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Publisher's version / Version de l'éditeur:
https://doi.org/10.1139/e65-003
Canadian Journal of Earth Sciences, 2, pp. 15-31, 1965-02

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SOME OBSERVATIONS ON THE INFLUENCE OF CLIMATIC AND TERRAIN FEATURES ON PERMAFROST AT NORMAN WELLS, N.W.T., CANADA

BY

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Reprinted from
CANADIAN JOURNAL OF EARTH SCIENCES
VOL. 2, FEBRUARY 1965, P. 15

RESEARCH PAPER NO. 236
OF THE
DIVISION OF BUILDING RESEARCH

PRICE 25 CENTS

OTTAWA
February 1965

NRC 8213

SOMMAIRE

Au cours des étés de 1959 et de 1960 des observations *in situ* concernant l'influence de quelques caractéristiques climatologiques et géologiques sur le permagel ont été effectuées à Norman Wells, dans les Territoires du Nord-Ouest. Cinq emplacements comportant des sous-sols de terrain gelé en permanence ont été choisis pour l'enquête. Un de ces emplacements, à Thornthwaite, comportait une possibilité d'évapotranspiration et une couverture végétale de Kentucky bluegrass poussant sur un limon argileux. Les quatre autres emplacements avaient les différents types de végétation qui poussent naturellement dans la région de Norman Wells. Les arbres étaient surtout des spruces et quelques tamaracks. Du Sphagnum et d'autres mousses, du lichen et des roseaux couvraient le sol. La couche de tourbe avait une épaisseur qui variait de 7 pouces à 2 pieds et le sol minéral était en grande partie du limon argileux. A chaque emplacement des mesures ont été faites quant à l'évaporation (y compris les possibilités d'évapotranspiration), à la radiation nette à la surface du sol à l'épaisseur du dégel et aux températures du sol dans la couche dégelée et dans le permagel. Quoique les conditions rencontrées sur place aient nécessité l'emploi de grossiers dispositifs de mesure, des renseignements quantitatifs ont été obtenus quant à l'importance relative de ces caractéristiques climatologiques et géologiques dans l'environnement du permagel. Les possibilités d'évapotranspirati ... cement de Thornthwaite
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SOME OBSERVATIONS ON THE INFLUENCE OF CLIMATIC AND TERRAIN FEATURES ON PERMAFROST AT NORMAN WELLS, N.W.T., CANADA

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Received August 3, 1964

ABSTRACT

During the summers of 1959 and 1960, field observations of the influence of some climatic and terrain features on permafrost were carried out at Norman Wells, N.W.T. Five sites, all underlain by perennially frozen ground, were selected for investigation. One site was a Thornthwaite potential evapotranspiration site with a vegetation cover of Kentucky bluegrass growing on clayey silt. The four remaining sites included the various types of vegetation growing naturally in the Norman Wells region. The tree growth was predominantly spruce with some tamarack. *Sphagnum* and other mosses, lichen, and sedge comprised the ground cover. The peat layer varied in thickness from 7 in. to 2 ft and the mineral soil was predominantly clayey silt. At each site, measurements were taken of evaporation (including potential evapotranspiration), net radiation at the ground surface, depth of thaw, and ground temperatures in the thawed layer and the permafrost. Although field conditions dictated the use of crude measuring devices, some quantitative information was obtained on the relative importance of these climatic and terrain features in the permafrost environment. Potential evapotranspiration was higher in the Kentucky bluegrass at the Thornthwaite site than in *Sphagnum* and in other mosses, in lichen, and in sedge at the other sites. Net radiation values appeared to be slightly higher for moss than for lichen. The depth of thaw under moss and lichen was less than in areas supporting other types of plant growth. Ground temperatures in the thawed layer and in the permafrost showed the same characteristics, being lower in the moss and lichen areas.

Field observations were carried out during the summers of 1959 and 1960 at Norman Wells to obtain quantitative values of the influence of some climatic and terrain features on permafrost. Evaporation (including potential evapotranspiration) and net radiation were measured at the ground surface. Depth of thaw measurements were carried out and ground temperatures were measured in both the seasonally thawed and perennially frozen ground.

Norman Wells (65° 18′ N., 126° 49′ W.) is located on the right bank of the Mackenzie River, 240 ft above sea level, 90 miles south of the Arctic Circle and about 500 miles north of the southern limit of permafrost (Fig. 1). The depth to permafrost at Norman Wells varies from 1 to 2 ft in undisturbed moss–peat areas to a maximum of 15 ft and more in areas disturbed by construction. Permafrost occurs everywhere under the ground surface and is about 200 ft thick.

DESCRIPTION OF OBSERVATION SITES

Observations were taken at five sites in the Norman Wells region. Site No. 1 was a Thornthwaite potential evapotranspiration site; the other four were chosen to include the various types of vegetation indigenous to the Norman Wells region.

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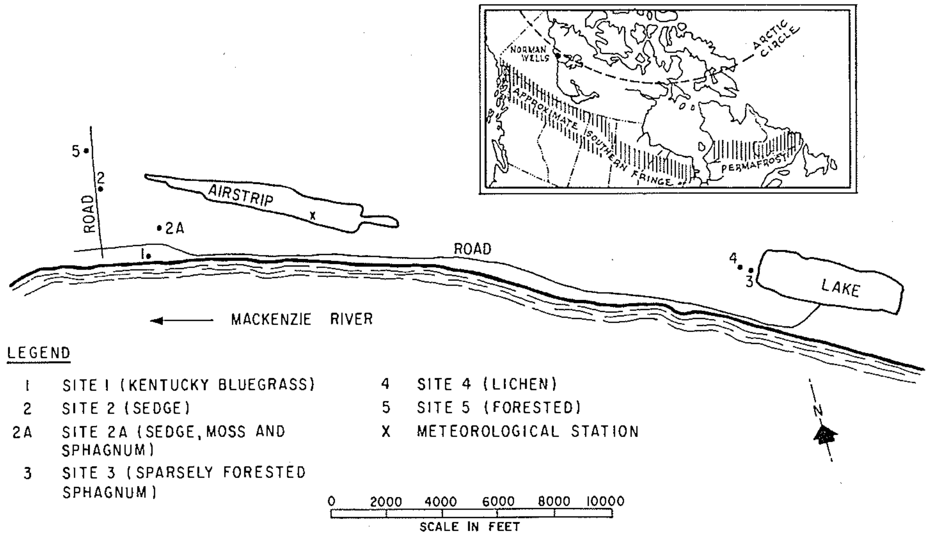


FIG. 1. Location of test sites at Norman Wells, N.W.T.

Site 1

Vegetation: Kentucky bluegrass, 2 in. high (Fig. 2).

Soil: 0 in. to 4 in. Black decomposed organic matter and silt.
Below 4 in. Brown clayey silt, scattered stones, organic matter.

Site 2

Vegetation: Grass-like sedge, 1 ft high with scattered dwarf willow and ground birch (Fig. 3).

Soil: 0 in. to 7 in. Black decomposed organic matter (peat).
7 in. to 1 ft 8 in. Black organic silt.
Below 1 ft 8 in. Clayey sandy silt.

Site 3

Vegetation: Scattered spruce and tamarack up to 6 ft high, dwarf willow and ground birch, 2 ft high with ground cover of Labrador tea and *Sphagnum*.

Soil: 0 in. to 5 in. *Sphagnum* (scattered patches exceeded 12 in.).
5 in. to 1 ft 11 in. Black decomposed organic matter (peat).
Below 1 ft 11 in. Grey clayey silt.

Site 4

Vegetation: Scattered spruce, tamarack, and birch up to 10 ft high, Labrador tea, *Sphagnum*, and lichen (*Cladonia alpestris*, *Cetraria nivalis*, *Cetraria cucullata*) (Fig. 4).

Soil: 0 in. to 2 in. Lichen.
2 in. to 4 in. Black decomposed organic matter (peat).
4 in. to 2 ft 0 in. Brown decomposed organic matter (peat).
Below 2 ft 0 in. Grey clayey silt.

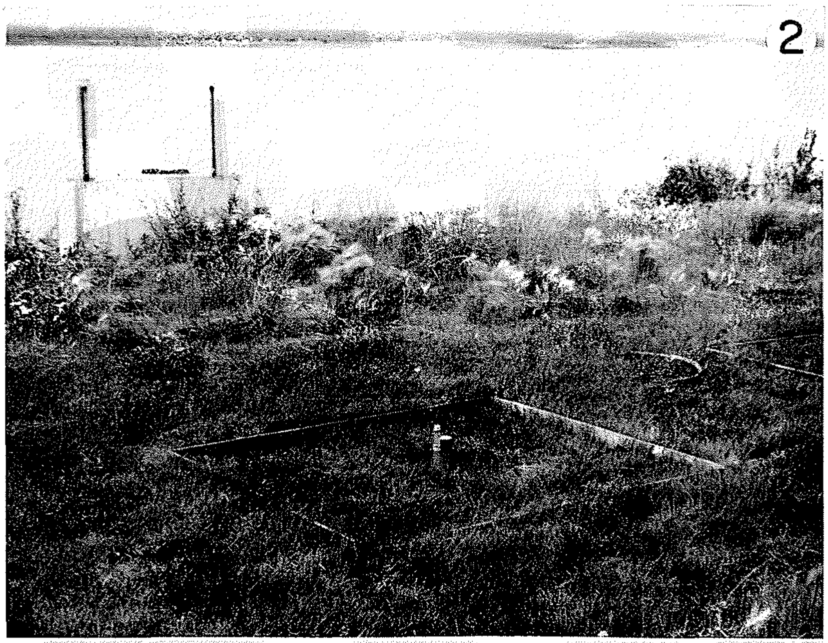
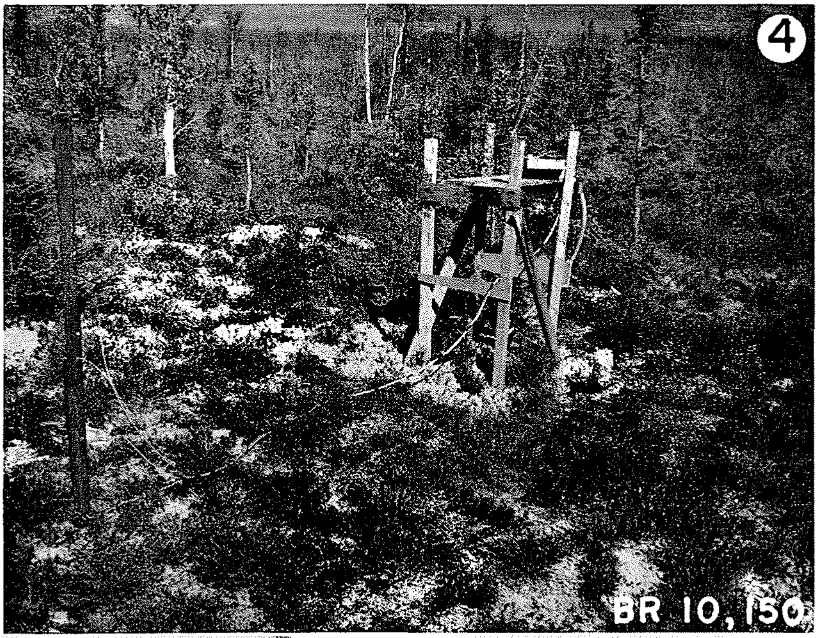


FIG. 2. Site 1 (Thornthwaite installation) at Norman Wells, N.W.T. Grass-covered pans with tensiometers in foreground. Supply tanks and overflow housing in background. August 1956.
FIG. 3. Site 2 (sedge area).



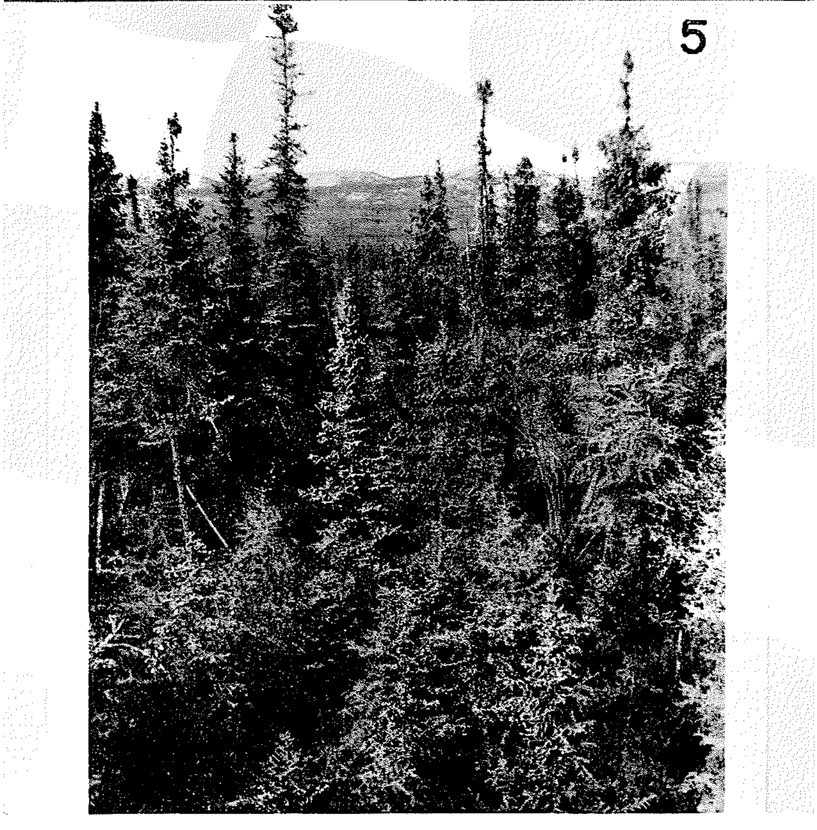


FIG. 4. Site 4 (lichen area) showing installation of thermocouple cable in permafrost. September 1960. FIG. 5. Site 5 (forested area). 29 August 1959.

Site 5

Vegetation: Dense spruce and tamarack up to 20 ft high, willow and alder up to 4 ft high with ground cover of Labrador tea, *Sphagnum* and other mosses (*Thuidium abietinum*, *Pleurozium* sp.) (Fig. 5).

Soil: 0 in. to 4 in. *Sphagnum* and other moss.
4 in. to 7 in. Black decomposed organic matter (peat).
Below 7 in. Brown clayey silt.

The Kentucky bluegrass at site 1 is not native to Norman Wells but is a cover commonly used at Thornthwaite installations in temperate non-permafrost regions (Thornthwaite 1948). At this site, the depth to permafrost is between 5 and 10 ft. The depth to permafrost at site 2 is about 6 ft and at the other sites it is less than 5 ft.

APPARATUS AND OBSERVATION METHODS

Evaporation (Including Evapotranspiration)

The purpose of the Thornthwaite installation at site 1 was to test the validity of the Thornthwaite world climatic classification system, which is based on potential evapotranspiration (PE), for northern areas that have long days during the vegetative growing season (Sanderson 1954). PE was measured at the other four sites to observe quantitative differences in various vegetation types which grow naturally in the permafrost region and to compare these with values obtained from the Thornthwaite installation.

At all sites a smaller evapotranspirometer was used; it consisted of half a 45-gal oil drum about 56 cm in diameter. On the bottom of each drum was welded a threaded outlet from which a pipe led to an overflow container about 3 ft away. Measurements were taken daily from 15 to 31 August 1959 and 30 June to 17 September 1960. After the overflow was recorded, a measured quantity of water in excess of the anticipated PE was sprinkled uniformly over the surface.

Air temperatures and rainfall were measured daily at each site. At sites 2 to 5, some perennially frozen soil had to be excavated to accommodate the oil drums and overflow apparatus but the low soil temperatures did not interfere with the evapotranspiration or overflow.

The latent evaporability of the air was measured with an Alundum disc atmometer, loaned by the Canadian Department of Agriculture. This atmometer was installed in the southwest corner of site 1. In 1959, daily readings were taken from the beginning of August until early September. In 1960, daily readings were taken from 11 June until 17 September. The results of both summers were compared with observations from the Thornthwaite installation.

In 1960, a class A evaporation pan was supplied by the Meteorological Branch, Canada Department of Transport, to measure the evaporation from the surface of water in an open pan. This installation was located 15 ft west of the Thornthwaite installation. Daily readings were taken from 11 June to

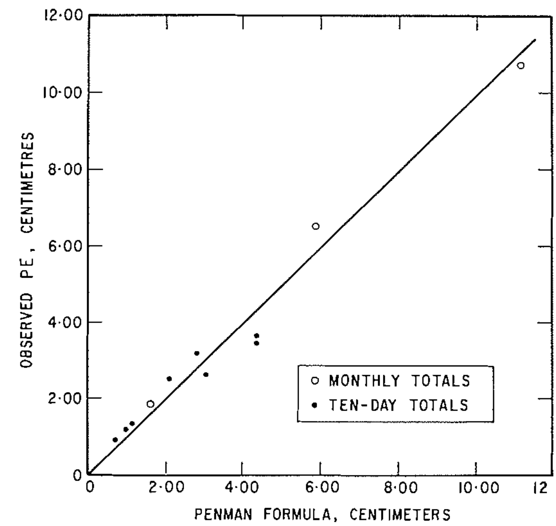


FIG. 6. Comparison of observed potential evapotranspiration from Kentucky bluegrass at site 1 (Thornthwaite installation) with Penman evaporation formula, for summer 1960.

17 September and the results compared with the observations from the Thornthwaite installation.

Net Radiation

In 1959, weekly readings of net radiation were taken at each site with an economic net radiometer (Suomi and Kuhn 1958) to obtain some estimate of the relative importance of the various ground plant species on the heat exchange between the atmosphere and the ground.

Ground Thermal Regime

In the summers of 1957 to 1959 inclusive, weekly depth of thaw measurements were made at each site to determine quantitative variations under different types of vegetative cover and to assess the relative importance of the individual species comprising the vegetative cover.

Ground temperatures were measured weekly in the thawed layer above the permafrost and in the permafrost at each site to observe variations in the thermal regime under the different types of vegetation. Thermocouples of 20-gauge copper–constantan duplex wire were used to measure the temperatures. In the thawed layer, thermocouples were placed at intervals varying from 3 to 12 in. to the following depths: site 1, 70 in.; site 2, 60 in.; site 3, 22 in.; site 5, 14 in. Weekly temperature readings were also taken on two special thermocouple strings installed in thick *Sphagnum* (site 3) and lichen (site 4). Thermocouples on these strings were spaced at 1-in. intervals from the ground surface to the 12-in. depth to obtain temperature gradients through the living plant cover to determine whether it was uniform throughout or whether it varied with depth, and to determine whether there was any difference in the gradient between *Sphagnum* and lichen. In the permafrost, thermocouple cables were placed at intervals varying from 1 to 1.5 ft to the following depths: site 2, 19.5 ft; site 3, 18.5 ft; site 4, 11.5 ft.

RESULTS AND DISCUSSION

Evaporation (Including Evapotranspiration)

The observed daily PE at site 1 (Table I) was compared with Thornthwaite's (1948) formula in which he derived PE from the length of day and a heat index related to the number of degrees of the mean daily temperature above 32 °F. The amount of precipitation was not considered because he assumed that the amount of water evaporated and transpired is determined by temperature and length of day. Using the formula, the computed PE for the 1959 and 1960 periods was 4.47 and 24.75 cm respectively compared with the observed PE of 3.28 and 19.41 cm respectively. In 1960 at site 1, the observed PE was 22.90 cm at the oil drum, which is slightly higher than the Thornthwaite installation.

Measurements of the latent evaporability (LE) of the air obtained from the Alundum disc atmometer were converted to PE using the formula suggested by the Canadian Department of Agriculture (Robertson 1954):

$$\text{LE} \times 0.0034 \times 2.54 = \text{PE (cm)}. \tag{1}$$

Applying this formula, the computed PE for the 1959 and 1960 periods were 4.19 and 19.47 cm respectively compared with the PE of 3.28 and 19.41 cm respectively observed at site 1.

The evaporation of water in 1960 from the class A evaporation pan was compared with the PE observed at site 1. The former was considerably higher, being 25.63 cm compared with 19.41 cm for the latter (Table I).

TABLE I

Evaporation (including evapotranspiration) at Norman Wells test sites

	Site 1, 1960		Site 2, 1960	Site 3, 1960	Site 4, 1960	Site 5, 1960	D.O.T. Station 1960
Elevation above sea level, ft	318		339	300 ft from site 5 at same elevation	348	344	340
Mean daily air temperature, °F	54.6		53.2	Not measured	53.6	54.2	55.2
Mean daily max air temperature, °F	64.3		64.7	Not measured	65.0	66.9	63.8
Mean daily min air temperature, °F	44.7		41.7	Not measured	42.2	41.5	46.5
Rainfall, cm	17.89		18.63	19.30	19.10	18.89	19.06
P.E., cm	1959	1960					
Thornthwaite installation	3.28	19.41					
Oil drum	—	22.90	12.51	13.37	10.75	11.76	
Class A pan	—	25.63					
Atmometer	4.19	19.47					
Thornthwaite (computed)	4.47	24.75					
Penman	4.51	19.32					

NOTE: 1959 period = 15 to 31 August inclusive (17 days).
1960 period = 30 June to 17 September inclusive (80 days).

In addition to being compared with Thornthwaite's formula, the PE observed at site 1 was compared also with the formula developed by Penman (1956).

Penman's mass transfer formula is:

$$E_0 = 0.35\ (e_0 - e_d)\ (0.5 + (U_2/100)), \tag{2}$$

where

E_0 = evaporation, cm;

$e_0 - e_d$ = vapor pressure difference between surface and air, mm of Hg;

U_2 = mean wind speed, miles per day.

It was assumed that the mean temperature of a saturated surface is approximately equal to the mean air temperature. Wind velocity and air temperature records were obtained from the Department of Transport's Meteorological Station at Norman Wells. The wind factor was adjusted to the 2-meter level by assuming that the wind velocity decreases with height according to the one-seventh power law. The Penman totals for the 1959 and 1960 periods were 4.51 cm and 19.32 cm respectively compared with the observed PE of 3.28 and 19.41 cm respectively. A comparison was made between the calculated Penman formula and observed PE for 10-day and monthly totals, resulting in good correlation (Fig. 6).

In 1960, the evaporation observed on the Alundum disc atmometer and computed by the Penman formula (Table I) gave the closest values to the PE measured at the Thornthwaite installation (80-day observation period). None of the values measured in 1959 was close to the PE measured on the Thornthwaite installation possibly because the observation period was so short (only 17 days).

The use of the Thornthwaite formula to compute PE at high latitudes has been criticized because the length of day factors and the heat index have been computed only north to 50° (Norman Wells lies at 65° 18′). Farther north the days are longer during the evapotranspiration period but the amount of incoming solar radiation is less because of the lower angle of the sun. It is not known how well these factors balance out.

The disregard by the Thornthwaite and latent evaporation formulae for different plant types would seem to be an objection particularly for northern areas where mosses and lichens grow widely. The mechanisms of moisture movement in these non-vascular plants are quite different from vascular plants. *Sphagnum* and other mosses are strongly hygroscopic and can lose moisture rapidly and in large quantities. Lichens, however, have very dry surfaces at times, even when lower layers near the soil are very wet. It is not certain whether the transfer of water vapor from the wet basal layer to the atmosphere above the lichen takes place by evaporation or merely by diffusion exhange. The area of vegetative surface per unit ground area of mosses and lichens may be very different from that for the higher plants. For these reasons, the quantity of moisture transfer (and resulting heat transfer) between the permafrost and the atmosphere may be quite different from temperate areas where mosses and lichens are not predominant.

PE measurements in 1960 at sites 2 to 5, inclusive, are presented in Table I. (Results from 1959 are not presented because they are so scattered probably because of the very short length of the observation period.) The PE at these four sites is considerably less than at site 1. Because of the uncertain accuracy of the oil drum method of measuring PE, it is impossible to give quantitative differences among sedge, moss, and lichen. Nevertheless PE from these plant types was significantly less than from Kentucky bluegrass.

Mean daily air temperatures were recorded at four of the five sites but there was no apparent correlation with PE. Site 1 had the highest PE; its mean temperature for the 80-day period of 54.6 °F was higher than that of site 5 (which was shaded) and site 2 but lower than sites 3 and 4 near a small lake. The higher degree of exposure to wind of site 1 would contribute to its having a higher PE, but sites 3 and 4 were also fairly exposed. These last two sites had PE values similar to site 5, which was sheltered.

It has been stated that meteorological factors play a prominent role in evapotranspiration rates where soil moisture is not the limiting factor. Nevertheless, it is possible that the physiological characteristics and radiation and thermal properties of plant materials such as moss and lichen, which maintain a high permafrost table, are significant factors in determining the contribution of evapotranspiration to the energy exchange of permafrost. One discrepancy that arises is the fact that the sedge does not maintain a high permafrost table, but has PE rates comparable to those for moss and lichen. This may be caused by its lower insulating qualities which permit a greater depth of thaw during the summer.

Net Radiation

During the summer of 1959, weekly net radiation measurements of various vegetative cover types in the Norman Wells area were taken using an economic net radiometer. To obtain net radiation with approximately 3 to 5% accuracy, the short expression for radiation in Langleys per minute was used:

$$R_n = 1.25\sigma\,(T_t^4 - T_b^4) + 0.0025\,(T_t - T_b) \tag{3}$$

where

R_n is net radiation, Langleys per minute;
σ is the Stefan-Bolz constant;
T_t = temperature of top face, °C;
T_b = temperature of bottom face, °C.

This expression considers incoming radiation positive and outgoing radiation negative.

The calculated net radiation results and air temperatures at the time of reading are tabulated in Table II. This table also includes the exact times at which observations were taken and the percentage of sunlight recorded during the hour in which each reading was made. No continuous measurements of incoming solar radiation were made with which the observed net radiation values could be compared. It was thus impossible to compare the differences of net radiation through different types of vegetative cover with the incoming solar radiation at the time of observation.

TABLE II

Net radiation values obtained from various types of vegetation at Norman Wells, N.W.T. using economic net radiometer, 1959

Date	Site	Net radiation g-cal/cm² min	Time P.S.T.	Air temp., °F	Sky conditions
Aug. 28	Site 1	0.34863	1155	57.3	Clear
"	Site 2	0.44000	1408	59.1	Clear
"	Site 3	0.38050	1447	60.0	Clear
"	Site 4	0.04525	1025	54.3	Cloudy bright
"	Site 5	0.55762	1522	60.0	Clear
Sept. 7	Site 1	0.12213	1343	38.4	Cloudy bright
"	Site 2	0.12525	1509	38.5	Overcast
"	Site 3	0.11250	1415	38.3	Overcast
"	Site 4	0.02288	0953	37.1	Cloudy bright
"	Site 5	0.24675	1059	37.3	Cloudy bright
Sept. 11	Site 1	0.27875	1351	42.9	Clear
"	Site 2	0.17400	1500	43.0	Clear
"	Site 3	0.12400	1532	43.0	Clear
Sept. 12	Site 4	0.09638	0913	37.4	Scattered cloud
Sept. 11	Site 5	0.06013	1603	43.0	Clear
Sept. 23	Site 1	0.05988	1604	43.3	Cloudy bright
Sept. 24	Site 2	0.08763	0935	34.8	Cloudy bright
"	Site 3	0.18175	1051	36.8	Cloudy bright
Sept. 23	Site 4	0.16550	1022	43.6	Cloudy bright
Sept. 24	Site 5	0.18713	1413	40.1	Cloudy bright
Sept. 30	Site 1	0.11425	0950	36.8	Overcast
"	Site 2	0.02275	1516	38.2	Overcast
"	Site 3	0.03413	1540	38.0	Overcast
"	Site 4	0.02288	1049	38.3	Overcast
"	Site 5	0.00563	1631	38.0	Overcast

Despite the questionable validity of the observations, a general qualitative pattern is evident. For example, it was anticipated that the net radiation values for lichen would be the lowest because of this plant's light color and consequent high reflective properties. This was true on clear days but not on partly cloudy or overcast days when differences in net radiation from one plant type to another were small. On the other hand, net radiation values for the sedge, which is also a light-colored plant, were much higher than for lichen on clear days and higher than the darker-colored plants such as grass and moss. Net radiation values at site 1 were the highest on some days but not on others. Net radiation through *Sphagnum* and other mosses was highest on clear days but not always on overcast days.

From these crude measurements, it appears that net radiation through moss is higher than through lichen. Nevertheless, these plants maintain the permafrost table at about the same level in a given area and near surface ground temperatures are similar under both plant types. Consequently, if lichen rejects a higher proportion of the net radiative flux than moss this may be compensated by the moss rejecting a higher proportion than the lichen of some other component of the energy exchange.

Ground Thermal Regime

Depth of thaw measurements in various types of vegetative cover were plotted against Fahrenheit degree days for the summers of 1957, 1958, and

1959. The use of degree days gives a more realistic comparison than calendar dates because of the variation in air temperature from one summer to another. For example, the depth of thaw in 1959 was considerably less than in the two previous summers because of the lower air temperatures. Nevertheless, a comparison of depth of thaw with degree days of thawing indicated a similar relationship for the three summers of observations. Average values of depth of thaw vs. degree days of thawing were obtained for each vegetation cover type and plotted (Fig. 7).

The greatest depth of thaw occurred at site 2, sedge and no moss cover overlying 7 in. of peat. The next greatest depth of thaw was observed in a forested area, probed only in 1957 and 1958. This site had a moss cover 4 in. thick overlying 3 in. of peat. Actually the 1958 depth of thaw was much greater than in 1957, a condition which may be explained by the inadvertent disturbance of the site in 1957 resulting in an unnaturally deep thaw the next year. A treeless area having a ground cover of sedge (*Scorpidium* sp.) and 3-in. thick cover of *Sphagnum* and other mosses (Fig. 1, site 2A) overlying 6 in. of peat experienced less depth of thaw than the previously mentioned area. The shallowest depth of thaw was observed at site 3, sparsely forested area that had a 5 in. to > 12 in. *Sphagnum* cover overlying about 18 in. of peat and site 5, forested area with 4 to 12 in. of *Sphagnum* and other mosses overlying several inches of peat.

The depth of thaw is greatly influenced by the thickness of moss and peat. The degree the depth of thaw is influenced by the shade of shrubs and trees is uncertain. This is probably a relatively minor factor compared with the influence of moss and peat. This is supported by the air temperature observations obtained at the various sites during the summer of 1960. The mean daily air temperature at the sedge area (site 2) for the period of 30 June to 17 September 1960, which includes a major portion of the thawing period, was 53.2 °F. The mean daily air temperature for the same period at the forested area (site 5) was 54.2 °F although the depth of thaw was several feet less. The predominating influence of the moss and peat is demonstrated by comparing maximum depth of thaw at locations with widely different thawing indices. At Aklavik, N.W.T. (68° N), the mean thawing index is about 2 300; at Thompson, Manitoba (56° N), it is about 3 100. Nevertheless, the maximum depth of thaw in areas of thick moss and peat accumulation at each settlement is similar.

Precipitation also influences the depth of thaw and soil temperatures. No observations were made at Norman Wells and there is little available information in the literature. Russian observations (Shvetsov and Zaporozhtseva 1963) indicate that the situation is complex and that two factors should be considered. First, the amount of moisture in the soil immediately before it freezes in the autumn determines the ice content and depth of thaw the following summer. Second, the moisture content of the soil surface and the infiltration of atmospheric water influence the heat transfer to the frozen soil during the thaw period.

Weekly ground temperatures taken during the summers of 1959 and 1960

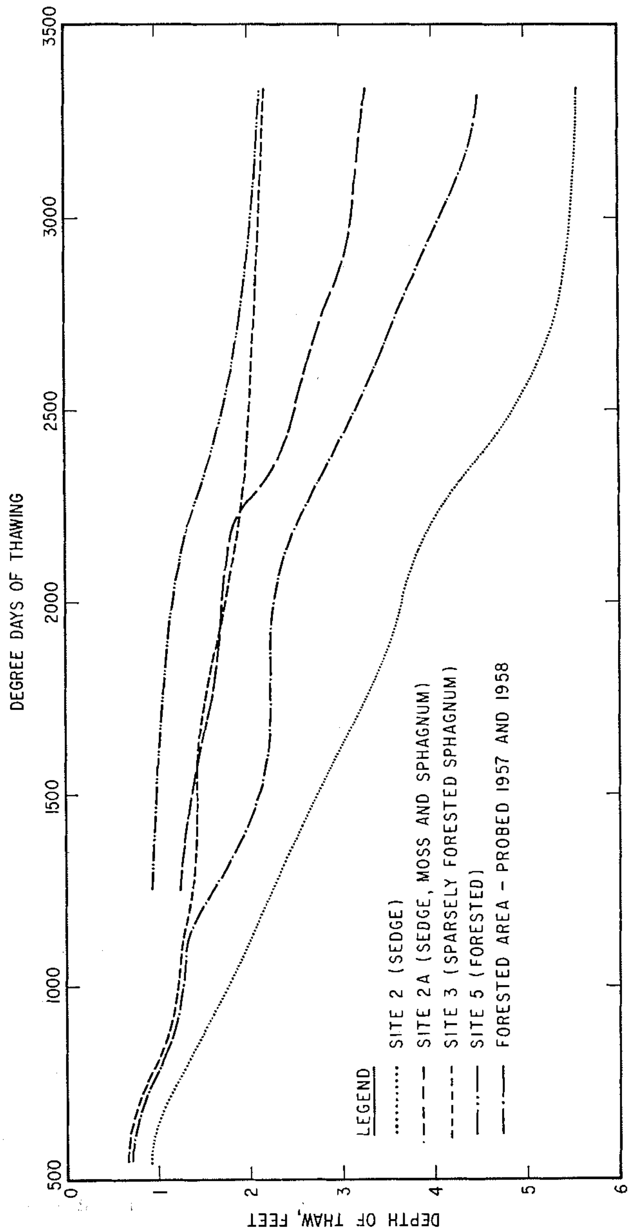


FIG. 7. Average depth of thaw vs. cumulative degree days of thawing at Norman Wells, N.W.T., 1957, 1958, 1959.

in the thawed layer above the permafrost showed that significant differences existed under different types of vegetation. The ground temperatures were the highest at site 1 and progressively less at site 2; in the treeless sedge area with a cover of *Sphagnum* and other mosses (site 2A); and at site 3. In August, site 3 had lower temperatures than site 5 and site 4 had higher temperatures. There appeared to be a general decrease in temperature with increased moss cover and peat thickness. Although the depth of thaw did not appear to be significantly less in areas shaded by trees, these areas experienced slightly lower temperatures in the thawed layer than treeless areas.

Ground temperatures were compared with degree days of thawing. The cooler nature of the 1959 summer was confirmed by the fact that the cumulative total of degree days of thawing on 30 September totalled 2 513 compared with 2 954 on 23 September 1960. A plot of ground temperatures vs. degree days of thawing did not produce similar patterns, however, for the two summers. For any given degree day total, the ground temperatures were much higher in the warmer summer of 1960. For example, in 1959, the temperature at the 12-in. depth at site 1 on 28 August was 46.6 °F, at which time the cumulative total of degree days of thawing was 2 232. Almost the same degree day total was reached on 5 August 1960 (2 202), at which time the temperature at the 12-in. depth was 54.5 °F.

Mosses and lichen maintain a high permafrost table. In summer, the air temperature frequently rises above 80 °F but the temperature beneath these plants remains close to 32 °F. At site 3, the *Sphagnum* exceeded 12 in. thickness at the location of the 12-in. thermocouple string so that its full length was in the *Sphagnum*. At site 4, the lichen was only 2 in. thick so that the 12-in. thermocouple string extended 10 in. below the lichen.

In 1959 the temperature gradients for the two strings were higher in the top 8 in., and lower in the bottom 4 in. This means that the gradient was uniform throughout the lichen and the top few inches of the underlying peat, in contrast to the *Sphagnum* where the gradient changed in the *Sphagnum* itself.

In 1960 the same large differences between surface temperatures and temperatures at the lower end of the thermocouple strings were evident. The chief difference between the two summers was that temperature profiles in 1960 showed changes in gradient at about the 4- or 5-in. depth in contrast to the 8-in. depth in 1959. In all cases, the temperature observed at the surface of the *Sphagnum* and lichen was several degrees higher than the screen air temperature observed at the time of the ground temperature readings.

In 1959, the temperatures observed at the 12-in. depth were the same in both the *Sphagnum* and lichen, but in 1960 the temperature at the bottom of the thermocouple string in the *Sphagnum* was consistently about 5 °F higher than in the lichen. It is difficult to know whether temperatures at the 12-in. depth actually varied by this amount between the two plant types or whether one of the thermocouple strings was faulty. It is possible that the thermocouple string in the moss was defective because the 12-in. thermocouple gave unreliable readings and the 11-in. thermocouple was used instead. The readings on the lichen were probably closer to reality but even they were about 4 °F higher than temperatures observed at the 12-in. depth in the wooded area.

Taking all the weekly readings from 28 August to 30 September 1959, which was the period when the depth of thaw reached its maximum and the differences caused by variations in vegetative cover were most pronounced, the average temperature at the 1-ft depth was calculated. It was noted in the hourly readings taken at site 1 (mentioned below) that over a 24-hour period the temperature fluctuation at the 1-ft depth was 1.5 °F. All the ground temperature readings at the various sites were taken between 9.00 a.m. and 4.00 p.m. during which period the temperature fluctuation at the 1-ft depth at site 1 was 0.8 °F. (This would probably be as large a variation as would ever occur during the summer because it was measured through a day which was clear with a large air temperature fluctuation.) The mean air temperature for this period was 41.2 °F. The mean ground temperatures were as follows:

Site 1	(Kentucky bluegrass)	40.0 °F
Site 2	(sedge)	36.5 °F
Site 2A	(sedge, moss, *Sphagnum*)	35.0 °F
Site 3	(sparsely forested *Sphagnum*)	33.7 °F
Site 3	(thick *Sphagnum*)	32.5 °F
Site 4	(lichen)	32.6 °F
Site 5	(forested)	32.8 °F

The lichen and *Sphagnum* had approximately the same average temperature over this period although the lichen was only 2 in. thick in contrast to the 12 in. of *Sphagnum*, both overlying similar thicknesses of peat.

Means of the weekly temperatures at the various depths for different time periods were calculated for 1960. Mean ground temperatures and ground temperature fluctuations for the period of 15 July to 16 September are plotted in Fig. 8 showing them to be much higher at sites 1 and 2 than under the *Sphagnum* and other mosses at site 5. Differences between the mean air and mean ground temperatures at the 12-in. depth at the various sites for the period of 28 August to 30 September 1959 were compared with the differences for the period of 15 July to 16 September 1960. The differences were:

Site 1	(Kentucky bluegrass)	1.2 °F (1959),		3.3 °F (1960)
Site 2	(sedge)	4.7 °F (1959),		5.6 °F (1960)
Site 3	(thick *Sphagnum*)	8.7 °F (1959),	about	12 °F (1960)
Site 4	(lichen)	8.6 °F (1959),	about	17 °F (1960)
Site 5	(forested)	8.4 °F (1959),		19.8 °F (1960)

This appears to confirm the thermal resistance of the moss and lichen because the much higher air temperature means in 1960 did not cause ground temperatures that were much higher than those recorded in 1959.

In 1959, a series of 27 consecutive hourly observations of screen air temperature, ground surface temperature, and temperatures at depths of 3, 6, 9, 12, 36, and 60 in. were taken at site 1 from 9.00 a.m. 14 August to 11.00 a.m. 15 August. A plot of these observations showed that the largest temperature

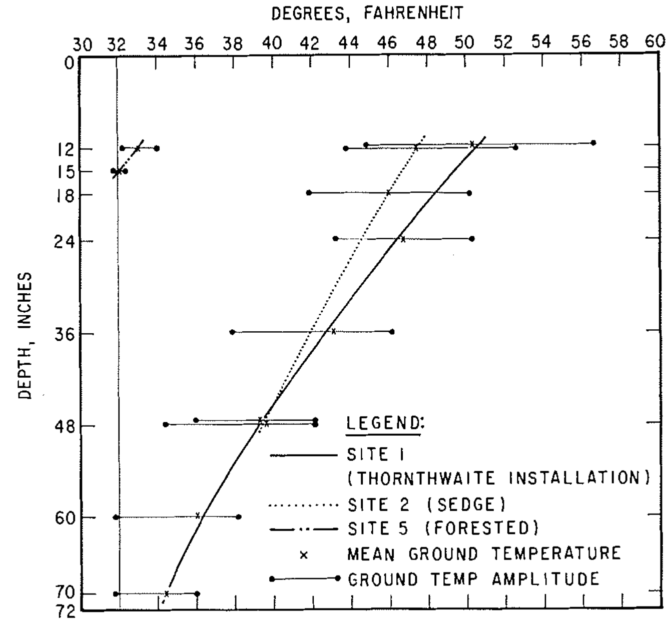


FIG. 8. Mean ground temperatures and ground temperature fluctuations (15 July to 16 September 1960).

fluctuations occurred in the air and at the soil surface; fluctuations decreased progressively with soil depth. The lag in maximum and minimum temperatures also increased with depth (Fig. 9).

Mean temperatures for the 24-hour period from 9.00 a.m. 14 August to 9.00 a.m. 15 August were calculated for the 3-, 6-, 9-, 12-, 36-, and 60-in. depths, the soil surface, and the screen air temperature (Fig. 10). A plot of the means on a graph indicates a linear decrease with depth from the surface to the frost table at the 60-in. depth and a decrease of amplitude. The highest mean temperature for the period occurred at the soil surface (52.9 °F) and the mean air temperature in the screen (51.7 °F) was almost the same as the ground temperature at the 3-in. depth (51.5 °F).

Weekly readings were taken in 1960 on the three thermocouple strings in permafrost from the end of July to 23 September. The means and fluctuations of the seven weekly sets of ground temperature readings taken in August and September 1960 are shown in Fig. 11. The lower summer ground temperatures under the moss and lichen as compared with the sedge are immediately evident. In addition, the temperature fluctuation in the top few feet is much greater under the sedge than under the moss or lichen.

CONCLUSIONS

1. The PE values computed from the evaporation recorded on the Alundum disc atmometer and from the Penman mass transfer formula compared favorably with the PE measured at the Thornthwaite installation during the 80-day

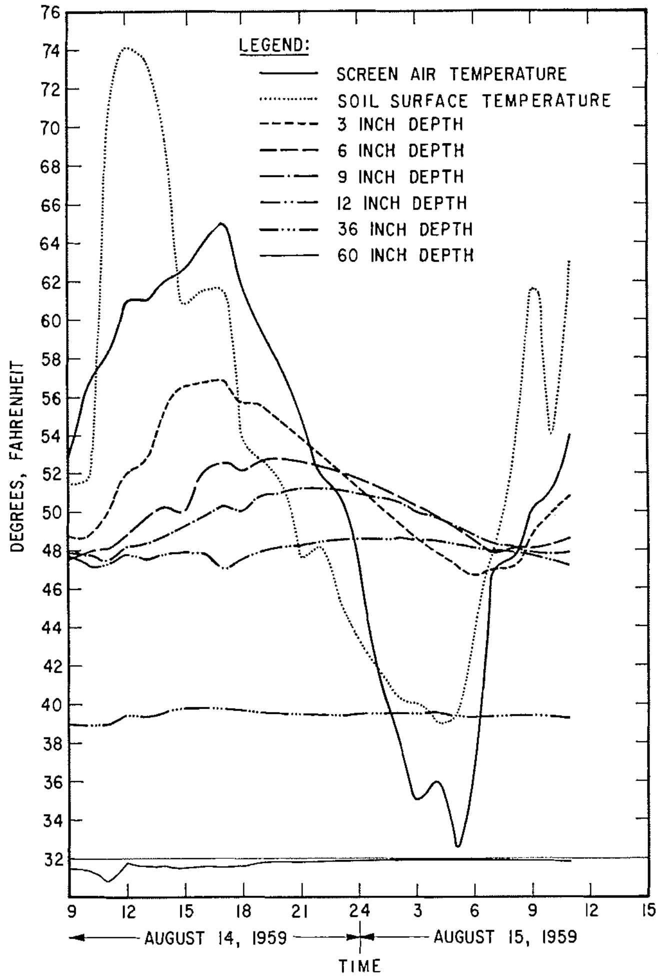


FIG. 9. Ground temperatures at site 1 (Thornthwaite installation) (hourly readings from 0900 on 14 August 1959 to 1100 on 15 August 1959).

period in 1960. There was not the same good correspondence in 1959 possibly because of the short observation period, only 17 days. The PE measured at the oil drum evapotranspirometer, and the PE computed from the Thornthwaite formula and from the evaporation recorded at the class A pan, were considerably higher than the PE measured at the Thornthwaite installation in 1959 and 1960.

2. The measurement of PE by adding water to the surface of a small plot of vegetation and recording the overflow is questionable because the daily addition of water actually changes the climate of the vegetation under test. In addition, the results do not give a true representation of the natural moisture regime.

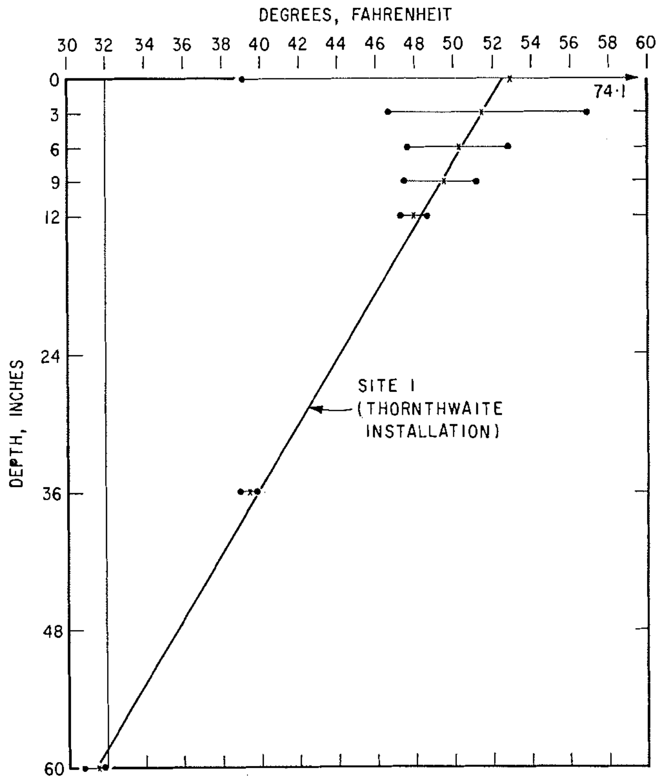


FIG. 10. Mean temperature of 24-hour period vs. depth at site 1 (Thornthwaite installation). (Hourly readings 0900, 14 August 1959, to 0900, 15 August 1959). Mean air temperature for this period +51.7 °F with fluctuations from 65.0 °F to 32.5 °F.

3. The use of very small test plots such as oil drums for measuring PE is questionable because the edge effect is so pronounced that it probably changes the evapotranspiration.

4. Despite the difficulties of measuring evaporation (including PE), it appears that the grass-like sedge, moss, and lichen at Norman Wells gave significantly lower PE results than the Kentucky bluegrass.

5. The economic net radiometer is a crude instrument capable only of spot measurements. A continuous recording net radiometer is required to measure the thermal energy entering the ground through the vegetative cover. Nevertheless, from the observations taken with the economic net radiometer, it appears that values are somewhat higher for *Sphagnum* and other mosses than for lichen. Because the thermal regime of the ground under moss and lichen appears to be similar, as manifested by similar depth of thaw and ground temperature regime, differences between the two plant types must occur in some other component of the energy regime which was not studied.

6. The depth of thaw under moss and lichen growing on peat was less than in areas supporting other types of plant growth.

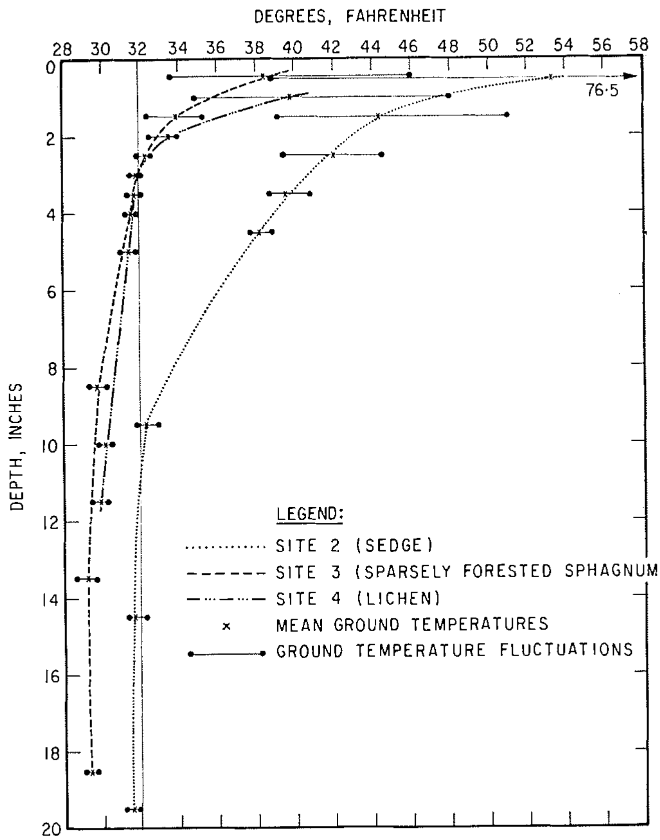


FIG. 11. Mean ground temperatures and ground temperature fluctuations (12 August to 23 September 1960).

7. Ground temperature observations in the thawed layer and in the perennially frozen ground showed that temperatures were lower in areas covered by moss and lichen than in areas supporting other types of plant growth.

The influence of climatic and terrain features is so complex and the features so closely interrelated that it is difficult to isolate each one or measure them accurately. The measurements at Norman Wells, described above, were carried out to provide some preliminary quantitative information on the relative importance of these features in the permafrost environment. More sophisticated instrumentation and a more comprehensive study program is required to obtain a complete picture of the permafrost regime and the role of the various features influencing it.

ACKNOWLEDGMENTS

The author gratefully acknowledges the assistance of J. C. Plunkett, C. J. English, and R. G. Clark in taking the daily readings. This paper is a contribution from the Division of Building Research, National Research Council, Canada, and is published with the approval of the Director of the Division.

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