Task No. NR 387-022
ONR Contract No. 1202(07)

Technical Report No. 37

Summertime Radiation Balance and Energy Budget of the Canadian Tundra

by

William F. Ahrnsbrak

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The University of Wisconsin
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January 1968

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INTRODUCTION

Among the areas of the world for which only sparse meteorological data are available is the Canadian Tundra. The area above the central Canadian tree line, a line running approximately northwest from Churchill, Manitoba, through Fort Reliance, N.W.T. past the north end of Great Slave Lake (Fig. 1), and bordered on the north by the Arctic Ocean and on the east by the Hudson Bay, is an area of some 400,000 square miles. In this area are approximately 15 synoptic observing stations, maintained by the Meteorological Division, Air Services Branch, Canadian Department of Transport. This synoptic network is maintained primarily as a service to aviation. While wide spacing of observing stations makes precise analysis difficult, Reed (1959) suggests that in the summertime the tree line is a frontal zone between two different airmass types, and Bryson (1966) states that in the summertime this large, rather homgeneous tundra area is predominantly occupied by a different air mass than the boreal forest to the south. Investigations of the interrelationships between landform, vegetation, and climate in this area would therefore be of interest.

According to the Canadian Department of Transport (1962) the map of mean daily temperature in January shows the -30° F isotherm (the lowest on the map) to enclose a circle whose diameter is approximately 300 miles, centered near Baker Lake, N.W.T. In substantiation of

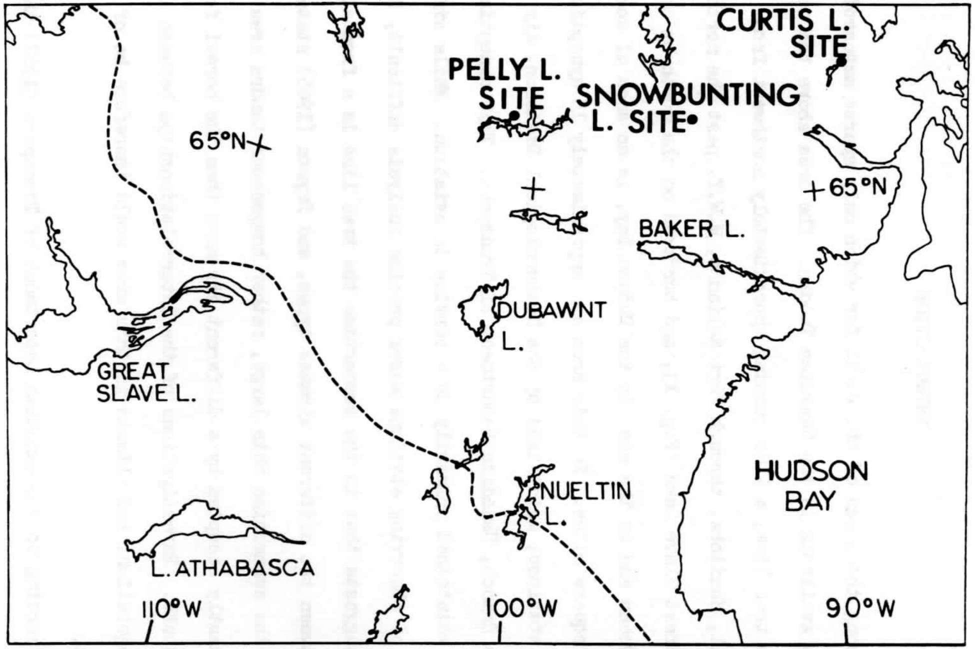

Figure 1. Location of the three sites where micrometeorological field studies were carried out in summer, 1966, and present location of the tree line (-----) (after Larsen, pers. comm.)

this, Larsen (Pers. Comm.) has found that certain unique characteristics of the vegetation of the area would appear to indicate that climatic conditions are especially severe in this region. This area is apparently the cold pole of continental North America, and as such is worthy of more detailed investigation than standard synoptic observations would allow.

Due to the scarcity of meteorological observations taken regularly in the region of interest, and also well into the boreal forest to the south and southwest, various authors have investigated several "natural climatic indicators" and their interrelationships with their environment. McFadden (1965), Peterson (1965), B. Lettau (1966), and Mitchell (1967) have investigated relationships between climate and lake ice, lake temperatures, sphagnum bogs, and tree growth rate, respectively, in central Canada. While these studies deal with the way in which particular natural indicators respond to climate as a forcing function, none of them is concerned with any "climate forming factor."

H. Lettau (1951) has developed a system of equations in which variations, both annual and diurnal, of temperature are described as responses to the harmonic oscillations of the net effect of all radiative processes, i.e., net radiation. According to Marshunova (1961), "The radiation balance is of great interest in the solution of the problem of the formation and transformation of air masses." Radiation balance and energy budget thus being a major key to climate formation, micrometeorological field investigations were carried out in the district of Keewatin, N.W.T. The primary aim of these investigations was to measure those parameters required to obtain a radiation balance and energy budget representative of the area of interest.

In the traditional form, the radiation balance of an area can be expressed by

$$R_n = R_s\downarrow - R_s\uparrow + R_l\downarrow - R_l\uparrow \qquad (1)$$

$$= R_s\downarrow\cdot(1 - a) + R_l\downarrow - R_l\uparrow \qquad (1a)$$

where

R_n = net flux of radiation

$R_s\downarrow$ = downward flux of shortwave (solar) radiation (both direct and diffuse)

$R_s\uparrow$ = upward flux of (reflected) shortwave radiation

$R_l\uparrow$ = upward flux of longwave radiation

$R_l\downarrow$ = downward flux of (back) longwave radiation

a = albedo.

Similarly, the energy budget at the earth's surface can be given by

$$R_n = Q_o + E_o + C_o \qquad (2)$$

where

Q_o = sensible heat flux to (or from) the atmosphere

E_o = latent heat flux to (or from) the atmosphere

C_o = storage of heat in the soil.

The same notation will be used throughout this discussion.

While generalizations to spatial distribution of these parameters based on observations at these three locations alone might seem somewhat premature, the extreme homogeneity of the surface in the area of interest suggests that such generalizations are justified.

PREVIOUS WORK

Attempts have been made in the past to evaluate the radiation balance and energy budget of the whole of the Arctic, in some cases as a segment of a larger scale study (e.g., Budyko _et al_., 1962), while in others as a study by itself (e.g., Fletcher, Keller, and Olenicoff, 1966). In most of these studies, however, the values presented have been arrived at by indirect means or by observations at a very few stations, not nearly an adequate sample.

Some attempts have also been made at evaluating some of the terms in the energy budget equation by using standard aerological data (e.g., Bryson and Kuhn, 1962).

Vowinckel and Orvig (1962), however, categorize all these avenues of approach to the radiation balance into two groups:

> "1. an empirical method of finding, from existing stations, the relation between radiation and another readily available element, e.g., cloudiness. With this relation the vast number of observations of the readily available element can be used, and accordingly radiation maps can be drawn.
>
> 2. a more physical method, where use is made of the knowledge of processes influencing the radiation from outside the atmosphere until it reaches the ground."

Of these two methods, Budyko's work is the best example of the first, and the second is exemplified by the works of Houghton (1954) and London (1957).

Budyko's 1955 atlas, based on statistical methods, gives values for insolation for the area of interest of 14 - 16 kilocalories per month, or 450 - 515 calories per day for July, and 10 - 12 kilocalories per month or 320 - 385 calories per day for August. For net radiation values for July, 6 - 8 kilocalories are given as a monthly value (195 - 260 calories for a daily value) and for August a monthly value of 2-4 kilocalories, which reduces to a daily value of 65 - 130 calories.

Values based on more physical considerations include those presented by London (1957) who gives a value for solar radiation absorbed at the ground between latitudes 60° N and 70° N in summer of 306 $\text{ly}\cdot\text{day}^{-1}$, and the study by Vowinckel and Orvig (1962). Their values for insolation in the study area are 450 - 460 $\text{ly}\cdot\text{day}^{-1}$ for July and 340 $\text{ly}\cdot\text{day}^{-1}$ for August. For absorbed solar radiation their values are 380 $\text{ly}\cdot\text{day}^{-1}$ for July and 300 - 320 $\text{ly}\cdot\text{day}^{-1}$ for August.

Mateer (1955) and Löf, Duffie, and Smith (1966) present compilations of observed insolation. Mateer gives a value for the area of interest in July of 720 $\text{ly}\cdot\text{day}^{-1}$ and in August of 540 $\text{ly}\cdot\text{day}^{-1}$. These values are based on observations, supplemented by calculated values based on water content of the atmosphere. More recently, Löf et al. have given observed values of solar radiation in the area of interest of 450 $\text{ly}\cdot\text{day}^{-1}$ for July and 350 $\text{ly}\cdot\text{day}^{-1}$ for August.

These values are summarized in Table 1.

Some more analytic studies of radiation balance and energy budget have been done at discreet points by various authors (e.g., Vowinckel, 1966). All these, however, have been done at locations other than in the area of interest.

TABLE 1

SUMMARY OF PREVIOUSLY REPORTED VALUES OF INSOLATION AND NET RADIATION IN THE STUDY AREA

(VALUES IN $LY \cdot DAY^{-1}$)

		Solar Radiation		Net Radiation
		Incident	Absorbed	
Budyko	July	450-515		195 - 260
	August	320-385		65 - 130
London	Summer		306	
Vowinckel and Orvig	July	450-460	380	
	August	340	300-320	
Mateer	July	720		
	August	540		
Löf *et al.*	July	450		
	August	350		

DESCRIPTION OF THE STUDY AREAS

Except for the very northwest corner, the entire region described in the introduction lies in the Western Churchill Province of the Shield Region of Canada, as described in Bostock's (1964) summary of the physiography of Canada. According to Bostock, "A marked feature of the province is the general sameness of its great areas of massive rocks, although in detail it is divisible into a mosaic of plateaux, uplands, hills, and plains . . . ." The entire region is one of many lakes and ponds with numerous bogs and marshy areas, indicating that it is poorly drained.

The Pelly Lake site is included in the Back Lowland but in the upland area toward the Thelon Plain. Craig (1964) states that "North of Pelly Lake and Upper Garry Lake a zone of pitted outwash many square miles in extent is found." It was atop this relatively flat outwash plain that the Pelly Lake site was located.

The Snowbunting Lake site is included in the area described (Rand, 1963) as being dominated by thick deposits of till and sand, heavily drumlinized, and with numerous well developed eskers and sand trains. The site was near the base of an esker, with a very wet, gravelly soil under the thin vegetative cover. In the nearby vicinity several low outcrops of bedrock were observable, however.

The Curtis Lake site is in an area where hills and rock ridges 250 to 300 ft. in height become significant (Rand, 1963). Between the hills are long valleys. It was in one of these valleys, overlain with depositional material that the site was located.

The entire region, including all three sites is thus one of thin glacial deposition on the Canadian shield. At all locations the soil found was largely sand with that at Snowbunting Lake being slightly more gravelly than the others. At the Curtis Lake site, while the surrounding terrain was somewhat more rugged, the instrument site was in one of the broad valleys, with the immediate area being quite similar to that at Pelly and Snowbunting Lakes.

At all three sites the vegetative cover was a lichen mat several centimeters thick. At the Snowbunting Lake site the community was one of <u>Cetraria</u> and <u>Cladonia</u> species, while at both the Pelly and Curtis Lake sites an <u>Alectoria</u> community with associated species and a few <u>Carex</u> species composed the cover on the relatively drier surfaces.

This lichen mat provided a very smooth surface at all three locations, nearly resembling a mown lawn. From a ground vantage point the surface at Snowbunting Lake was somewhat lighter in color than the other two sites, but from the air, the surfaces appeared quite similar.

PROCEDURES

METHODS

In an attempt to obtain representativeness of the area in consideration, three locations along latitude 66° N were visited during the summer and measurements were taken at each. The three sites are shown in Figure 1. The first visited was near the north end of Pelly Lake (66° 03' N, 101° 03' W), the second at Snowbunting Lake (66° 10' N, 94° 25' W), and the third at the northeast end of Curtis Lake (66° 50' N, 88° 55' W). At each of these sites a series of instruments was set up and maintained for several days, thereby obtaining a short but hopefully representative sample of the desired atmospheric processes. The instruments are described later in this section.

While simultaneous observations were not taken at the three sites, it was expected that the homogeneity of the surface and nearly identical latitude of the observation sites suggests that the results are comparable. Seasonal differences can be systematically accounted for.

To obtain the radiation balance, measurements were made of as many of the terms in the radiation balance equation (1) as possible. Direct measurement of both the upward and downward fluxes of solar radiation were made as well as both the upward and downward fluxes of total radiation, thus leaving only the upward and downward fluxes of long wave radiation, which are readily obtainable as remainder terms in the two equations

$$R_{tot}{\downarrow} - R_s{\downarrow} = R_l{\downarrow} \qquad (3)$$

$$R_{tot}{\uparrow} - R_s{\uparrow} = R_l{\uparrow}$$

In addition, net radiation, R_n, was measured directly.

Evaluation of the various terms in the energy budget (2) can be accomplished by one of two methods. The first, referred to as the aerodynamic approach, requires observations of wind and temperature structure which will yield independent estimates of transfer processes in the surface boundary layer. The other method, referred to as the heat balance approach, requires a measurement of values for only some of the terms, and deriving the others by "forcing" equation (2) to balance.

Ideally, independent measurement or calculation of all the terms is most desirable, with these measurements resulting in a balanced equation (2). In this study, however, since field considerations imposed time and equipment limitations, a combination of the two approaches was attempted. Measurements, by various means, of R_n were taken as described in the previous paragraph.

In an attempt to evaluate the "storage" term, C_o, measurements were made of the rate of permafrost melt. It was assumed that heat required for warming the soil was negligibly small compared to that required to melt the ice in the soil. Soil flux plates were used to determine phase relationships between R_n and C_o.

Determination of Q_o by the aerodynamic approach was attempted by measuring air temperature at three levels and wind speed at the top level. To calculate Q_o, the method used by Stearns (1967) was used to construct theoretical temperature and wind profiles, with the use of a digital computer, for given values of z_o, the surface roughness, τ_o, the surface stress, and Q_o. A graph of Q_o as a function of wind at a specific height and temperature gradient in a given layer was then plotted, and from this graph Q_o values were read for values of temperature gradient and wind speed observed.

Calculations of E_o were based on the assumption that convection of latent heat is proportional to convection of sensible heat, the constant of proportionality being the Bowen ratio, B. This term, defined as the ratio of sensible heat transfer (by convection and turbulence) to latent heat transfer, can be computed from

$$B = 6.1 \times 10^{-4} \times P \times \left(\frac{\Delta T}{\Delta e}\right)$$

where ΔT and Δe are the gradients of temperature and moisture, respectively, and P is atmospheric pressure.

INSTRUMENTS

The instruments used in this study were basically those in use by the micrometeorological section of the Department of Meteorology at the University of Wisconsin, with little modification, and are discussed by Stearns (1962, 1967).

Radiation

Measurement of incoming short wave radiation was made with an Eppley, 10-junction, 180° pyrheliometer, which measures total shortwave radiation of wave lengths less than 3.5μ incident on a horizontal surface. This instrument was calibrated by comparison with other Eppley pyrheliometers as well as a Linke-Feussner pyrheliometer and a Kipp and Zonen solarimeter. The most recent of these calibrations, a few months prior to this study, was used for purposes of this work.

Three instruments were used to measure net radiation, a Suomi (1954) Ventilated Net Radiometer, a Suomi-Kuhn (1958) shielded Economical Net Radiometer, and a modified shielded net radiometer (Stearns, 1967). This instrument consists of an Economical Net Radiometer in which the black absorbing surfaces and insulating layer have been replaced by a flux plate, from which heat transfer by conduction and convection is minimized by the two polyethelene sheets.

The Ventilated Net Radiometer was constructed according to the description by Suomi et al. (1954), by the mechanician shop, College of Engineering, University of Wisconsin. The instrument was calibrated in the field by alternately shading it and the Eppley to note the difference in the deflection on the record caused by extracting the direct solar beam from the incident radiation on each. This instrument, being the most accurate, should be considered to be the primary one.

The Suomi-Kuhn (1958) Economical Net Radiometer was equipped with thermistor beads as temperature sensors. The temperature readings were converted to upward, downward, and net fluxes of radiation (both solar and terrestial) by the method used by Wendland (1965). This instrument, being completely independent of the ventilated instrument, was used as a cross check on it. Since other authors, Wendland (1965), Orvig (1961), Davies (1963), have also used duplicates of this instrument, comparisons with their findings are possible and are discussed in a later section. Since the economical net radiometer requires no sophisticated recording apparatus, it is easily portable, and was therefore also used to measure net radiation over other surfaces at the Pelly Lake site.

A modified shielded net radiometer of the type described by Stearns (1967) was also used to measure the total flux of net radiation. This instrument was calibrated against the ventilated instrument in the field and thus is considered as a secondary source of data, its use as a primary source being unnecessary due to the continuous record provided by the ventilated instrument.

Albedo

Measurements of surface albedo were taken using a silicon solar cell which was calibrated against one of the University of Wisconsin Eppley pyrheliometers. The instrument was first held in an upward facing position, then downward, with the output current in each position being read on a small portable ammeter. By the use of parallel resistors, output current from the cell was maintained in the linear response region of the instrument.

Wind Speed and Direction

Wind speed was recorded by a Bendix Model 339.3 three-cup anemometer, which closed an electrical contact for each 1/60th of a mile of wind passage. Wind direction was detected by a vane driven potentiometer, constructed at the mechanician shop, College of Engineering, University of Wisconsin. Stearns (1967) found this instrument to be linear to ± 1.8 degrees, thus providing sufficient accuracy for the purpose of this study.

An Esterline-Angus 0-1 ma, clock driven strip chart recorder was used to record both wind speed and direction. Output from the windvane was adjusted by resistors such that full scale deflection on the chart corresponded to 360° rotation. Anemometer contacts were recorded by shorting out input current to the recorder.

Surface Temperature

The problem of measuring surface temperature proved to be one of the most perplexing, due to the nature of the vegetation cover of the surface. For this measurement, a platinum wire resistance thermometer was built. The sensing element, along with the thermopiles for measuring temperature gradients from the surface, was encased in a length of quarter inch aluminum tubing which was then packed with DuPont RTV. The difficulties arose when trying to establish the proper position for the instrument. The surface at all three locations was covered by a mesh-like lichen mat three to five cm. thick.

Placement of the instrument near the top of the lichen mat allowed considerable solar radiation to fall on it, thereby indicating an erroneously high temperature, while moving the instrument downward to lessen this effect resulted in measuring something other than a true "surface" temperature. It was decided that the best location of the sensor was sufficiently below the lichen mat as to make it invisible when looking down from above. This was usually approximately two cm.

Temperature Gradients

Temperature gradient between the surface and the air at a height of 20 cm. was measured with a two junction copper-constantan thermopile. At Pelly Lake the 20-320 cm. air temperature gradient, and at Snowbunting and Curtis Lakes the 20-220 cm. gradient were measured with an eight junction thermopile. All temperature sensors were shielded from incident solar radiation by putting them inside of two concentric tubes, each coated with aluminized mylar, which were aspirated at approximately 5 m/sec.

Moisture Content

Wet bulb depression was measured by a two junction thermopile between ends of an aluminum bulb, one end of which was covered with a wick leading to a water reservoir. This apparatus was then installed in the air temperature intake snout at 20 cm.

Conduction to Soil

Soil heat flux plates, constructed similarly to the radiometer flux plates were used to determine conduction of heat into or out of the soil. The sensors were placed just under the surface of the vegetation, but sufficiently low in the cover as to eliminate the effect of incident radiation discussed in the surface temperature paragraph. Since the calibration for these sensors depends on thermal contact with the medium and must be determined in the medium, no calibrations were available. Therefore these flux plates could be used only to determine phase relationships between conduction of heat into the soil and net radiation. A 24 hour integrated value of C_o was obtained by measuring permafrost melt.

Recorder and Power Supply

Data from the radiometers, surface thermometer, temperature gradient sensors, wet bulb depression sensor, and soil flux plates were recorded on a Brown "Electronik" 24 channel recorder. Power for this recorder, along with all other instruments requiring a 110 volt AC supply was provided by a 1500 watt gasoline powered generator.

RESULTS

Albedo

Similarities of the vegetative cover at the Pelly and Curtis Lake sites are shown in their albedos, shown in Table 2. In both cases, the instrument set up was over an Alectoria community. For 10 readings at the Pelly Lake site the average value was .149 $\pm \sigma = 0.041$. At the Curtis Lake site 14 readings gave a mean value of .142 $\pm \sigma = 0.006$.

In contrast, the site at Snowbunting Lake was set up over a Cetraria - Cladonia community which was wetter and much lighter in color. The 39 readings yielded a mean albedo of .240 $\pm \sigma = 0.016$.

Solar Radiation

Diurnal curves of incoming solar radiation (direct plus diffuse) are shown in Figures 2 - 4. The curve shown for the Pelly Lake site (Fig. 2) is for July 8, 1966, each point representing a 15 minute average. The curves for Snowbunting (Fig. 3) and Curtis Lakes (Fig. 4) are also 15 minute values, but these values are averages for all days on which measurements were taken at the indicated time. For most times, it is an average value obtained over two or three days. The values obtained for Snowbunting Lake were measured between July 27 and August 1, and those at Curtis Lake between August 10 and 14.

The curves for Pelly and Curtis Lakes are obviously the truncated cosine curves which one should expect (a perfect cosine curve being expected at latitude 66° 30' N. on June 21), while the curve for

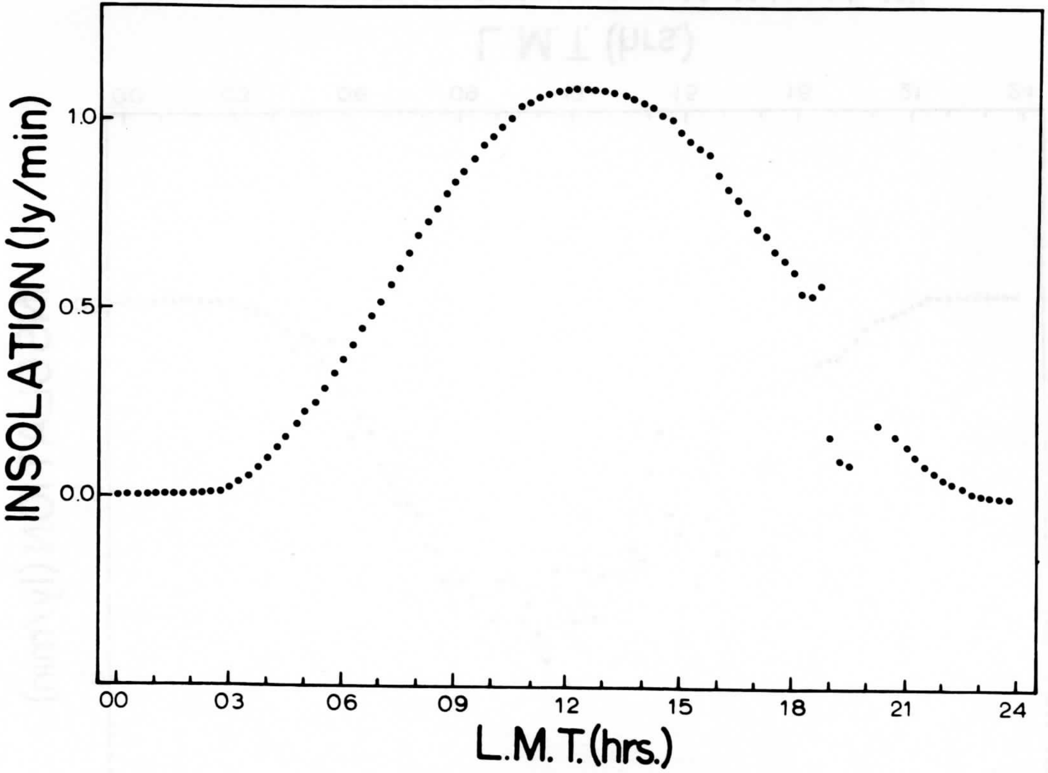

Figure 2. Rs↓ for Pelly Lake, July 8, 1966.

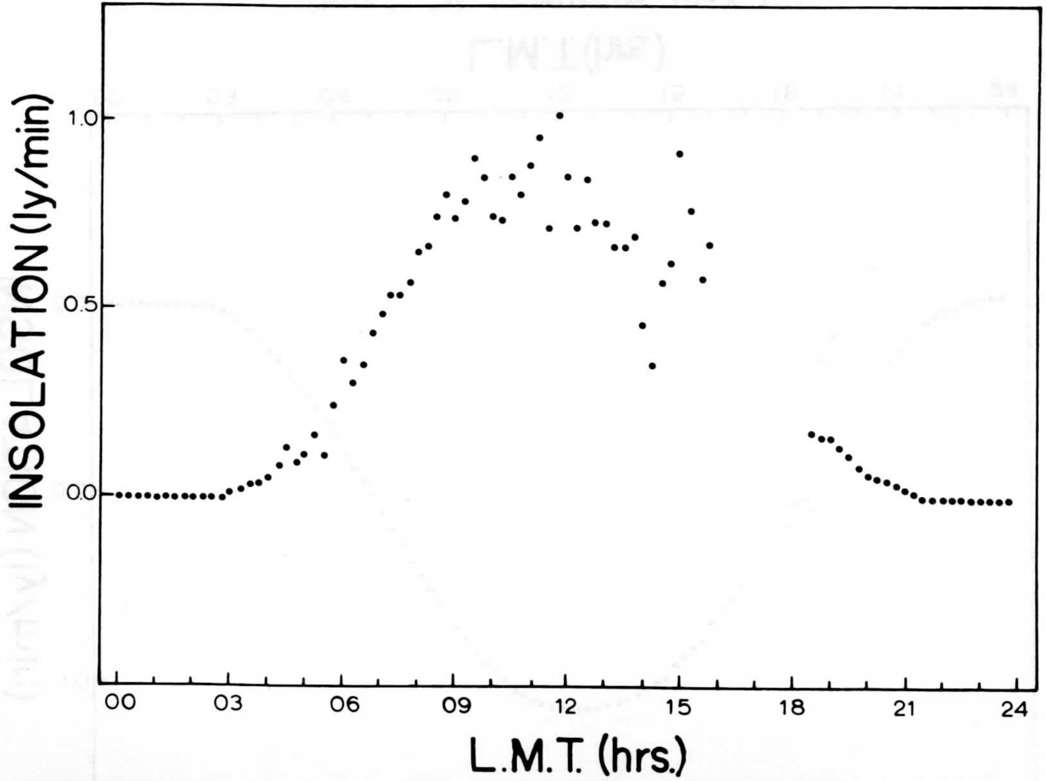

Figure 3. Rs↓ for Snowbunting Lake, July 30-August 1, 1966.

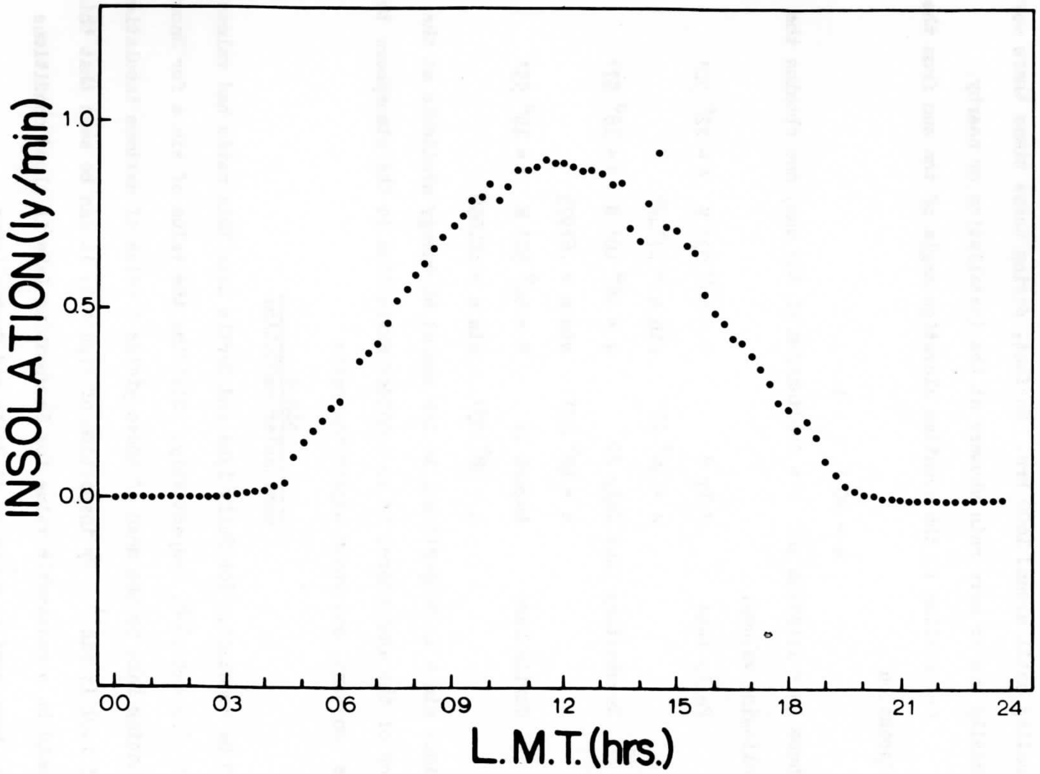

Figure 4. Rs↓ for Curtis Lake, August 10-14, 1966.

Snowbunting Lake shows a much greater degree of scattering. This is due to the fact that during the time spent at Snowbunting Lake, no day went by without considerable development of cumulus clouds by 1000 hrs., lasting until around 1600 hrs. In fact, during these times there were usually one or more rain showers at the installation or nearby.

Calculating a, the noontime elevation angle of the sun from the expression

$$a = 90 + \delta - \Phi$$

where Φ = latitude and δ = declination of the sun, one obtains the following values:

Pelly Lake	July 8	$\Phi = 66^\circ\ 03'$ N	$\delta = 22^\circ\ 30'$
	$a = 46^\circ\ 27'$	$\sin a = .72477$	
Snowbunting Lake	July 29	$\Phi = 66^\circ\ 10'$ N	$\delta = 18^\circ\ 57'$
	$a = 42^\circ\ 47'$	$\sin a = .67923$	
Curtis Lake	August 12	$\Phi = 66^\circ\ 50'$ N	$\delta = 14^\circ\ 55'$
	$a = 38^\circ\ 05'$	$\sin a = .61680$	

Since sin a is proportional to the amount of energy available at the top of the atmosphere, if we consider extinction in the atmosphere to be constant, one would expect the ratio

$$\frac{\sin a}{\text{max. solar radiation}}$$

to be constant. For Pelly Lake and Curtis Lake this ratio had values of .669 and .678, respectively. Dividing the value of sin a for Snowbunting Lake by the mean of these yields a value of maximum insolation of 1.01 ly min^{-1}. By inspection of Figure 3, it can be seen that this would be a reasonable value for Snowbunting Lake if cloud conditions had been similar to those at Pelly and Curtis Lakes.

By interpolating values on the 3 curves to obtain values for those times when the data are missing and summing over 15 minute intervals, one obtains an integrated value for total solar radiation received for a 24 hour period. The amount of solar radiation absorbed at the surface is given by the product of the incident radiation and (1 - albedo). A summary of these values is given in Table 2.

Net Radiation

Diurnal curves of net radiation, as measured by the Suomi Economical Net Radiometer, are shown in Figures 5 - 7. Like the solar radiation data, the curves for Pelly and Curtis Lakes are nearly approximated by truncated sine curves, and the data for Snowbunting Lake again show the effect of the increased cloud cover at that location. Integrating the three curves as before yields values in $ly \cdot day^{-1}$ of 377 for Pelly Lake, 322 for Snowbunting Lake, and 256 for Curtis Lake. These values are also given in Table 2.

The net radiation at Snowbunting Lake is not decreased by the increased cloud cover as much as is the incident solar radiation because the clouds themselves are absorbing both solar and terrestrial radiation and re-emitting long wave radiation, increasing the value of $R_1\downarrow$ in equation (1).

Storage of Heat in the Soil

To evaluate C_o, the conduction of heat into or out of the subsoil, it was assumed, prior to going into the field, that the storage of heat in the soil above the permafrost would be negligible compared to the heat necessary to melt the permafrost. For this reason no detailed study of the soil temperatures was planned or carried out

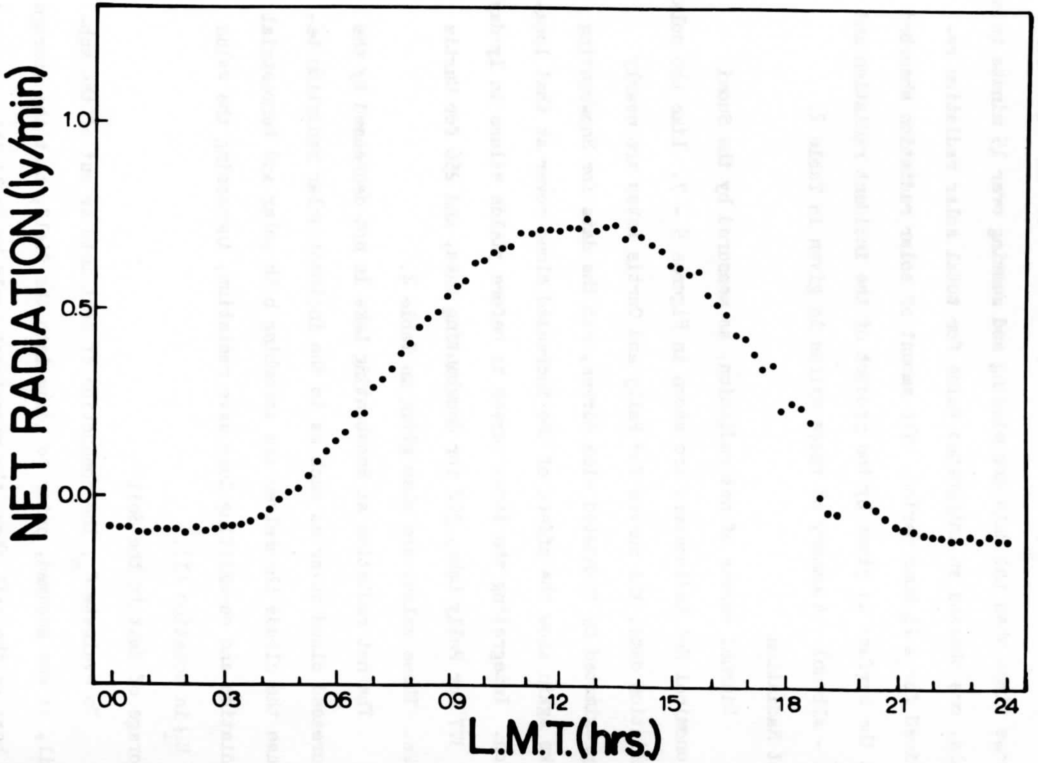

Figure 5. Net Radiation (Rn) for Pelly Lake, July 8, 1966.

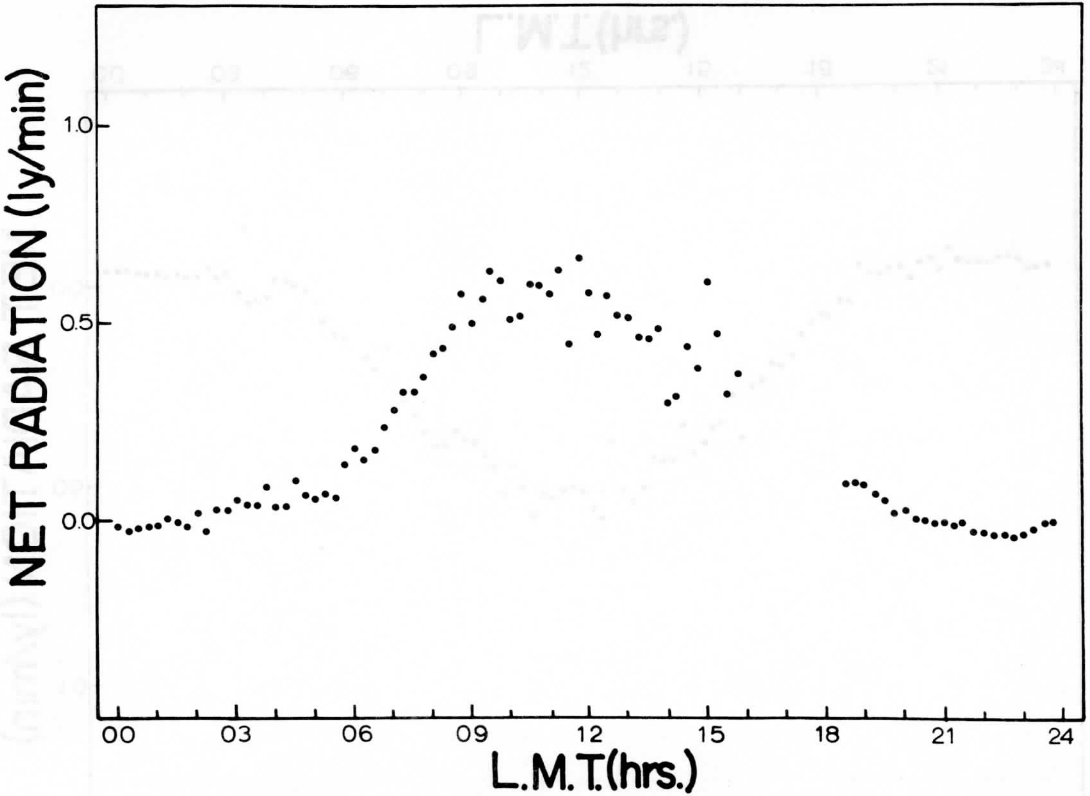

Figure 6. Net Radiation (Rn) for Snowbunting Lake, July 27-August 1, 1966.

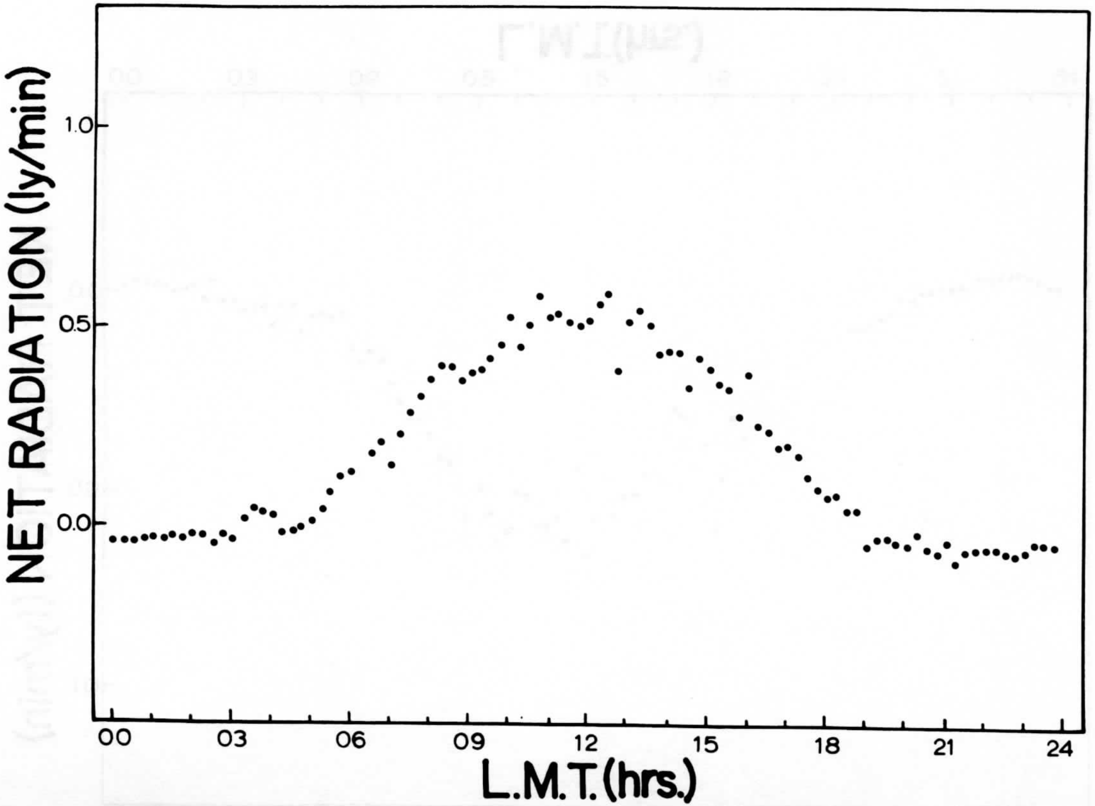

Figure 7. Net Radiation (Rn) for Curtis Lake, August 10-14, 1966.

in the field. However, on the basis of laboratory determination of water content of permafrost samples, found to be 30 ± 5 percent by volume, and the depth of the permafrost below the ground (35 - 85 cm.) it was deicded that heat storage in the soil above the permafrost was not negligible and should therefore be taken into consideration.

On the basis of two available temperature profiles, obtained by digging a pit down to the permafrost and horizontally inserting liquid in glass thermometers into the walls, evaluation of the storage of heat in the soil was attempted.

In Figure 8a soil temperatures from the Pelly Lake site on July 5 are plotted against the logarithm of depth. The dashed line shown represents the logarithmic equation $T = 6.74 \cdot e^{-.031049z}$, obtained by least squares regression techniques. To eliminate the relatively large diurnal changes of the surface temperature, that value was neglected in computing the above equation. The other temperature profile, shown in Figure 8b was obtained on August 17 at Curtis Lake and will be discussed later.

Since the top of the permafrost is melting ice, the temperature at this depth should be 0° C, a condition not met by the regression equation for temperature as a function of the logarithm of depth. However, this equation is only a statistical representation of the data, and not based on physical principles. In addition, the accuracy of the temperature values is probably no better than $\pm 1^\circ$C, since the thermometers were not pre-calibrated, readings could have been affected by parallax, and also, conduction of heat through the thermometers themselves would tend to make the readings erroneously high.

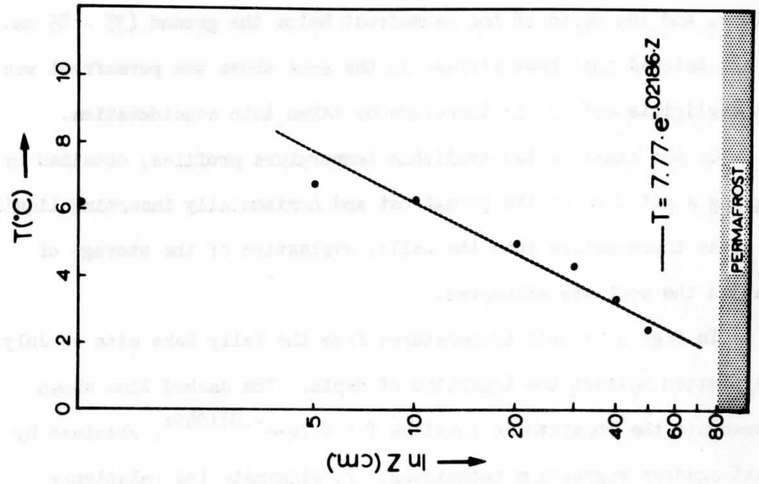

Figure 8b. Temperature vs. ln Z for Curtis Lake, August 17, 1966.

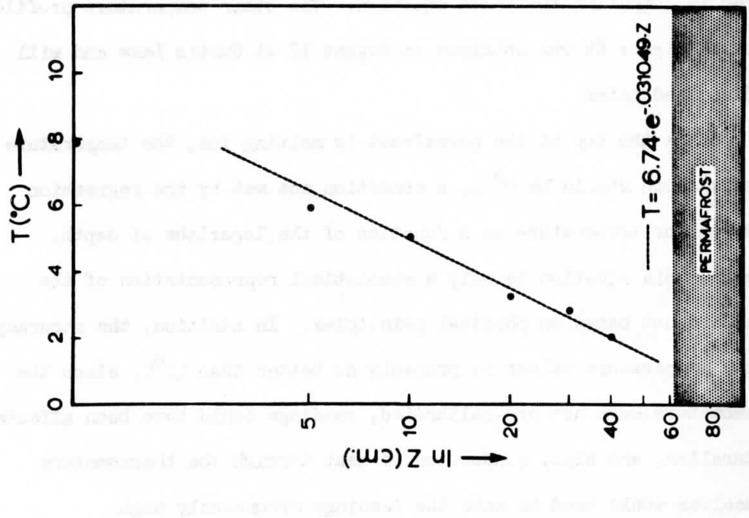

Figure 8a. Temperature vs. ln Z for Pelly Lake, July 5, 1966.

Furthermore, the soil temperature data and derived regression curves are used to estimate the changes in heat storage. In view of this last consideration, the discrepancy at the permafrost boundary does not seriously detract from the usefulness of the data.

By applying least squares regression techniques to the 1800L surface temperatures, it can be seen that surface temperature was increasing at a rate of 0.5°C per day. Evaluating the integral

$$.5 \int_{0}^{60} e^{-.031049 \cdot Z} dZ$$

gives a value of 13.5 $^{o}C \cdot cm \cdot day^{-1}$, or, for a column 1 cm^2 in area, 13.5 $^{o}C \cdot cm^{3} \cdot day^{-1}$.

The heat storage represented by this temperature change is given by the product of the temperature change and the volumetric heat capacity of the soil, 0.6 an approximate value for wet sand (H. Lettau, pers. comm.). The resulting storage term is 6.9 $ly \cdot day^{-1}$.

By means of a steel rod probe measurements of permafrost depth were taken under various surface types at the three locations. Figure 9 shows permafrost depth as a function of time for the Alectoria community at Pelly Lake. Values shown are averages for 8 points distributed non-systematically over an area of several hundred square meters around the instrument site. On the basis of the least squares regression equation giving depth to permafrost as a function of time $Z = 34.94 + 1.98t$ (t in days), it can be seen that the permafrost was melting at a rate of approximately 2 cm. per day. Coefficients for the regression coefficients for all surface types at all three

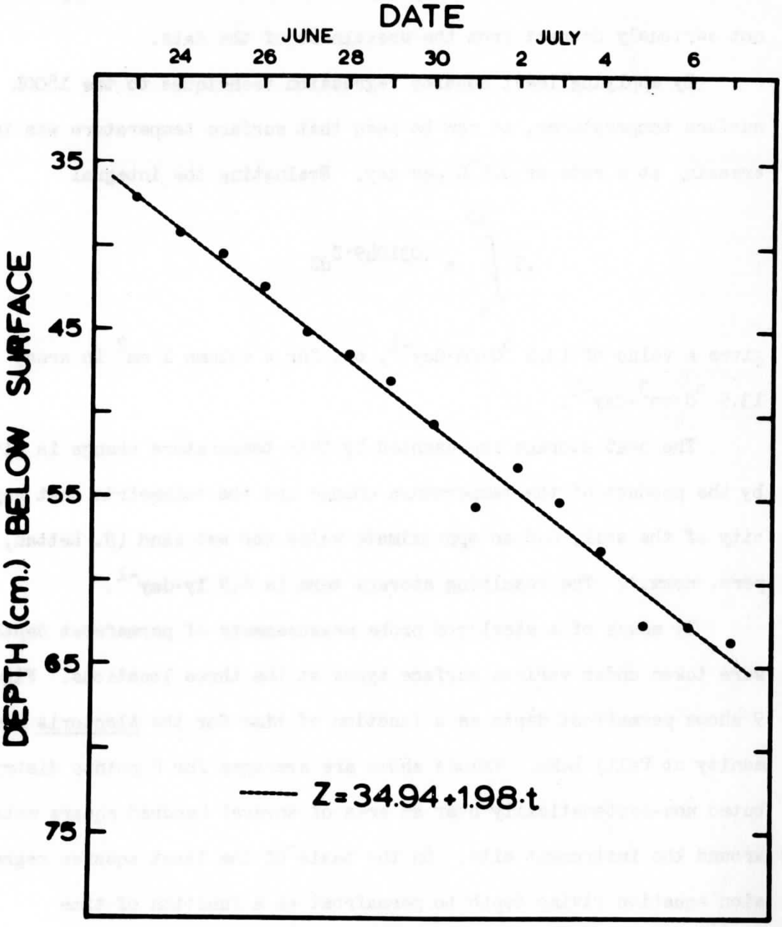

Figure 9. Permafrost depth vs. time (in days) for Pelly Lake, June 23-July 7, 1966.

locations are given in Table 3. With a value of 30 percent by volume for water content of the permafrost, to achieve a rate of melting of 2 $cm \cdot day^{-1}$ would require 48 $ly \cdot day^{-1}$.

TABLE 2

VALUES OF ALBEDO, INCIDENT AND ABSORBED SOLAR RADIATION, AND NET RADIATION

Location	Incident Solar Radiation ($ly \cdot day^{-1}$) (measured)	Albedo (percent) (measured)	Absorbed Solar Radiation ($ly \cdot day^{-1}$) (calculated)	Net Radiation ($ly \cdot day^{-1}$) (measured)
Pelly Lake	729.5	14.9	620.8	376.7
Snowbunting Lake	501.7	24.0	430.4	322.5
Curtis Lake	498.4	14.2	378.8	256.3

For Pelly Lake we have thus obtained, for the heat used in melting the permafrost, 48 $ly \cdot day^{-1}$, and for the heat being stored in the soil above the permafrost, 7 $ly \cdot day^{-1}$. These two values added together yield a value for C_o of 55 $ly \cdot day^{-1}$, 12 percent of which is being stored in the soil and 88 percent being used to melt the permafrost.

On the basis of this value, a calibration for the soil flux plates was derived from the data shown in Figure 10, by assuming that the integrated value for 24 hours was equal to 55 calories. This flux plate calibration was then applied to the Snowbunting and Curtis Lake data, shown in Figures 11 and 12, giving values for C_o of 74 and 72 $ly \cdot day^{-1}$ for those two locations, respectively. It must be

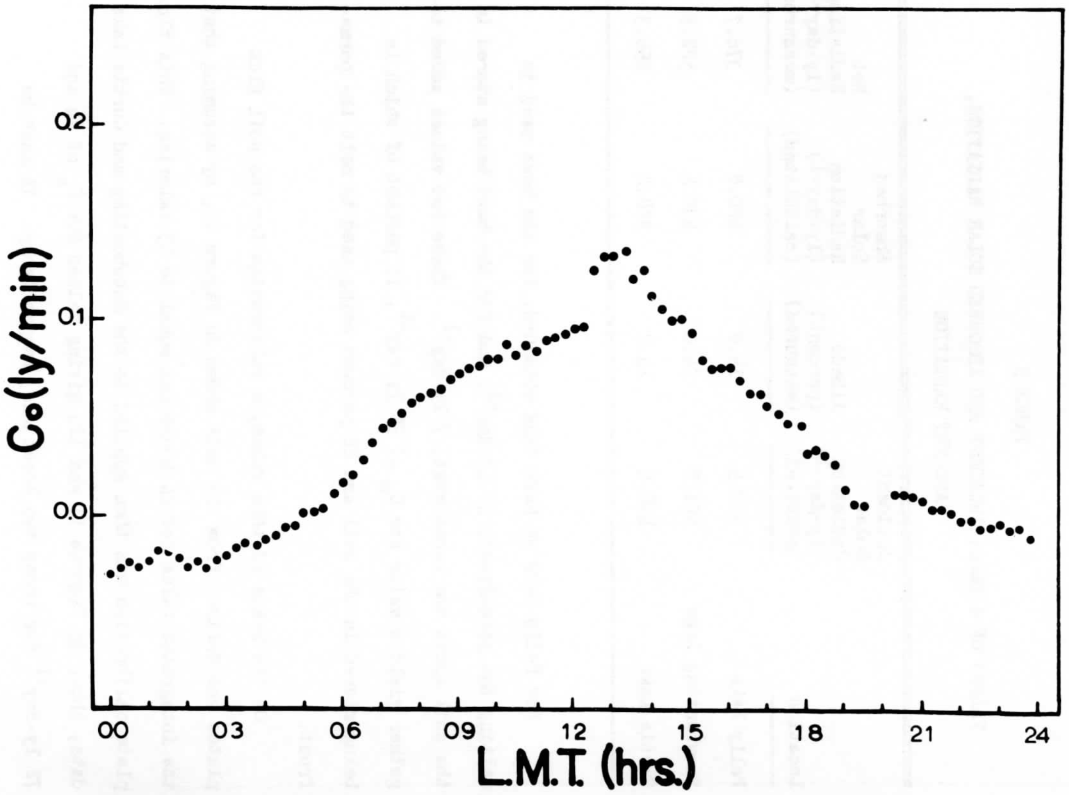

Figure 10. Conduction of heat to the subsoil (Co) for Pelly Lake, July 8, 1966.

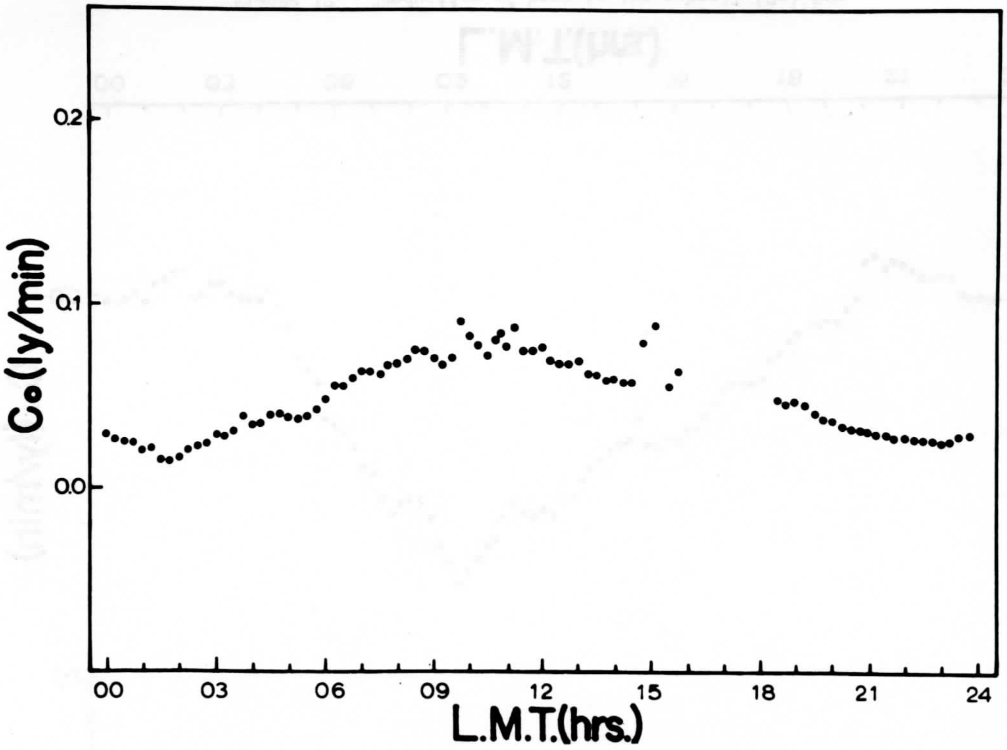

Figure 11. Conduction of heat to the subsoil (Co) for Snowbunting Lake, July 27-August 1, 1966.

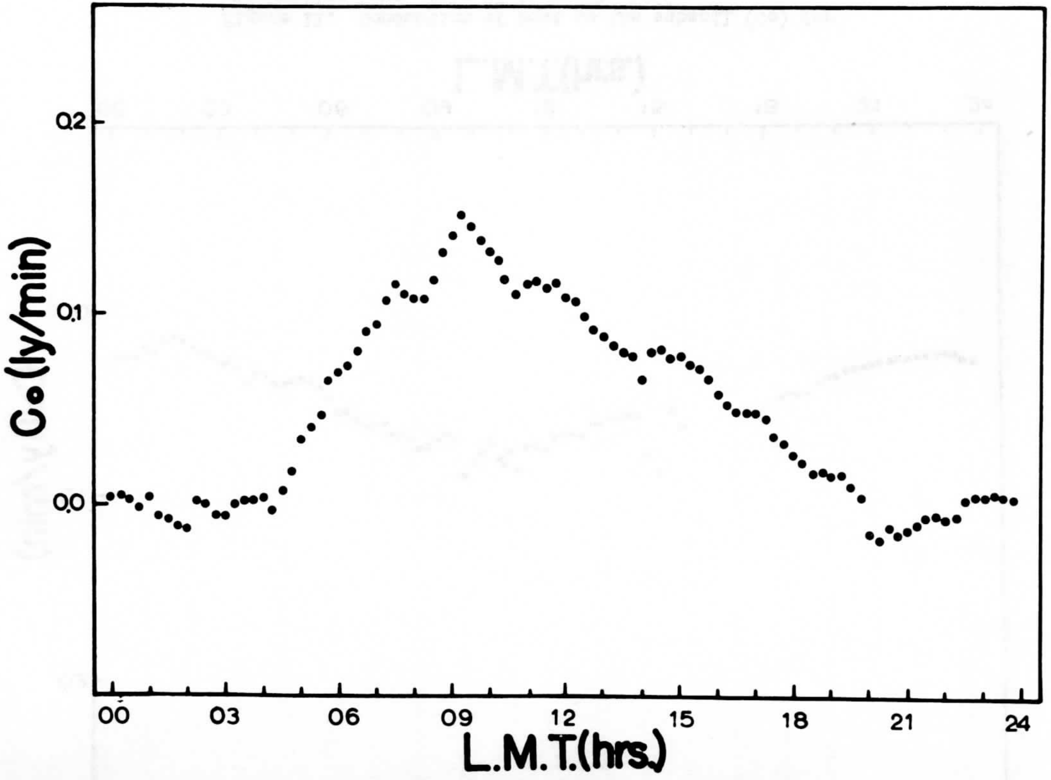

Figure 12. Conduction of heat to the subsoil (Co) for Curtis Lake, August 10-14, 1966.

remembered that the calibration for Pelly Lake is not necessarily valid for the other locations since thermal contact between the sensor and the medium, on which the calibration is strongly dependent, was probably not identical at all three locations due to the variable nature of the surface cover.

No temperature profile was measured at Snowbunting Lake, nor were any permafrost samples obtained because any hole dug in an attempt to do so immediately filled up with water. On the basis of the presence of so much more water in the soil, it seems likely that due to the increased specific heat of the soil and heat required for melting the ice, that the value of C_o for Snowbunting Lake is significantly larger than that at Pelly Lake, perhaps as large as 100 $ly\cdot day^{-1}$ or more.

From energy balance considerations it can be seen (in Table 4) that the sum of C_o and E_o for Curtis Lake must be nearly zero. Since a non-negative value for E_o is very unlikely, C_o must be either near zero or negative for a balanced equation (2), and the value of 72 $ly\cdot day^{-1}$ is probably in error.

In Figure 8b temperature values are plotted against the logarithm of depth for the Curtis Lake site on August 17. While heat flow based on the regression equation $T = 7.77\cdot e^{-.02186\cdot Z}$ would indicate a positive value for C_o, the departures of the points from the line suggest that the upper layer of the soil is nearly isothermal and that the permafrost melt observed is due to the lag of the temperature wave as it propagates downward, as described by B. Lettau (1965) rather than the steady state, an assumption implicit in the linear

TABLE 3

REGRESSION COEFFICIENTS FOR THE EQUATION $Z = A_o + A_1 X$, GIVING DEPTH TO PERMAFROST AS A FUNCTION OF TIME, FOR DIFFERENT SURFACE TYPES AT VARIOUS LOCATIONS

Location	Date	Surface Type	A_o	A_1
Pelly Lake	(June 23 - July 8)	Small Pond (100 m. diam., 20 cm. deep)	53.42	2.30
"		Tussock Muskeg & Low *Carex* Meadow	17.40	.93
"		*Alectoria* Community	34.94	1.98*
Snowbunting Lake	(July 25- August 5)	*Cetraria*-*Cladonia* Community	50.15	1.21*
Curtis Lake	(August 9 - 18)	Alectoria Community	67.61	.94*
"		Low *Carex* Meadow	43.00	.95
"		*Cetraria*-*Cladonia* Community	37.49	.92

*Site of energy budget measurements.

method for evaluation of the storage term for the Pelly Lake site, and that, in fact, the value of C_o for the Curtis Lake site in mid-August is very nearly zero.

Transfer of Sensible and Latent Heat to the Atmosphere

Diurnal curves of convective and turbulent transfer of sensible heat to the atmosphere, Q_o, as calculated by the method of Stearns (1967) are shown in Figures 13 - 15. Data shown are for the same periods as the radiation data and are 15 minute values except for Snowbunting Lake where hourly values are given. The three curves integrate to values (in ly·day^{-1}) of 316.3 for Pelly Lake, 127.8 for Snowbunting

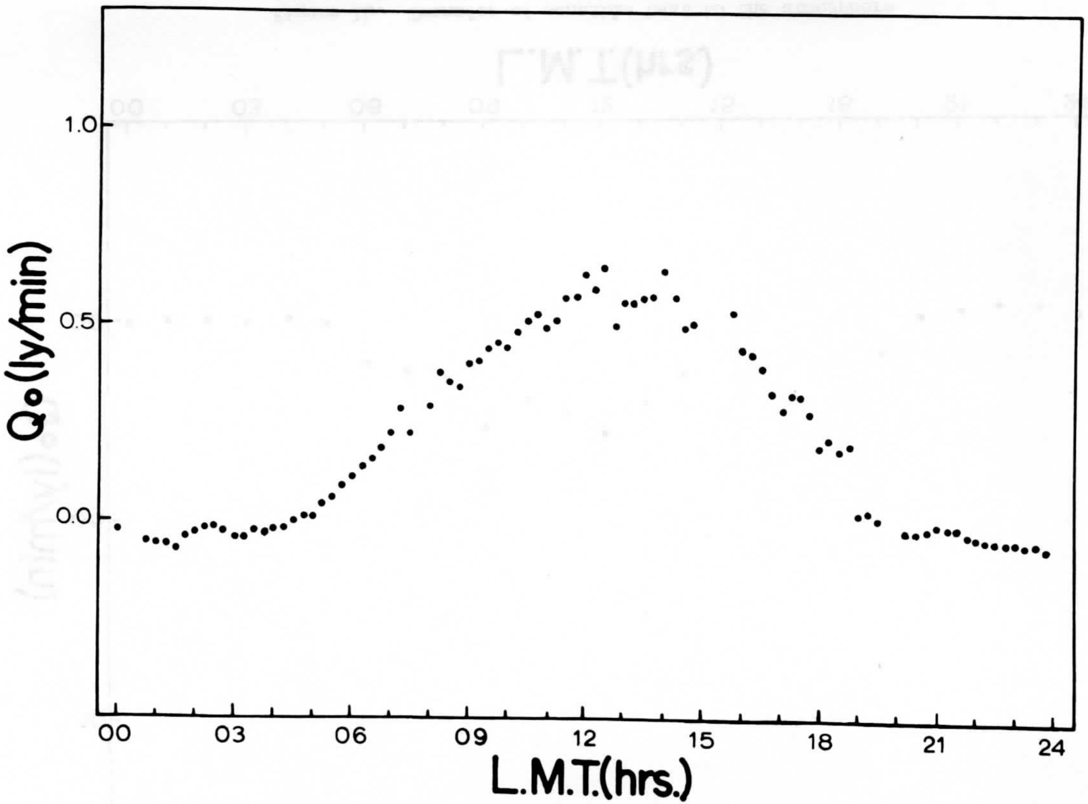

Figure 13. Transfer of sensible heat to the atmosphere (Qo) for Pelly Lake, July 8, 1966.

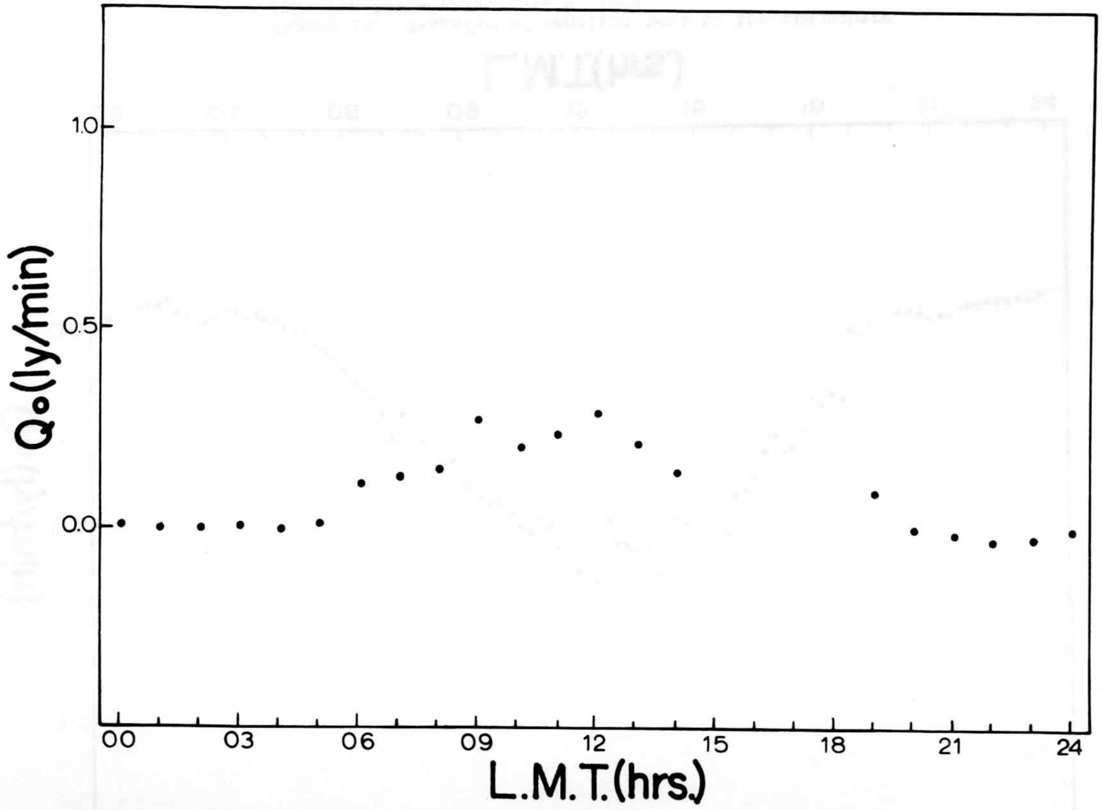

Figure 14. Transfer of sensible heat to the atmosphere (Q_o) for Snowbunting Lake, July 27-August 1, 1966.

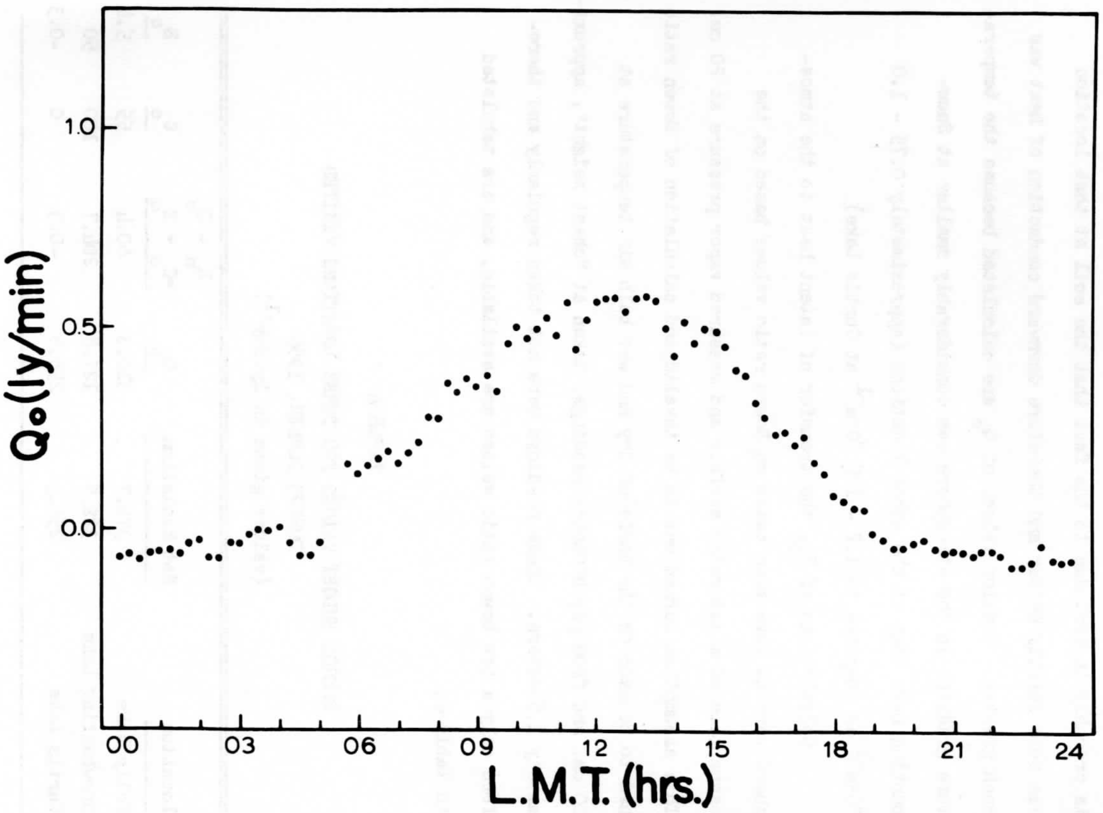

Figure 15. Transfer of sensible heat to the atmosphere (Qo) for Curtis Lake, August 10-14, 1966.

Lake, and 256.6 for Curtis Lake. The low value for Snowbunting Lake is probably in part due to the fact that the soil at that location was considerably wetter and therefore downward conduction of heat was much greater. Smaller values of Q_o are calculated because the temperature gradient in the atmosphere was considerably smaller at Snowbunting Lake than at the other locations (approximately 0.75 - 1.0 $^{\circ}C \cdot m^{-1}$ as compared to 1.2 - 1.5 $^{\circ}C \cdot m^{-1}$ at Curtis Lake).

Calculations of E_o, the transfer of latent heat to the atmosphere were to have been based on Bowen ratio values based on the assumption of a saturated surface and measured vapor pressure at 20 cm. This assumption turned out to be invalid and calculation of Bowen ratio had to be made on the basis of dry and wet bulb air temperature at 20 cm. and from psychrometer readings, taken at "chest height", approximately 1.5 meters. These readings were not taken regularly and therefore only a few Bowen ratio values are available, and are tabulated in Table 5.

TABLE 4

ENERGY BUDGET VALUES FOR THREE LOCATIONS VISITED
DURING SUMMER, 1966
(values given in $ly \cdot day^{-1}$)

Location	Net Radiation	Q_o	$R_n - Q_o = C_o + E_o$	C_o	E_o
Pelly Lake	376.7	316.3	60.4	55	5.4
Snowbunting Lake	322.5	127.8	204.7	100	50
Curtis Lake	256.3	256.6	-0.3	0	-0.3

These values verify the energy balance calculation, namely, that latent heat transfer is very small when compared to sensible heat transfer. Calculating E_o for the three sites as the residual in the energy budget equation (2), or from

$$E_o = R_n - C_o - Q_o$$

gives values of 5.4 ly·day^{-1} for Pelly Lake, 104.7 ly·day^{-1} for Snowbunting Lake, and -.3 ly·day^{-1} for Curtis Lake.

For Pelly Lake and Curtis Lake these values are somewhat smaller than the Bowen ratios would indicate, suggesting that perhaps the Q_o values are slightly too high. For Snowbunting Lake the value is considerably larger than the Bowen ratios would indicate, suggesting that values of Q_o are underestimates. That the latent heat terms in the energy budget for Snowbunting Lake is significant is substantiated by the greater availability of water for evaporation at the Snowbunting Lake site.

TABLE 5

BOWEN RATIOS FOR THE THREE STUDY SITES, EVALUATED ON THE BASIS OF 20 cm. TEMPERATURE AND MOISTURE CONTENT AND PSYCHROMETER TEMPERATURE AND MOISTURE CONTENT

Time	Pelly Lake	Snowbunting Lake				Curtis Lake	
0000	7.7	-.7				12.7	13.5
0100		55.2				15.6	
0200		.7	-1.8	5.3		11.3	
0300	7.8	4.1	13.0			8.7	
0400		2.4	4.6			13.6	
0500		7.2					
0600	4.3	9.1	6.7			7.7	
0700		11.0	7.7			6.4	
0800		-1.4	-0.3				
0900	1.5	7.0	4.7	9.8			
1000		10.8	-5.8	3.4	6.9		
1100		10.3	7.6	12.4	5.7		
1200	-14.6	16.9	8.6	6.5		-3.1	
1300		6.1	6.6	7.2		-3.8	
1400		-2.0	6.0	5.5		-13.8	7.9
1500		4.5				-2.0	7.6
1600						15.1	7.2
1700						3.1	8.0
1800	15.0					2.7	195.0
1900		-1.7					
2000		4.3				17.4	
2100	7.9	6.8				14.6	
2200		.2				16.3	9.4
2300		-3.4				12.1	13.5

DISCUSSION AND CONCLUSIONS

In this study, sampled summertime values for the various terms in the radiation balance and energy budget of a surface have been presented for the Canadian tundra. Values of net radiation given are 60 to 90 percent higher than those given by Budyko (1955) for the area of interest. While some of this difference may be attributed to the fact that most of the observations here presented were taken during fair weather, the values do suggest that Budyko's values are underestimates, probably by a significant amount. The values are also larger than those given by Wendland (1965), for Ennadai and Yellowknife.

The values of incident solar radiation agree best with those given by Mateer (1955) suggesting that some degree of representativeness was lost in considering primarily fair weather situations. However the Snowbunting Lake data show that the effect of cloudiness on the net radiation is relatively small.

Variation in the values given can be seen to be primarily seasonal. Presumably, latitudinal differences would also be significant, however both of these effects can be systematically accounted for, and the assumption of the homogeneity of the area is seemingly valid. Therefore a thorough understanding of the complete radiation balance and energy budget of one station in the area of interest would be meaningful in any model which necessitates data of this type as input.

The summertime climate of the region is shown to be one in which absorbed solar radiation is nearly balanced by effective longwave radiation is nearly balanced by effective longwave radiation plus the exchange of sensible heat with the atmosphere, or, net radiation is nearly balanced by sensible heat transfer. During July the conduction of heat into the soil accounts for approximately 15 percent of the energy budget, but by August this term becomes negligible. During the entire season the transfer of latent heat over the surfaces studied is seen to be very small.

In comparison, the June energy budget at Point Barrow, Alaska, is one in which the net radiation, approximately 350 $ly \cdot day^{-1}$ is balanced by transfer of latent (approximately 28 percent) and sensible (approximately 67 percent) heat, to the atmosphere, with the storage term accounting for, at most, 5 percent (Bryson, pers. comm.). In contrast, the July energy budget at Resolute Bay (Vowinckel, 1966) is one in which the net radiation, 181 $ly \cdot day^{-1}$, is nearly balanced by the storage term, with the transfer of sensible and latent heat accounting for only 10 percent of the energy budget. By August, however, the sign of the storage term reverses and heat exchange with the atmosphere is balanced by net radiation (96 $ly \cdot day^{-1}$) and heat from the soil (4 $ly \cdot day^{-1}$).

Although the very small values for transfer of latent heat to the atmosphere in the study area, one of much open water, would seem to be paradoxical, hydrological balance considerations indicate that E_o should be very small in value. The Canadian Department of Transport (1962) shows annual precipitation in the area of interest to be less than 20 cm. per year. Assuming no runoff, this would mean 20 cm. evaporation per annum. If this were all to take place during the three summer months this would imply slightly over one mm. evaporation per day, or 60 $\text{ly}\cdot\text{day}^{-1}$, or less than 20 percent of R_{net}. This, however, is an average value for all surfaces. In actuality most of the evaporation is probably taking place over the lakes and other standing water, and evaporation over the relatively drier land surfaces is most likely much less.

Values given in this study are meaningful because they are based on consistent measurements over natural surfaces in the area of interest, and result in a balanced energy budget for two of the three locations. Although values for E_o are derived from energy balance considerations, they are substantiated by Bowen ratio values.

While the analysis presented is representative of the land surfaces in the area of interest, caution should be exercised in using these results in large scale studies of the climate of the region since a large portion of the area is covered by an entirely different surface type, open water. A study of the interaction between the atmosphere and these surfaces would be a useful supplement to this discussion.

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APPENDIX I

On June 29 an Economical Net Radiometer was set up over a small frozen lake near the Pelly Lake site and maintained for 32 hours. Measured net radiation values are given below. During the period of observation, the ice was very "candled" and the shore lead was widening at approximately 2 feet per hour. Three days after the instrument was removed, all ice was gone from the lake. During the afternoon of June 29 there was 3 to 4 tenths strato-cumulus sky cover, and the sky on June 30 was cloudless.

NET RADIATION VALUES ($ly \cdot min^{-1}$) OVER FROZEN LAKE NEAR PELLY LAKE, JUNE 29-30, 1966

Date	Time	R_{net}	Date	Time	R_{net}
June 29	1330	1.031	June 30	0530	-.004
	1430	1.419		0630	.156
	1530	.767		0730	.283
	1630	.616		0830	.641
	1730	.499		0930	.853
	1830	.087		1030	1.023
	1930	.035		1130	1.052
	2030	.020		1230	1.268
	2130	-.024		1330	1.247
	2230	-.012		1430	1.022
	2330	-.061		1530	.979
June 30	0030	-.057		1630	.795
	0130	-.059		1730	.612
	0230	-.047		1830	.450
	0330	-.043		1930	.151
	0430	-.038		2030	.022

APPENDIX II

The Economical Net Radiometer was also set up over a small pond (diameter 100 m, depth 20 cm) about 100 meters from the site of the energy budget measurements at the Pelly Lake site. In addition, three liquid-in-glass thermometers were hung in the pond to measure water temperature. The bulbs of these thermometers were wrapped with rubber tape to slow the instrumental response time. The bulbs were also shielded from incident solar radiation by wrapping them with aluminum foil. The mean value of these three temperatures, along with net radiation values, follow.

NET RADIATION ($ly \cdot min^{-1}$) OVER AND WATER TEMPERATURE (^{o}C)
IN A SMALL POND NEAR PELLY LAKE, JULY 7-9, 1966

Date	Time	R_{net}	Temp	Date	Time	R_{net}	Temp
July 7	2130	-.172	15.0	July 8	1330	.972	17.0
	2230	-.194	14.0		1430	.920	18.2
	2330	-.163	13.3		1530	.803	18.3
July 8	0030	-.172	12.3		1630	.463	18.5
	0130	-.152	11.7		1730	.392	18.3
	0230	-.153	11.0		1830	.237	18.0
	0330	-.144	10.3		1930	-.107	17.0
	0430	-.083	10.0		2030	-.091	16.1
	0530	-.021	9.9		2130	-.156	15.3
	0630	.144	10.0		2230	-.181	14.1
	0730	.416	10.6		2330	-.184	13.2
	0830	.656	11.2	July 9	0030	-.189	12.3
	0930	.764	12.2		0130	-.176	11.7
	1030	.852	13.9		0230	-.151	11.1
	1130	1.039	14.9		0330	-.083	10.6
	1230	.951	16.1		0430	-.118	10.2

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13. ABSTRACT

As a step toward understanding the interrelationships between landform, vegetation, and climate of the Canadian tundra, summertime radiation balance and energy budget data obtained during July and August, 1966, at three locations in the district of Keewatin, N.W.T., are presented. Comparisons are made between these findings and estimates from other authors' global and hemispheric radiation balance studies and also with energy budget studies of other investigators at Resolute Bay, N.W.T., and at Point Barrow, Alaska. The climate is shown to be one in which latitudinal and seasonal differences account for most of the variation. While during July the storage of heat in the soil accounts for fifteen percent of the energy budget, during the rest of the snow-free season net radiation is nearly balanced by transfer of sensible heat to the atmosphere. (U)

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