperatures near the tundra surface.

when the surface was snow-free and the radiation was undergoing strong diurnal changes.

In October, the amount of insolation was small and the tundra surface layers were refreezing. There was a small diurnal variation in the surface and air temperatures, but very little variation 16 cm. in the ground. By November, the temperatures at the surface and 16 cm. level were about the same. From early December until the end of May, there was sufficient snow cover for any diurnal changes in the air temperature not to affect appreciably the thermal regime under the snow. The diurnal variation of the surface temperature and that at the 16 cm. level were greatest in July. The maritime climate along the arctic Alaskan coast is in part characterized by variable wind and cloudiness which affects the profile of the diurnal temperature variation during any day. A typical profile for the diurnal course of temperature and radiation on clear days, during the summer, is shown in Fig. 4. The surface temperature exhibits a minimum near sunrise,
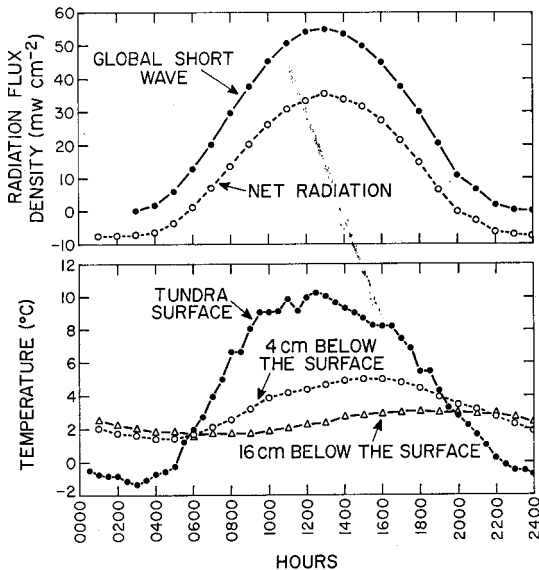
FIG. 4. The diurnal course of tundra temperatures and solar radiation on a cloudless day.

a steep rise during the morning, a maximum near local noon (1225 A.S.T.), an inflection point near sunset, and a less steep drop during the night. Departures from the smoothness of the surface temperature profile occurred with changes in the wind speed and direction. The average wind speed per day as measured at the Barrow U.S. Weather Bureau Station was 11 knots and varied during the day from 8 to 16 knots. Short-period temperature fluctuations were damped out at the 4 cm. level which usually reached its minimum value two hours after the minimum at the surface. Its maximum temperature occurred about two hours after the maximum at the surface. The minimum temperature at the 16 cm. level occurred about three hours after the minimum at the surface, whereas the maximum was attained about five hours after the maximum at the surface.

These data indicate that the flora and fauna inhabiting the tundra surface undergo a temperature change during the day of nearly 12°C., those living 4 cm. below the surface a change of about 3.5°C., and at 16 cm. a change of only about 1.4°C.

Seasonal Freeze and Thaw

Drew *et al.* (1958) show that there are marked variations in soil temperature and thicknesses on the beach ridge near Barrow. The well-drained, uplifted marine sediment beach ridge permits deeper thawing owing to its lower heat capacity. The thaw penetration also varies with differences in summer air temperatures and precipitation. It should also be noted that the ridges are snow-free at an earlier date than are the lowlands.

The seasonal freeze-and-thaw zone is called the active zone (Muller 1947; Stearns 1966). Environmental factors such as vegetation, soil moisture, exposure, temperature, and snow cover affect the depths of seasonal freeze and thaw. Below the active zone lies the perennially frozen ground (permafrost) in the Barrow area; it is reported to be 314 m. deep (McCarthy 1952).

Fig. 5a and c shows the average daily temperature of the tundra from the surface to 16 cm. below the surface during the period of freeze and thaw. Fig. 5b and d shows the date of freezing and thawing at each level. The temperature of the tundra surface about 15 September 1965, and 20 September 1966, was within a few tenths of $0°C$. At about the same time the temperature at the 16-cm. level in the tundra remained relatively constant at about $0°C$. until all of the water in the soil above was frozen.
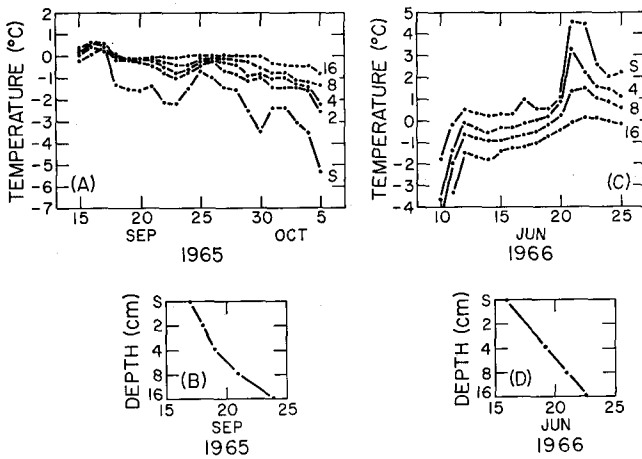

FIG. 5. Temperatures in the surface layers of the tundra during the periods of freezing and thawing.

This phenomenon is called the zero curtain (Muller 1947) with its depth and duration controlled by the available moisture, thermal properties of the soil, and weather conditions. The zero curtain effect lasts for a longer time as the moisture increases (Cook 1955). The zero curtain occurs when the air temperature falls below $0°C$. followed by a rapid drop in soil temperature which holds at the freezinz point because of compensation by the latent heat of fusion given off by the ground water until it has turned to ice. This process lasted about two weeks in September 1965 and more than a month in 1966.

As soon as the tundra surface was frozen, the temperatures of the near-surface layers began to rise reaching a maximum on 16 September 1965, and 26 August 1966. Within three days after the rise, the temperatures of the underlying layers fell again, and remained near $0°C$. for about two weeks in 1965 and nearly a month in 1966.

A possible source of heat to account for the initial rises in temperature during the freeze period may be solar radiation. Brewer (1958) observed a similar rise in an arctic lake which may have been caused by solar radiation absorption in the lake. During the freezing period the surface of the tundra is covered with a thin frozen layer. The tundra surface during the thaw period is covered with snow and melt water. The short-wave solar radiation can penetrate snow, water, and ice and heats the ground. During freeze-up, heat is removed mainly from the surface by radiation and sensible heat flux. Thus the water, ice, and snow act as a radiation trap for heat stored in the underlying layers of the ground.

A similar condition prevailed during the thaw period in June 1966. However,

unlike the freezing period with its absence of snow, there was a snow cover on the tundra in June. The thaw period was characterized by a steady rise in the tundra temperatures at all levels to a maximum on 12 June 1966. After 12 June, the temperatures at all levels temporarily decreased and further increases at all levels were gradual until melting of the ice occurred. In late July and August, the thaw rate was greatly diminished and the depth of the active layer remained constant for about two weeks just before the freeze-up.

An empirical equation describing the progression of thaw may be written

$$Z = L(1 - e^{at})$$

where
                      Z is the depth of thaw in cm.
                      t is the time in days
                      a and L are empirical constants
                      $(a = 0.082d^{-1}, L = 63.3$ cm.$)$.

The data are shown graphically in Fig. 6. The empirical curve was fitted to the observed data by the least squares method of differential correction.
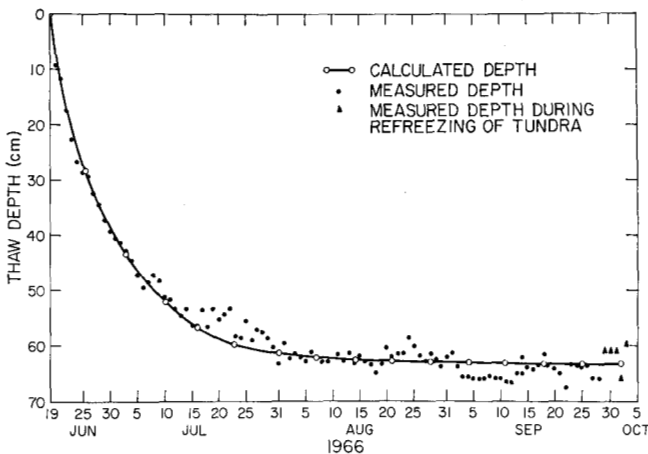

FIG. 6. The progression of tundra thaw at North Meadow Lake during the summer, 1966.

The contribution of net total radiation to depth of thaw is shown in Fig. 7. At the onset of the tundra thaw the cumulative net total radiation was $1{,}800$ J cm.$^{-2}$. As the thaw progressed, further increases in the cumulative net total radiation to a maximum summer value of $96{,}500$ J $-$cm.$^{-2}$ have a decreasing effect on the depth of the thawed layer.

The Energy Balance

Energy fluxes which influence the state or temperature of the soil may be related by the energy equation

$$q(w) = F_r + F_s + F_L + F_c$$

where $q(w)$ is the energy required to melt the snow cover, F_c the conductive heat flux through the soil, and F_r is the radiative heat flux. The sensible heat flux, F_s and the latent heat flux, F_r, were not measured and are not known.
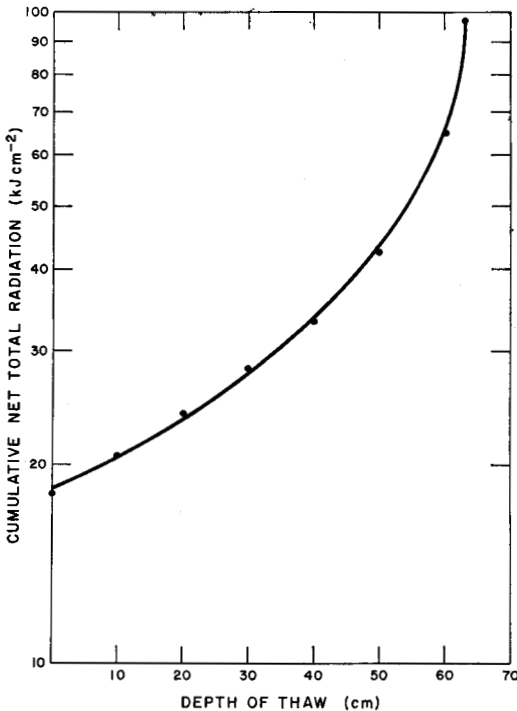
FIG. 7.   Effect of cumulative net total radiation on the depth of thaw during the summer, 1966.

The amount of heat lost or gained by the 16 cm. soil layer over various time periods may be expressed as $\Delta H = \Delta h_1 + \Delta H_2$, where ΔH is the total heat change, Δh_1 the heat change resulting from temperature changes of the soil and Δh_2 the heat lost or gained by the soil freezing or thawing.

According to Mather and Thornthwaite (1956) the heat capacity of unfrozen Barrow soil of 50 per cent by weight water content is 0.63 cal. cm.$^{-3}$ °C.$^{-1}$. We assume 30 per cent water content for the better drained beach ridge soils giving a heat capacity of 0.44 cal. cm.$^{-3}$ °C.$^{-1}$ or 1.84 joules cm.$^{-3}$ °C.$^{-1}$ for unfrozen soil and 1.4 joules cm.$^{-3}$ °C.$^{-1}$ for frozen soil. The heat lost or gained in freezing or thawing of 30 per cent water content soil is 100 joules cm.$^{-3}$.

If we take the temperature differences occurring for the soil layers between the surface and -16 cm. on 15 September 1965 and 15 September 1966, multiplied by the heat capacity, we find a difference of only 33 joules. This small value justifies an assumption of steady state for the period of investigation.

In solving the energy fluxes for the year, we noted that about 50 cm. of snow with a measured density of 0.2 gm. cm.$^{-3}$ resulted from the 1965-66 winter accumulation. The energy used in melting the snow is

$$q(w) = (50 \text{ cm.}) (0.2 \text{ gm. cm.}^{-3}) (334 \text{ joules gm.}^{-1})$$
$$q(w) = 3,340 \text{ joules cm.}^{-2}.$$

The net total radiation balance if taken from September 1965 through August 1966, F_r, was 49,800 joules cm.$^{-2}$ (Weaver 1969a and b) for the year. The conductive heat flux, F_c, is zero assuming steady state conditions with ΔH essentially zero.

Therefore, of the 49,800 joules cm.$^{-2}$ given to the system by the net total radiation balance, 3,340 joules cm.$^{-2}$ are used to melt the snow cover with the remaining 46,460 joules cm.$^{-2}$ removed by the sensible and latent heat fluxes.

The year may be separated into time periods corresponding to the physical and temperature changes experienced by the soil layer itself. We define six periods.

Period I: The tundra soil layer was in the process of freezing and once frozen, cooling. The date of freezing at each level is shown in Fig. 5b. The delay in freezing at the 16 cm. level was caused by a warming trend from 24 to 28 September 1965. Also, the first snow accumulation occurred during this period and provided an insulating blanket.

Freezing and cooling of the tundra surface layers occurred from 1 to 30 September 1966. It is difficult to determine the exact day of freeze-up as the transition may occur over many days changing between freeze and thaw as influenced by general weather conditions.

After 1 September 1966 the daily averages at all levels from the surface to 16 cm. were at or below 0°C. During September, the surface was usually frozen, but might warm or even thaw under sunny skies.

The active layer remained essentially thawed until the end of September 1966 (Fig. 6). The tundra soil then froze up from the bottom of the active layer and downward from the surface towards a mid-depth. The layer of tundra from the surface to 16 cm. was frozen by 1 October 1966.

Period II: Cooling of the 16 cm. thick soil layer continued from 1 October to 15 March. Fluctuations in the tundra surface temperatures of several degrees Celsius during the period resulted from changes in net total radiation and sensible heat flux associated with storm passages and other weather phenomena. The sun was at very low angles or below the horizon and net total radiation values were negative for all but five days.

The 40 cm. snow depth by 15 March at the thermocouple site provided an insulating blanket over the tundra. As a result, soil temperatures were warmer than ambient air as heat is conducted upward from the warmer permafrost layers. Lower soil temperatures than those measured at the thermocouple site probably prevailed in areas with less snow cover.

Estimates of conductive heat flux F_c, through the soil and snow layers showed much greater flux rates for the soil than for the snow. Since the heat leaving the soil must also leave the snow layer, it must be assumed that convection exists in the snow and is the predominant means of heat transfer. This assumption is supported by ground-surface CO_2 investigations conducted at the same site which indicate a flushing mechanism which removes high concentrations of CO_2 from the snow by the wind blowing over the snow surface (Kelley *et al.* 1968). Convection within the snow has also been reported by Benson (1969).

Period III: From 15 March to 18 June the Arctic slowly warmed, heat being supplied by the increasing short wave radiation flux. Net total radiation at the beginning of the period was positive only during the noon hours. Towards the end of period III, the average daily net total radiation became positive. As a result, the soil temperatures increased initially at a rate of 0.17°C. per day. However,

after 1 June when the snow cover was broken, the net total radiation increased rapidly as the surface albedo markedly decreased. The soil temperatures then increased at a rate of 0.5°C. per day. This increase slowed considerably after 12 June because much of the energy entering the system was being used to melt the snow layer. By 18 June, nearly all of the snow was melted and the exposed tundra was thawing and warming, with conspicuous melt water on the flat tundra landscape.

Period IV: Thawing and warming of the tundra surface layers occurred between 18 and 28 June 1966. Some surface thaw may have occurred as early as 12 June as melt water at 0°C. percolates through the snow to the tundra surface.

Absorption by the tundra surface of the short wave radiation penetrating the decreasing snow cover provides another means for surface thaw. If we assume an extinction coefficient for snow of about $2(10^{-2})$cm.$^{-1}$, as much as 8 per cent of the total short wave radiation flux may be absorbed by the tundra beneath a 40 cm. snow cover, and as much as 14 per cent can be absorbed under a 10 cm. snow cover (Roulet 1968, personal communication). This effect may be of considerable importance on ridges and hummocks as the often very shallow snow cover may absorb and trap large amounts of solar energy during the two to three (usually sunny) months before actual melting begins. While both melt water and solar radiation may cause the uppermost tundra layers to thaw, the depth is small and actual thawing is considered to occur after the tundra is snow free (on 18 June, in the present instance). As the snow cover disappears, the albedo decreases, and the net total radiation balance increases.

Period V: From 28 June to 15 July 1966 the thawed tundra soil warmed steadily to its yearly maximum temperature. Large temperature fluctuations at the tundra surface are common and are related to storm passages and other meteorological

TABLE 3.   Summary of radiative energy flux, heat change, and average temperatures near the tundra surface during 1965, 1966.

PERIOD	Ia	II	III	IV	V	VI	Ib
F_r	368	−14,000	458	14,896	20,070	38,683	7,580
F_s	≃ 0	+	+	—	—	—	≃ 0
F_L	≃ 0	≃ 0	—	—	—	—	≃ 0
F_c	—	—	+	+	+	—	≃ 0
ΔH	−1,622	−320	330	1,640	86	−110	−1,600
Δh_1	−22	−320	330	40	86	−110	≃ 0
Δh_2	−1,600	0	0	1,600	0	0	−1,600
T_a	−2.8	−23.2	−15.2	−3.1	4.0	2.5	−0.6
T_s	−1.4	−14.5	−13.4	3.6	6.1	3.6	−0.1
T_{-16}	0	−13.6	−12.7	−0.3	4.2	2.2	−0.2
q_w			−3,340				

F_r = net total radiation flux; F_s = sensible heat flux; F_L = latent heat flux; F_c = conductive heat flux; ΔH = total heat change of the 16 cm. soil layer; Δh_1 = heat change from soil temperature change; Δh_2 = heat change resulting from freezing to thawing and thawing to freezing; T_a = average ambient air temperature 300 cm. above the ground; T_s = average soil surface temperature; T_{-16} = average temperature of the soil 16 cm. below the tundra surface; q_w = energy used in melting the snow. Period Ia = 15 September to 1 October 1965; Ib = 1 to 30 September 1966.

phenomena. Temperatures of the upper levels closely followed the diurnal varia-
tion of short wave solar and net total radiation as shown in Fig. 4. In general, the
temperature gradient in the tundra surface layers is positive for daily averages
but tends to be negative during the night-time when the sun is low on the horizon.
The soil continued to gain heat during period V, but by mid July substantial heat
may have been lost at night or on cold days.

Period VI: A cooling trend at the tundra surface occurred between 15 July and
1 September 1966. Less than three weeks after the tundra surface thawed, the
upper layers of the tundra began to cool while the thaw continued at lower levels.
After 15 July, the thin layer of the tundra surface froze on clear nights when the
net total radiation was negative. After mid August, the surface remained frozen
throughout some of the colder days. Light snowfall occurred on several occasions
during August.

   Soil temperatures, air temperatures and energy fluxes are summarized in
Table 3.

SUMMARY

   Our investigations conducted from 15 September 1965 to 1 October 1966 on
a well-drained inland beach ridge near Barrow, Alaska, indicate the following:

   1. The average annual temperature of ambient air at 300 cm. was $-12.2°C.$;
the soil surface temperature was $-8.4°C.$ and soil temperature at -16 cm. was
$-8.2°C.$

   2. The net total radiation heat balance for the period of investigation was
49,800 J cm.$^{-2}$.

   3. The final freeze-up date of the 16 cm. soil layer was 1 October.

   4. The tundra soils began to thaw on 18 June with depths of thaw reaching
a maximum of 66 cm. three months later.

   5. The depth of thaw as a function of time can be represented by an empirical
equation.

   6. The tundra surface was snow free from 18 June to late September.

   7. Maximum and minimum temperatures reached by the tundra surface were
17°C. and $-22.5°C.$, and occurred on 17 July and 14 March respectively.

   8. The daily average temperature was above 0°C. for 85 days in the ambient
air 300 cm. above the surface, 72 days at the surface, and 62 days at a depth of
16 cm. below the surface.

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