Microclimate of low Arctic tundra and forest at Churchill, Manitoba

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Detailed energy balance measurements collected in 1978 and 1979 at Churchill, Manitoba for an open tundra site and a contiguous outlier forest site were examined along with one year's data for a snow-fenced site in the tundra. All sites were located on a raised beach system about 1 km inland from the Hudson Bay coast. Measurements made or derived were net radiation, ground heat storage, snow depths, rainfall, soil moisture, and soil temperature at all sites, and additionally, the latent and sensible heat fluxes at the open tundra site.

In the outlier forest site, the forest creates its own ameliorated soil climate, through the agency of wet soils and prolonged zero curtain effect. The snow-fenced site has a curtailed frost-free period at all depths due both to the late-lying snow cover in spring and the early-accumulating snow cover in fall.

Energy-balance measurements at the open tundra site showed that the ground heat flux during the thaw period for both years comprised 18 per cent of the net radiation and, as such, constituted an important term in the energy balance equation. This magnitude is a response to the high ice content of the soils and the larger latent heat of fusion needed to melt it. During the freeze-back period, Q^* becomes very small, either positive or negative, so that the large amounts of latent heat released in the soil and directed to the surface overwhelm Q^* in magnitude. There is a definite seasonal trend in the Bowen Ratio, ß, from large values at the start of the thaw period to small values in mid-summer, followed by an increase in late summer. Overall the evaporation is less and the sensible heating of the air greater than in a comparable study on open tundra at Barrow, Alaska.

Des mesures détaillées de bilan énergétiques effectuées en 1978 et 1979 à Churchill (Manitoba) dans un site de toundra et un îlot forestier contigu ont été comparées aux données obtenues tout au long d'une année dans un site de toundra entouré de barrières à neige. Tous les sites étudiés sont situés sur des plages soulevées à environ 1 km du littoral de la mer d'Hudson. Furent mesurés ou dérivés pour tous les sites la radiation nette, le stockage de chaleur, l'épaisseur de neige, les chutes de pluie, l'humidité et la température du sol; à cela il faut ajouter les flux de chaleur latente et sensible pour le site de toundra.

Dans l'îlot forestier, la forêt contribue, par la combinaison de sols humides et la stagnation du front de gel, à créer un micro-climat du sol particulier. La saison sans gel du site entouré de barrières à neige se trouve réduite à toutes les profondeurs par la persistance du couvert nival au printemps et son établissement précoce en automne.

Les bilans énergétiques établis pour le site de toundra montrent que pour les deux années le flux thermique du sol pendant le dégel représente 18 pour cent de la radiation nette Q^* et, comme tel, constitue un élément important de l'équation du bilan énergétique. Ceci est dû à la teneur en glace élevée des sols et à la grande quantité de chaleur latente nécessaire à sa fusion. Lors du regel, Q^* devient très faible, soit positif, soit négatif, de sorte que les grandes quantités de chaleur latente libérées dans le sol en direction de la surface dépassent Q^* en importance.

Le rapport de Bowen ß présente une tendance saisonnière très nette; élevé au début du dégel, il diminue au milieu de l'été pour augmenter de nouveau à la fin de l'été. Dans l'ensemble l'évaporation est moindre et le réchauffement de l'air plus important que dans le cas d'une étude comparable dans la toundra ouverte de Barrow (Alaska).

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Introduction

The narrow strip of land paralleling the southwestern and southern Hudson Bay coast is unique in displaying open tundra with true Arctic climate characteristics and continuous permafrost at such low latitudes. The occurrence of forest outliers, open scattered forest, and denser gallery forest lining the stream and lake banks a few kilometres inland, is characteristic of the main northern tree-line extending across the continent at higher latitudes.

The Arctic climatic conditions are largely due to proximity to Hudson Bay where the ice remains intact on the coast until late June and where floating ice is still present until late July. At Churchill, any winds blowing from a 180° sector from west through north to east have their course over the cold ocean waters. Only south and south-west winds are fully free of this influence and these occur only during 20 per cent of the summer period. The summer climatic period with snow-free ground, substantial net radiation, and above-freezing air temperature is largely confined to the months of June, July, and August. Summer is a period when frequent squalls generated over Hudson Bay occur on "fair-weather" days which are interspersed with extended periods of major cyclonic activity with continuous light rain.

Snow is normally measured at the airport during ten months of the year for a total of 184 cm. One-half falls in the early winter months of October, November, and December and little of this usually melts until the following May. Average snow depths on the open tundra rarely exceed 25 cm so that there is a great deal of wind scouring of snow to depositional areas in stream valleys, lakes, and other accumulation hollows and especially forested areas where depths of several metres are achieved. The delay of thawing in these forest accumulation areas, compared to the tundra, is in the order of three weeks and, since this occurs during the critical time of high sun and long day periods in late May and early June, it might be suspected that it would exert an influence on the ground thermal regime which is one of the topics considered in this paper.

The objectives of this study are first, to understand the thermal and hydrologic behaviour of the permafrost active layer within a complete energy-balance framework, before, during, and after the thaw season, in a low Arctic environment; secondly, to study the effects of the longevity of the spring snow cover on development of the active layer; and thirdly, to compare the microclimates of open tundra and forest environments at the tree-line by making simultaneous measurement on contiguous sites.

Methods

A detailed microclimatic measurement program at Churchill, Manitoba (lat. 58°45′N, long. 94°04′W) was begun in late winter 1978 and pursued until late summer. It was then recommenced in late winter 1979 and carried through until the following mid-winter. As such it spanned two complete thaw seasons and one freeze-back period.

Site

Measurements were made simultaneously at an upland tundra site (T) and a forest outlier site (W) to the east of Churchill Airport (Figure 1). After the summer of 1978 a snow-fenced enclosure was constructed so that measurements at a third site (S) with a longer-lasting spring snow cover could be added. All three are located contiguously on a former beach ridge. The top 5 cm of soil has an organic content of 5 per cent for sites T and S and 20 per cent for site W. Beneath 5 cm they are virtually pure sand with two

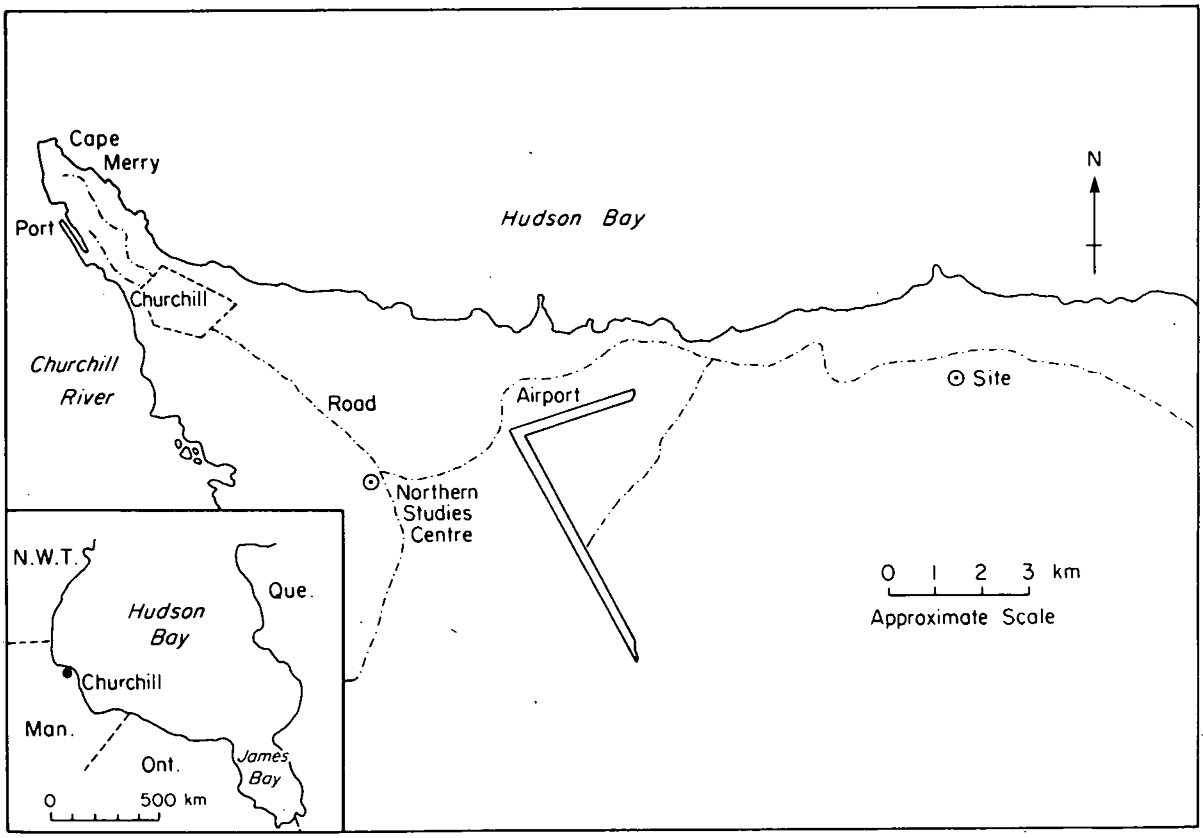

FIGURE 1. Location of the research site.

thin stony layers between depths of 5 and 200 cm. Thus the soil type is essentially the same and a common factor for all sites. The vegetation at sites T and S has a 70 per cent ground cover of short grasses with some representation of ground lichen and Labrador tea. The trees at site W are stunted black spruce averaging 6 m in height and 2 m between trunks. Averages are not too meaningful as horizontal and vertical heterogeneity is always the normal for wooded areas near the tree-line. The understory at site W comprised mosses, lichens, Labrador tea, and small shrubs such as bearberry and cranberry.

Theory

The energy balance is a balancing of the energy available from net radiation, Q^*, whether it be positive or negative, with the heat storage in the subsurface layer, Q_G, the sensible heat flux between surface and atmosphere, Q_H, and the latent heat flux involved in evapotranspiration, sublimation, and condensation, Q_E, where

$$[1] \qquad Q^* = Q_G + Q_H + Q_E$$

Each term on the right hand side is positive when the energy flow is away from the surface. When Q^* is negative one, two or sometimes all three of the terms on the RHS will be negative or directed toward the surface. The latter is a common winter situation.

Q_G, as a flux across the soil–air interface, in a homogeneous soil environment which is either frozen or thawed, can be expressed in terms of the thermal conductivity of the soil, k, and the vertical soil temperature gradient $\Delta T_s/\Delta z_s$ where

$$[2] \qquad Q_G = k \, \frac{\Delta T_s}{\Delta z_s}$$

in which T_s is soil temperature and z_s is depth in the soil. Equation 2 is positive when the soil temperature decreases with depth which is a situation persisting through the melt period because T_s at the melting front is always 0°C and T_s at the soil surface is usually >0°C. During the freeze-back period, T_s at the freezing front is still 0°C, but near the soil surface $T_s < 0$, so Q_G is persistently negative. The conductivity term, k, is greater in frozen than thawed soils since k for ice is about 4 times as great as for water. The wetter the soil, the higher its thermal conductivity upon freezing. Q_G can be treated as a heat storage over time, in terms of the soil heat capacity, C, the temperature change over time $\Delta T/\Delta t$ for a given depth increment Δz_s, and the latent heat of fusion, L_f, which accompanies the melting and freezing of soil water, giving

$$[3] \qquad Q_G = C \, \frac{\Delta T_s}{\Delta t} \, \Delta z_s + L_f$$

which is positive when the soil temperature increases over time and melting of the soil water occurs. Equation 3 has been used operationally at Churchill for the calculations of Q_G dividing C into its subcomponents

$$[4] \qquad C = C_s X_s + C_w X_w$$

where the subscripts s and w refer to soil solids and soil water or ice respectively, and X is the volume fraction of the component in the soil. The heat capacity of air is so small it is ignored.

The latent heat flux is derived from the energy balance by employing the Bowen Ratio, ß, in the form

$$[5] \qquad Q_E = \frac{Q^* - Q_G}{1 + \beta}$$

in which $\beta = Q_H/Q_E$. Equation 5 can be expressed in terms of vertical wet and dry bulb temperature gradients ΔT and ΔT_w where

$$[6] \qquad Q_E = (Q^* - Q_G)\left(1 - \frac{\gamma}{S+\gamma} \, \frac{\Delta T}{\Delta T_w}\right)$$

in which γ is the psychrometer constant and S is the slope of the saturation vapour pressure-temperature curve at the mean air temperature. In employing equation 6, the remaining term in the energy balance equation, Q_H, is calculated as a residual quantity.

Measurement

Net radiation was measured above each site using a C.S.I.R.O. type net pyrradiometer. These were mounted 1 m above the ground at sites T and S and 1 m above average canopy height from a tower at site W. All measurements were integrated half-hourly on a data system, stored on cassette tape, and analysed by a computer.

All ground heat storage terms presented in this paper were derived using equation 3. Soil heat capacity, C, was calculated using equation 4 and L_f from the soil moisture data, on the assumption that as soon as the soil temperature exceeded 1°C thawing of the ground water had occurred. In similar fashion, when soil temperature fell below -1°C, it was assumed the ground water had frozen.

The evaporative heat flux was derived from equation 6. Vertical temperature and humidity gradients were determined using two different systems. In 1978, aspirated, shielded thermopile transducers were used in the same manner as described by Rouse and Stewart (1972). These were placed at heights of 25, 50, 75, and 100 cm and three ΔT and ΔT_w gradients were established for intervals 25 to 50, 25 to 75, and 25 to 100 cm. These were then averaged. The sensors were regularly rearranged to see if systematic measurement error showed up but none was evident. In 1979, thermometer diodes of a type described by Munro (1980) were substituted for the thermopiles. The diodes have the advantage of eliminating a constant temperature reference bath which is a distinct advantage, and they performed well. The evaporative heat flux has been calculated only for the tundra surface and measurements were integrated for half-hourly periods and stored on tape as with net radiation.

It is difficult to assess the absolute accuracy of the energy balance results since there is no standard against which to compare. Q^* should be accurate to ± 5 per cent. A large component of Q_G is comprised of the latent heat of fusion L_f and when soil temperatures are at 0°C one does not know if this is frozen or thawed. Since the zero curtain effect extends over a long time period, as will be noted later, this is a persistent problem. As a result a realistic accuracy of Q_G would be ± 15 per cent for daily calculations. Over a longer time period the error level diminishes so that for 25 days it drops to around ± 5 per cent. As presented by Spittlehouse and Black (1980) the accuracy of calculating Q_E and Q_H from the Bowen Ratio varies dramatically, depending first on whether ß is positive or negative, secondly on the magnitude of ß, thirdly on the magnitude of ΔT and ΔT_w, and fourthly on the height interval between sensors. In this study, where Bowen Ratios are normally fairly large and ΔT and ΔT_w are big, the probable relative error in ß can be placed at ± 20 per cent for daily totals and ± 10 per cent for periods approaching a month. Using a root mean square calculation for the likely errors in each term gives a probable error in Q_E and Q_H of ± 25 per cent for daily totals and ± 12 per cent for periods in excess of 25 days.

Soil temperatures were measured at sites T and W in 1978 and in 1979 measurements at site S were added. They were made at depths of 5, 10, 20, 40, 80, and 160 cm using thermistor probes. Replicate measurements were made at each site at locations 2 m apart. In 1978, the measuring interval encompassed the period April 26 to September 12, inclusive, a period of 140 days. Readings were made manually at two-hour intervals using a digital potentiometer. As a result, the record usually spans only the daytime period between 0600 and 2000 hours although occasionally a 24-hour record was achieved. In 1979, the measurement interval extended from April 25 to December 5th, a period of 225 days. The thermistors with an accuracy of 0.1°C were monitored in a calibrated module of the digital integrator. The record was continuous during this period, with half-hourly integrated averages being recorded on tape until September 9th and two-hour averages thereafter. For each site, the measurement replicates are presented as averages. The depth of the permafrost active layer when it exceeded the lowest measurement depth at 160 cm was estimated by extrapolating the 80 to 160 cm soil temperature profile downward. The thermistors at site S were installed in late summer, 1978 and during the remainder of that summer they compared closely at all depths with site T. Therefore a realistic assessment of the temperature effects due to greater snow depths and longevity of the snow pack at site S can be achieved.

Soil moisture was measured every three days at replicated locations at site T and W in 1978 and T, W, and S in 1979. Measurements could not be started until near final snow melt when the neutron probe access tubes were visible. The soil surface moisture, 0 to 5 cm, was determined gravimetrically as the average of 10 samples. Probe readings were taken at increments of 10 cm from 5 to 85 cm. Soil baskets 10 cm thick and 30 cm in diameter were placed over each tube in order to give reliable near surface measurements by temporarily deepening the soil column and preventing the escape of neutrons into the air. The baskets were housed in the soil surface during non-measurement periods so that they could maintain the moisture characteristic of the surrounding surface soils.

Rainfall was measured at four sites on the open tundra using standard rain gauges which were sunk into the ground so their tops were even with the tundra surface. Snow depths were averaged from snow course data in which 20 points, chosen randomly, were used for depth and density measurements. The average depths give an accurate picture of site differences in snow water equivalents, since snow densities were the same at all sites in the late winter, averaging about 500 kg/m^3.

Results

General Climate

The snow depths at sites W, S, and T and at the airport (site A) are recorded in Figure 2. Very large depth differences between sites W and T occurred in both years, the windswept snow from the tundra accumulating deeply in the forest. The snow disappeared from the tundra in late May of both years but remained on the ground an extra 21 to 24 days at site W. Snow depths at site S were more comparable to site W than site T, but the snow melted very rapidly, disappearing only five days later than at site T. In 1978, the airport measurement closely duplicated site T, with final snow melt occurring on the same day. During snow melt in 1979, depths at site A were triple

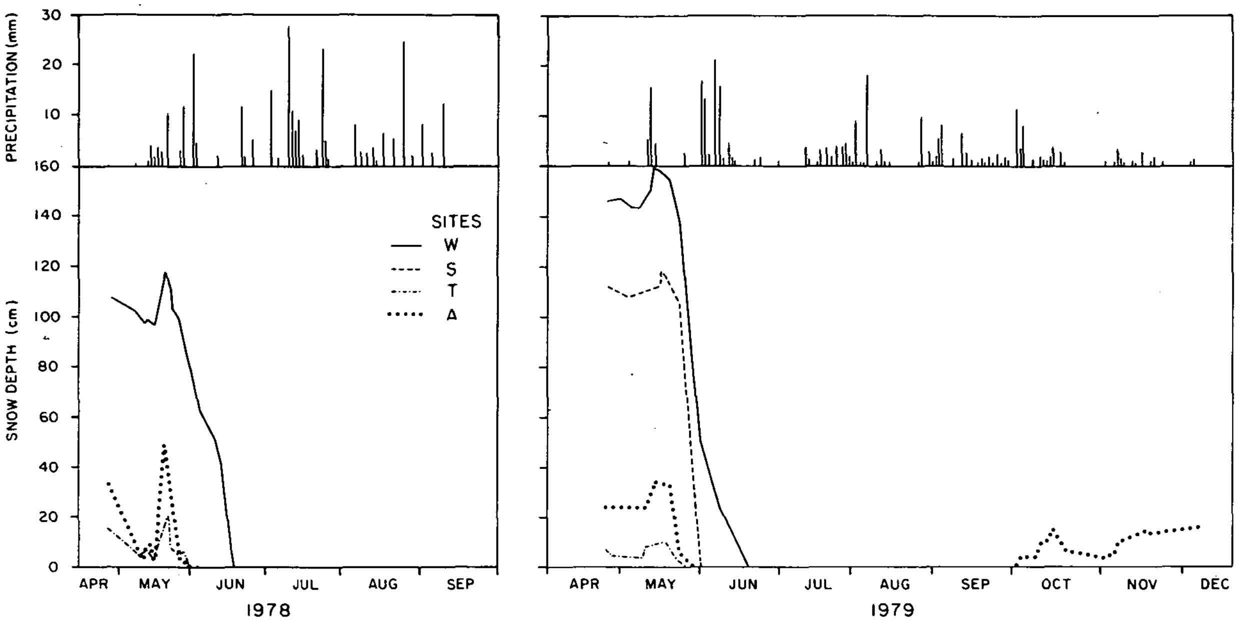

FIGURE 2. Snow cover and precipitation. Sites W, S, T, and A refer to woods, snow fence, tundra, and airport respectively.

those at site T, but final snow melt occurred only one day later. Thus the airport measurement gives a good indication of snow cover longevity on the open tundra but no indication of either longevity or depth for the woods.

Individual precipitation events for both years are also shown in Figure 2 and rainfall data for the summer months are given in Table 1. The normal yearly precipitation at Churchill is about 397 mm of which 37 per cent falls in June, July, and August. It is, in this respect, fairly typical of the low Arctic. In 1979 it had normal rainfall amounts except for a dry September, but in 1978 it was much wetter than usual in July and August. The importance of proximity to Hudson Bay where frequent showers are generated is evident in the number of rain days. In both years there was measurable rain on about half the days and if one includes trace rainfall, rain actually fell on about three-quarters of the summer days.

The summer temperatures were somewhat below normal in 1978 and above normal in 1979, but considering the whole summer period the departure from average was not great in either year.

In general the summer research period in 1978 was cooler and much wetter than normal while 1979 had near normal rainfall but was somewhat warmer than average (*see* Table 1).

Energy Budget of the Tundra

The energy budget of the tundra during the meas-

TABLE 1. Summer precipitation and temperatures

	1978				1979				
	JUN	JUL	AUG.	TOTAL	JUN	JUL	AUG	SEPT	TOTAL
Normal rainfall (mm)	40.0	49.0	57.7	146.7	40.0	49.0	57.7	52.1	198.8
Measured rainfall (mm)	28.1	98.7	98.8	225.6	49.7	43.2	59.1	23.3	175.3
Measured/Normal	.70	2.01	1.71	1.54	1.24	.88	1.02	.45	.88
Days with measurable rain	16	15	20	51	14	15	13	13	55
Days with trace amounts	3	9	7	19	10	7	8	7	32
Total rain days	19	24	27	70	24	22	21	20	87
Rain days/Total days	.63	.77	.87	.76	.80	.71	.68	.67	.71
				AVE					AVE
Normal mean temp (°C)	6.1	12.0	11.5	9.9	6.1	12.0	11.5	5.7	7.6
Measured mean temp (°C)	5.3	10.2	9.0	8.2	8.1	13.5	11.3	3.6	9.2
Measured/Normal	.87	.85	.78	.82	1.33	1.13	.98	.63	1.21

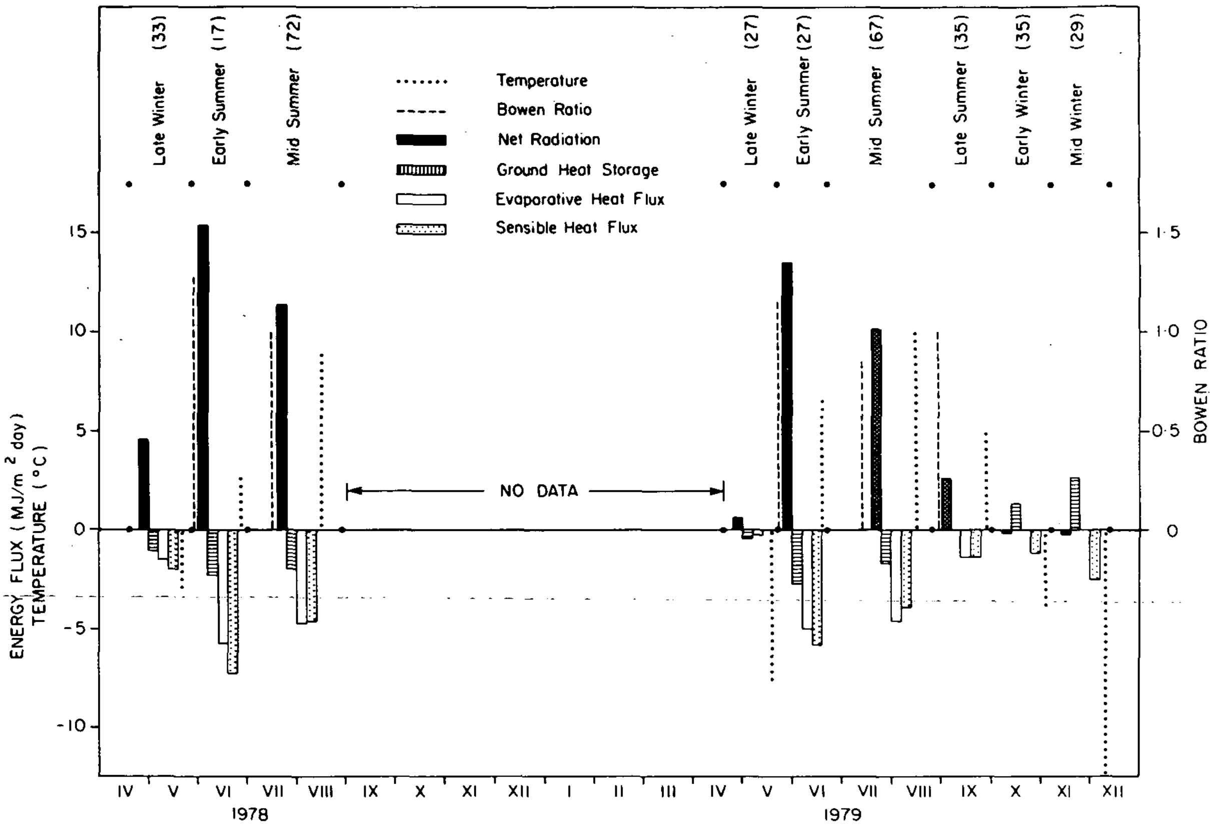

FIGURE 3. Energy budget of the tundra. The number in brackets after a seasonal period designates the number of days of measurement in that period. No Bowen Ratios are plotted for the winter periods.

urement periods in 1978 and 1979 is presented in Figure 3. The late winter period is one in which the tundra has a total or partial snow cover. Early summer is defined by a snow-free tundra surface, but there is snow still in the woods and average soil temperatures near the surface are < 4°C. In mid-summer the average air and soil temperatures are > 8°C whereas in late summer Q^* is small, falling to one-quarter the mid-summer value, average air-temperature is one-half the mid-summer values, and there is no soil heating or cooling. Early winter sees the onset of a permanent snow cover, is a period of negligible Q^*, shows a reversal to a negative soil heat flux and has small subzero air temperatures. In mid-winter Q^* is small and negative, the heat loss from the ground is large and subzero air temperatures are large. In 1978, the dates for the periods are late winter (April 26 to May 28), early summer (May 28 to June 15), and mid-summer (June 16 to August 27). In 1979, the periods are late winter (April 25 to May 21), early summer (May 22 to June 18), mid-summer (June 19 to August 25), late summer (August 26 to September 30), early winter (October 1 to November 5), and mid-winter (November 6 to December 4).

A very great variation in net radiation occurs from the late winter period through to late summer (*see* Figure 3). In late winter Q^* is small, in spite of relatively long-days and small cloud cover, due to the very large snow albedos which averaged 0.60 throughout the late winter period. The soils have started to warm and the small available energy is proportioned more on less equally amongst Q_G, Q_E, and Q_H, all of which are small.

In early summer, the energy regime of the tundra grows suddenly large. Q^* is great due to small albedo at 0.14, relatively small solar zenith angles and long days. Soils thaw and warm rapidly with 25 per cent greater heat storage (Q_G) than in mid-summer. The evaporative heat flux (Q_E) and sensible heat flux (Q_H) are 15 and 35 per cent greater respectively than for mid-summer so that the local contribution to atmospheric heating from the upland tundra is large during this period.

In the long mid-summer period the average daily net radiation remains large by middle latitude standards and, although the evaporative heat flux is less

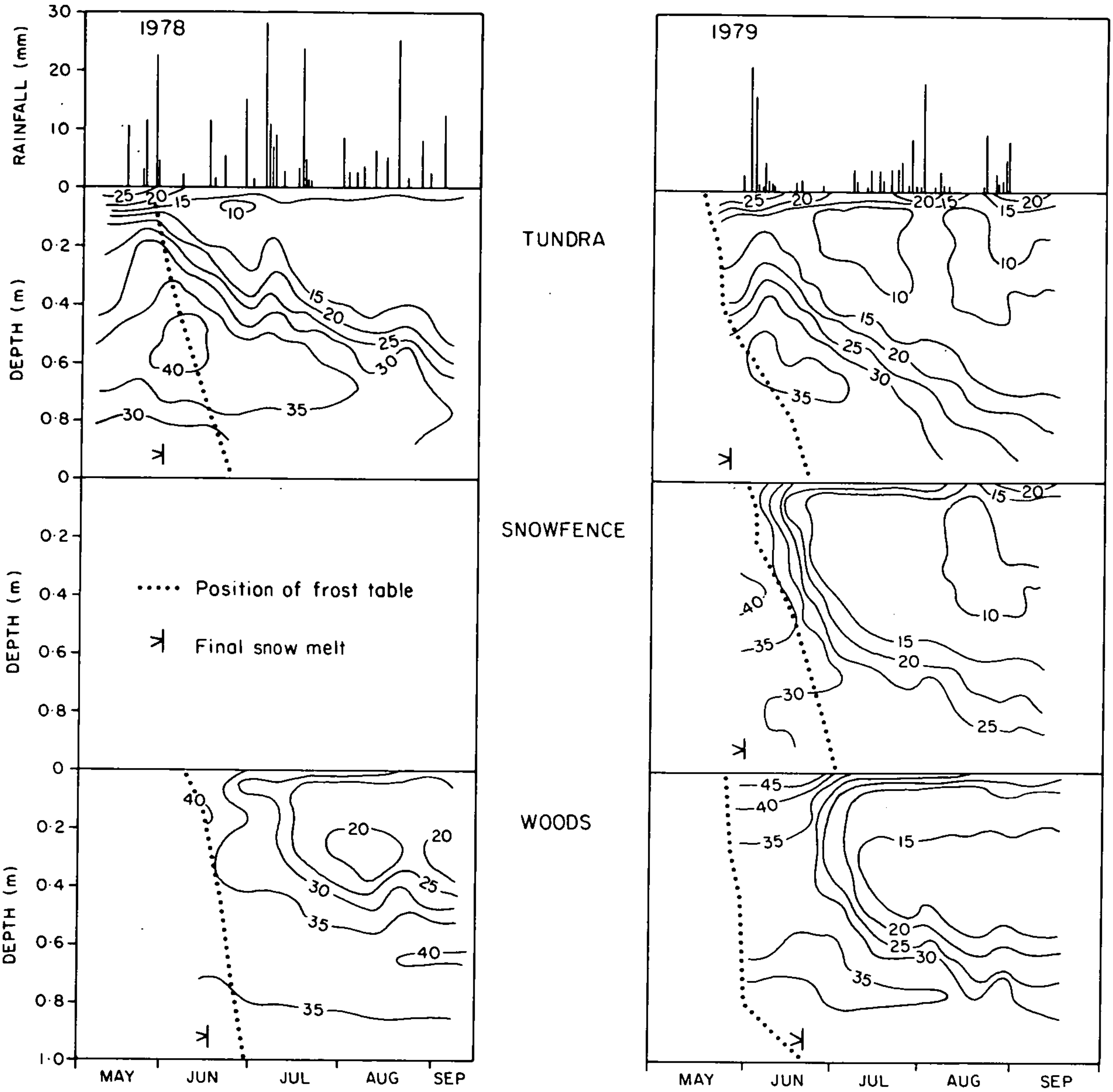

FIGURE 4. Soil moisture in per cent by volume.

than in early summer, the surface reaches its greatest evaporative efficiency, whereby Q_E/Q^* is 0.43 compared to 0.37 in both early and late summer periods.

By late summer, Q^*, Q_E, and Q_H are once again small and Q_G becomes negligible. This is in spite of the fact that air temperatures are almost as large as in early summer and shows the impact of short days in creating small Q^*.

In early winter, the soil rapidly loses heat and this dwarfs in magnitude the energy of Q^* which is almost negligible. Q_E ceases due to the frozen tundra surface and sub-zero air temperatures. Thus, the upward ground heat flux is largely dissipated as a sensible heat flux to the atmosphere.

Mid winter witnesses a large ground heat loss comparable in magnitude to the early summer ground heat gain. This large Q_G compensates for the small negative Q^* and produces a substantial Q_H flux to the atmosphere.

Soil Moisture

There is standing water on the soil surface immediately after snow melt before the surface soils have thawed to any great depth. Patterns of soil moisture

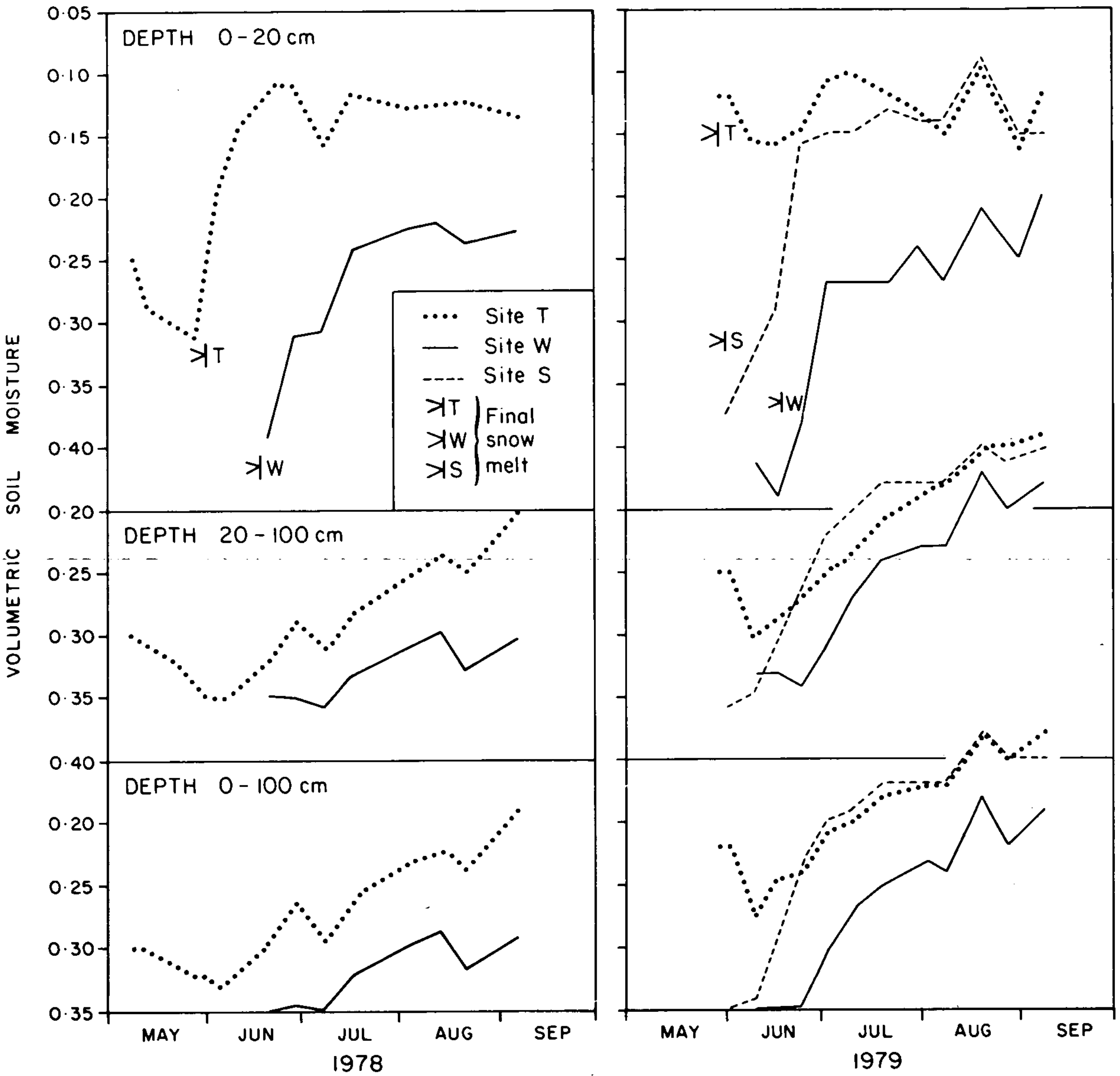

FIGURE 5. Total soil moisture (volumetric fraction) for various depth intervals.

change during the summer period are plotted in Figures 4 and 5. A comparison between site T and W in both years shows that near the surface (0 to 15 cm), site W remains at least twice as wet during the summer as does the tundra site. At site W the effect of water withdrawal by the tree roots is particularly evident in 1979, in the zone 20 to 60 cm, where volumetric soil moisture levels of 15 per cent are sandwiched between layers above and beneath which maintain levels up to 30 per cent, during the summer period. Site S, although it starts off very wet, dries quickly, (after final snow melt), so that by mid-summer its soil moisture is almost the same as at site T. At no site did the soil moisture fall below five per cent in either year so that, even on sandy upland areas, this is a wet environment. In 1978, the soil moisture averaged for the top 1 m throughout the summer periods was 26 and 31 per cent for sites T and W respectively while in 1979 it was 20, 26, and 18 per cent at sites T, W, and S respectively.

Soil Temperature

Time–depth patterns of the soil temperature at the three sites are plotted in Figure 6. The zero curtain effect which is plotted is derived from the soil temperature record. The uptake of latent heat for melting

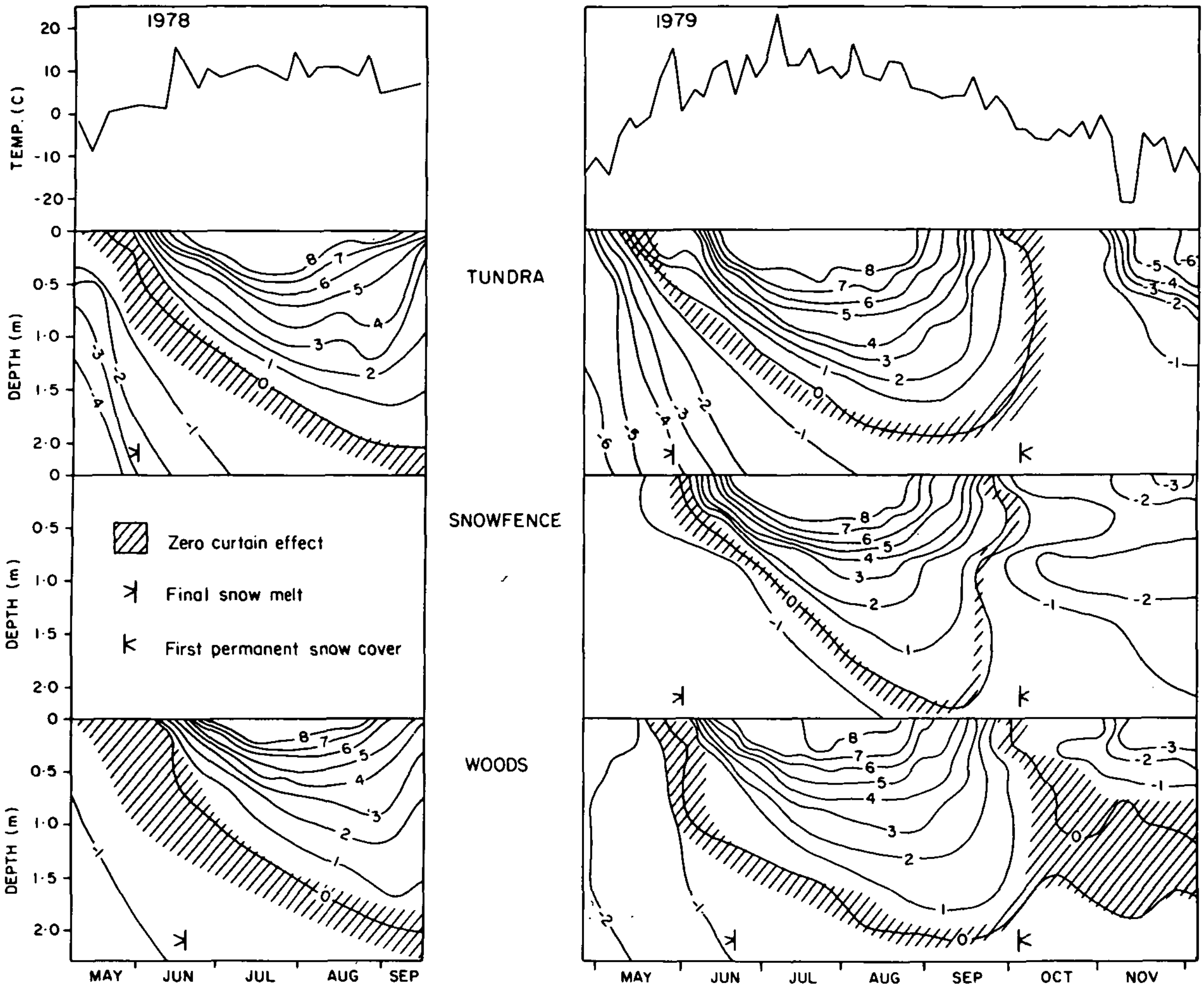

FIGURE 6. Soil and air temperatures (°C).

of the soil water in spring does not allow the soil temperature to rise much above 0°C until most of the ice has melted. In opposite fashion, with winter cooling the latent heat release prevents temperatures dropping substantially below 0°C until most of the freezing has occurred. There appears to be no zero point depression presumably due to the small salt content of the soil water in the sandy soils and lack of any hydraulic pressure build-up.

The zero curtain exerts a substantial influence in these wet soils. With the very wet soils in spring of 1978, the zero curtain effect during the thaw period was more pronounced than in 1979 when the soils were, on average, ten per cent drier in total water volume in the active layer. The importance of more soil water is also seen in the fact, that the curtain effect lasts longer in the very wet soil at site W, than in the drier soils of sites T and S. By maintaining relatively high temperatures at site W until a substantial snow cover became established, the zero curtain insures that winter soil temperatures are moderate compared to the tundra. At site T, where the shallow snow pack allows strong soil cooling, as seen in spring 1978 and especially spring and winter 1979, soil temperatures are anywhere from 3 to 5°C colder than at sites S and W.

Ground thawing usually precedes final snow melt. At site T, the frost table had receded by final snow melt to 20 and 45 cm in 1978 and 1979 respectively. At site W, the comparable depths are 20 and 102 cm. Only at site S was there no soil thawing until final snow melt. The reasons for these differences are not obvious. Soil thawing at site T begins before mean air temperatures rise above freezing, indicating that absorbed solar radiation and the resulting ground heat flux plays an important part in heating the soil beneath the shallow snow cover. At site W, the trees strongly increase the absorbed solar radiation in comparison to site S. They in turn, act as radiators in thermal wave-lengths, which serves to warm the snow pack in the forest. This heat is imparted through the snowpack to the forest floor, either as a conductive heat flux which is not important in the early stages of snowpack ripening, or as a downward heat translocation, due to meltwater, which reaches its peak in the period of rapid snow decay. The very small absorbed solar radiation at site S creates very small net radiation and there is little heat source to the snow pack until daily mean air temperatures rise above freezing.

Maximum active layer depths are shown in Table 2. In 1978, at sites T and W, there were 200 and 202 cm respectively and were reached on September 11. Maximum depths in 1979 were achieved on the same date and were 190, 200, and 180 cm at sites T, W, and S respectively. In 1975, the length of thaw period at site W was less than at site T because of its long lasting snow cover so that the average thaw rates were greater at 2 cm/day in comparison to 1.7 cm/day at site T. In 1979 there was greater variation in active layer depths (*see* Table 2). Thaw rates show a similar variation with sites W and S having rates which were substantially greater than at site T.

The length of the frost-free period at different depths in the soil presents an interesting picture (Figure 7). In the top 40 cm, site T, due to its early spring warming, has a greatly prolonged frost-free period in comparison to sites W and S. Below 40 cm, site W has the extended frost-free period, due to the slowed freeze-back. Thus, in much of the rooting zone the forest creates its own ameliorated soil climate through the agency of wet soils and prolonged zero curtain effect. Site S has a curtailed frost-free period at all depths due both to the late lying snow cover in spring and the early accumulating snow cover in fall. Averaged for all depths, sites T and W have the same length of frost-free periods whereas site S is shortened by 13 per cent or 15 days.

Ground Heat Storage

The components of the ground heat storage are presented in Table 3 for thaw and freeze back periods. It is apparent that for all sites the bulk of heat storage and release is associated with the latent heat of fusion, so that soil wetness becomes a major factor in the energy budget of a surface. It is also apparent that the bulk of heat input comes from the soil heat flux component of the energy budget. Even in this, a relatively high rainfall area, the heat input from infiltrating rainfall is small.

The seasonal trends of ground heat storage for the 1979 season are plotted in Figure 8. It shows that site T has a significant Q_G flux 14 days before site S starts to warm or thaw significantly and 22 days before site W exhibits any warming. However, upon final snow melt at the latter sites, Q_G is so rapid that the seasonal totals are the same for all sites one month after final snow melt in the woods. Subsequently site W maintains a larger total heat gain through to the start of the mid winter period when Q_G for all sites again becomes equal. Thus site W gains and loses more heat than sites T and S, these latter of which, by midsummer, behave in similar fashion.

Discussion

The thinly wooded areas at the tree-line appear to maintain their own soil microclimate. The delayed final snow melt of some three weeks in early summer

TABLE 2. Active layer development

Parameters	1978 T		1978 W	1979 T		1979 W		1979 S
Maximum active layer depths (cm)	200		202	190		200		180
T: W: S	1	:	1.01	1	:	1.10	:	0.95
Period of active layer development (days)	118		100	124		109		101
T: W: S	1	:	0.85	1	:	1.10	:	0.95
Thaw rate (cm/day)	1.7		2.0	1.5		1.9		1.8
T: W: S	1	:	1.2	1	:	1.3	:	1.2
Soil heat flux, Q_G, over the period (MJ/m^2)	235		235	206		230		199
T: W: S	1	:	1	1	:	1.1	:	1
Net radiation, Q^*, (MJ/m^2)	1306		1377	1150		1213		987
Q_G/Q^*	.18		.17	.18		.19		.20

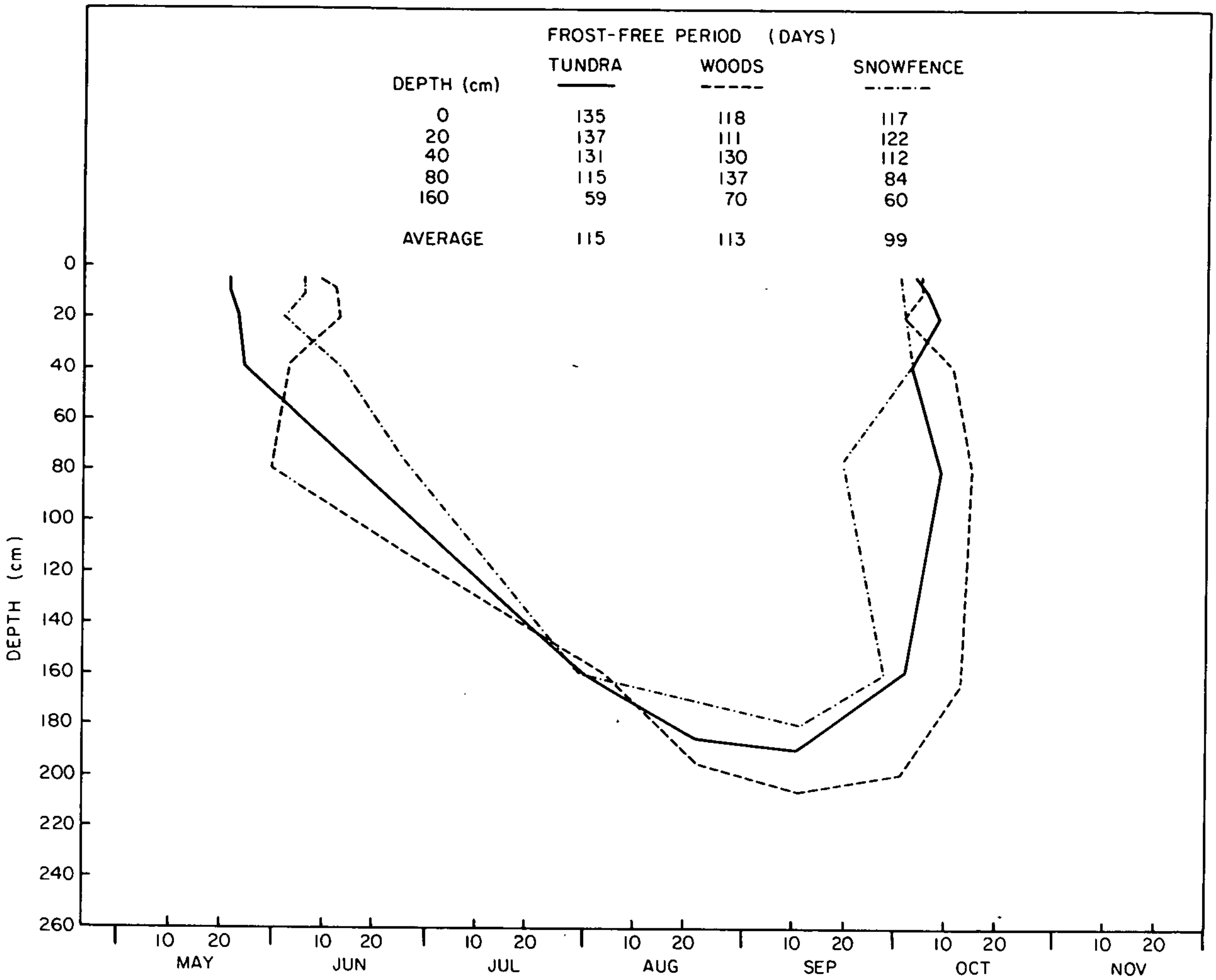

FIGURE 7. Frost-free period in the soil.

TABLE 3. Components of heat storage and heat flux in 1978 and 1979, presented as percents of total storage change during the period

Period	1978 T	1978 W	1979 T	1979 W	1979 S
THAW:			(%)		
Storage					
Heat gained by ice before thawing	2		3	1	1
Latent heat gain during thawing	92	96	87	93	94
Heat gain by water after thawing	3	2	4	3	3
Heat gain by soil solids	3	2	6	3	2
Input					
Soil heat flux from energy balance	98	99	98	99	99
Infiltrating rain water	2	1	2	1	1
FREEZE-BACK:				(%)	
Heat lost by soil solids			6	3	4
Heat lost by water			3	1	2
Latent heat released during freeze			90	95	93
Heat lost by ice			1	1	1

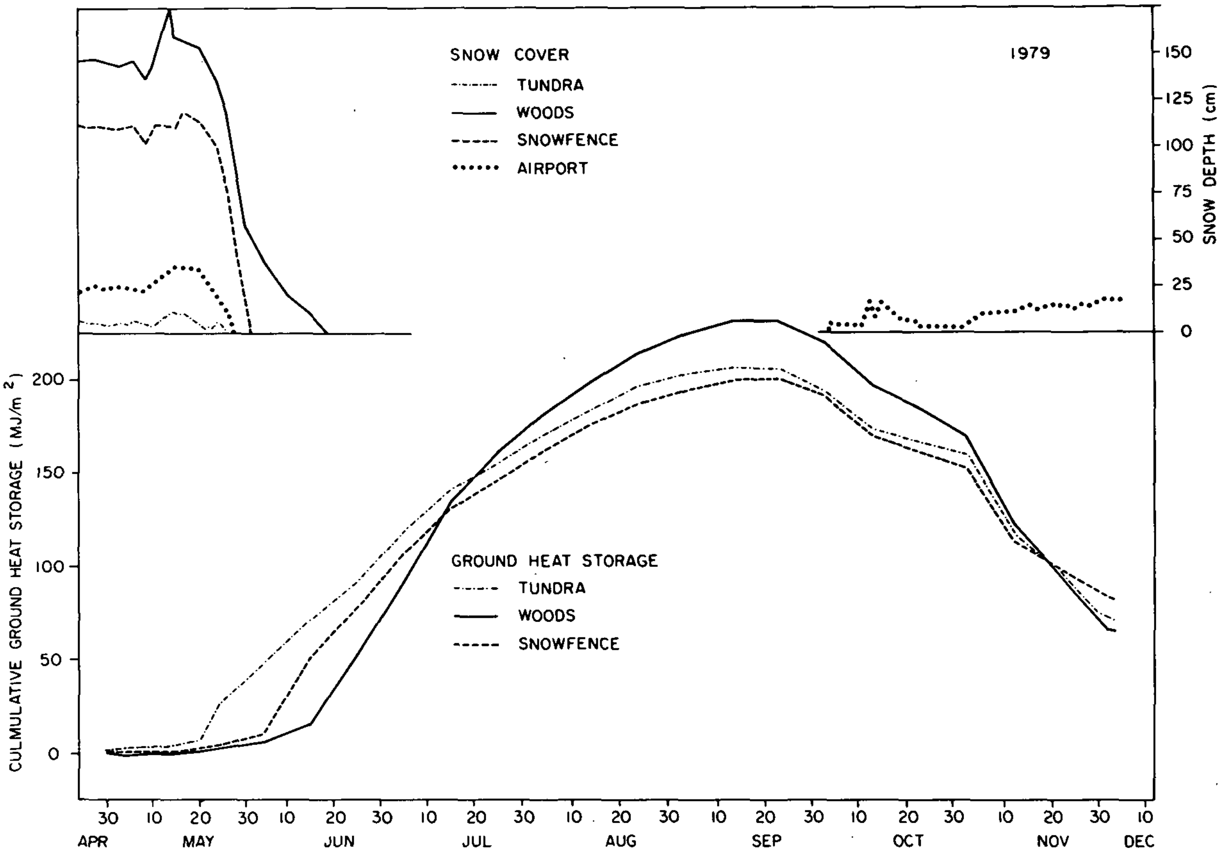

FIGURE 8. Ground heat storage.

inhibits evapotranspiration from still frozen soils and yields a substantial input of melt water to the soil during the high sun period. As a result of these factors plus tree shading of the surface throughout the summer period, the forest soils remain wet. this favours a pronounced zero curtain effect in early winter which extends right into the mid-winter period keeping the soils warm until an insulating layer of deep snow is established. Retarded winter freeze-back and early summer thaw creates an extended frost-free period in the lower rooting zone which presumably favours physiological activity. The soil moisture data suggest that vigorous transpiration begins just after final snow melt.

The influence of the forest on the microclimate has been in operation for many decades and yet it has not significantly influenced the maximum depth of the active layer. Hence, it is not exerting the same influence as the snow fence experiment at Schefferville, Québec, reported by Nicholson (1978) in which of snow accumulation in the snow-fenced area resulted in a rapid increase in active layer depths. The winter time retarding of soil cooling by the forest is the same affect as created by Nicholson's snow fence, so that the difference probably lies in the shading of the surface by the trees to decrease summer warming.

The results of the snow fence experiment are inconclusive. There is a suggestion that as in Nicholson's work, it serves to maintain warmer winter temperatures. However, there is no indication in the one year's data, of an increase in active layer depths and indeed there is some evidence that the length of frost-free period in the soil is substantially decreased. This could be attributed to the wetness of the soil after snow melt and a large initial consumption of available heat for evaporation. In the post-melt period, this evaporation proceeds more rapidly than in undisturbed tundra, until mid-summer when the soil moisture in sites S and T becomes the same. Any conclusive results for the snow fence experiment at Churchill, however, must await the analysis of further data.

One of the noteworthy results of the detailed energy budget measurements is the magnitude of the soil heat flux. With $Q_G/Q^* = 0.18$ for the whole summer period, it assumes more importance than in other reported studies. For example, in work at Barrow, Alaska, Weller and Holmgren (1974) found that during the summer season Q_G/Q^* averaged only 0.05, and that only during the short snow-melt period did it assume substantial magnitude at 0.22. Similarly Smith (1975), in a limited set of summer measurements in the Mackenzie Delta, measured ratios averaging 0.08. Neither study specified the volumetric soil moisture. The large storage and release of ground heat, primarly latent heat, at Churchill, means that in the winter period there is a substantial input of sensible heat energy to the snow pack and atmosphere until all the soil water has frozen. Since study sites reported here are amongst the driest in the Hudson Bay lowlands, it indicates the importance of these wet terrain types as a source of winter heat energy.

The ratios of evaporation/net radiation from the tundra site are much less than quoted by Weller and Holmgren (1974) for Barrow, Alaska. Whereas in their study Q_E/Q^* averaged about 0.70, at Churchill it was only 0.42 for the comparable period. In contrast, Q_H/Q^* was 0.22 at Barrow and 0.40 at Churchill. The temporal patterns, however, are similar with the largest values of Q^*, Q_G, Q_E, and Q_H in the early summer (post-melt) period. The reasons for the major differences in the energy budgets between these tundra locations are complex and lie beyond the scope of this report.

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