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Publisher's version / Version de l'éditeur:

Proceedings: Permafrost International Conference, 1963, pp. 241-246, 1963-10-01

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RELATION BETWEEN MEAN ANNUAL AIR AND GROUND TEMPERATURES IN THE PERMAFROST REGION OF CANADA

BY

R. J. E. BROWN

31905

REPRINTED FROM
PROCEEDINGS: PERMAFROST INTERNATIONAL CONFERENCE
NOVEMBER 1963
P. 241 - 246

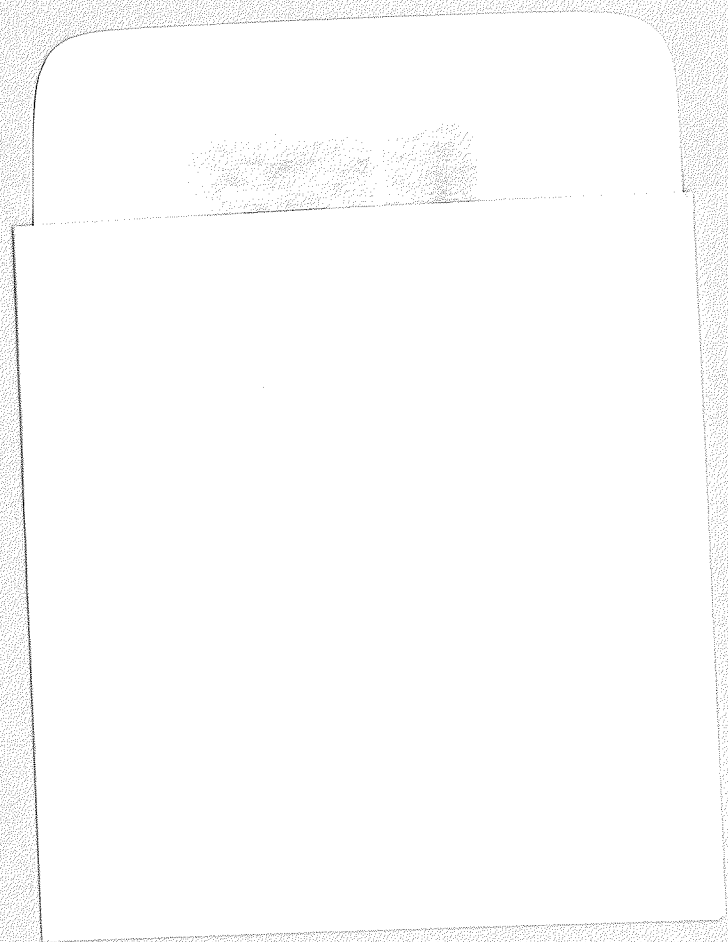
RESEARCH PAPER NO. 296
OF THE
DIVISION OF BUILDING RESEARCH

OTTAWA

OCTOBER 1966

PRICE 10 CENTS

NRC 9272



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SESSION V
THERMAL ASPECTS

RELATION BETWEEN MEAN ANNUAL AIR AND GROUND TEMPERATURES IN THE PERMAFROST REGION OF CANADA

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Climate is basic to permafrost formation and is a most important factor influencing the existence of this phenomenon. Of all climatic factors, air temperature is the most readily measured and is most directly related to ground heat loss and heat gain. Observations in Canada and other countries indicate a broad relation between mean annual air and ground temperatures in permafrost.

Many investigators have estimated the mean annual air temperature required to produce and maintain permafrost [1]. There is, however, much disagreement on this matter. Terzaghi reported that the southern limit of permafrost coincides very roughly with the 32°F mean annual air isotherm [2]. Black reported that, because of local conditions, the mean annual air temperature required to produce or maintain permafrost varies many degrees; he suggested that it is generally between 24 and 30°F [3]. Nikiforoff in his hypothesis of the origin of permafrost suggested that the southern boundary coincides approximately with the 28.4°F isotherm [4].

In Canada, the southern limit of permafrost as presently known lies between the 25° and 30°F mean annual air isotherms except in western Quebec [5] (Fig. 1). West of Manitoba, the known limit of permafrost coincides approximately with the 30°F isotherm. In Manitoba, however, it cuts eastward from the 30° to the 35°F isotherm. In Ontario it coincides with the 25°F isotherm. In western Quebec it lies north of the 25°F isotherm from whence it extends southeastward into southwestern Labrador (and perhaps even further southward). Although observations are limited, the southern limit appears to cross the 25°F isotherm in southern Labrador and then extend northeastward between the 25° and 30°F isotherms to the Atlantic coast.

Apparently, the mean annual ground temperature differs from the mean annual air temperature by several degrees and this difference is not constant. Hence, precise prediction of permafrost distribution cannot be based solely on this factor.

Attempts have been made to relate permafrost distribution in Canada with freezing indexes [6, 7, 8] and thawing indexes [6, 7]. These indexes reflect annual fluctuations of air temperature about the freezing point and indicate the amount of heat added to and withdrawn from the ground. A station with a mean annual air temperature of 32°F will therefore have equal freezing and thawing indexes. As with mean annual air temperature, there is a broad relation between permafrost distribution and these indexes, but accurate prediction of permafrost occurrence cannot be based solely on this factor because of the influence of other climatic and terrain factors [1].

Nevertheless, a review of the literature and examination of the known southern limit of permafrost, shows some general correlation between mean air and ground temperature as indicated by the correspondence between certain isotherms and the permafrost boundary as well as by other evidence [1, 6].

INFLUENCE OF TERRAIN AND OTHER CLIMATIC FACTORS

The difference between mean annual air and ground temperature, and variations in this difference from place to place are caused by climatic factors other than air temperature in combination with surface and subsurface terrain factors. The complex energy exchange regime at the ground surface, which is influenced by these factors, is such that the mean annual ground temperature is several degrees warmer than the mean annual air temperature. Factors which seem particularly influential are net radiation, vegetation, snow cover, and ground thermal properties that vary with time; other factors include relief slope and orientation and surface and subsurface drainage.

The difference between mean annual air and ground temperature can be explained in part by the fact that the ground surface is heated by solar radiation during the day to a much higher temperature than the air above; this excess heating more than balances the cooling of the ground surface by radiation during the night. Snow cover contributes to this situation by insulating the soil from the cold air above [9].

It is suggested that the difference between mean annual air and ground temperature would be greater in interior continental localities than in maritime locations because of the greater snowfall and accumulation in the former areas [10].

Variations in net radiation, vegetation, snow cover, and other factors contribute to observed differences in the thickness and temperature of permafrost in neighboring areas of the continuous zone having similar mean annual air temperature; they also help explain the patchy occurrence of permafrost at a particular location in the southern fringe of the permafrost region. The mean ground temperature in permafrost can vary at any given depth within a region of only a few square miles due to variations in surface cover, ground type, moisture content, geological structure, or geothermal gradient. In the discontinuous zone, variations in mean ground temperature frequently occur between the middle and edge of an individual body of permafrost.

Fluctuations in the permafrost boundary generally within confines of the 25 and 30°F mean annual air isotherms across Canada, and local variations in the permafrost within a small area, appear to be influenced by microclimatic and terrain features. Heavy snowfall in late autumn east of Hudson Bay may be responsible for the absence of permafrost at latitudes similar to those west of Hudson Bay where permafrost is widespread and late autumn snowfall is considerably less [6].

GROUND TEMPERATURE REGIME IN PERMAFROST

In permafrost, the temperature decreases steadily from the ground surface to a depth of about 50 to 100 ft [11]. Below this depth, the permafrost temperature increases steadily under the influence of heat from the earth's interior. Fluctuations in air temperature during the year produce a temperature oscillation in the ground to depths on the order of 50 ft with a time lag increasing with depth. At these depths, temperature variation is extremely small (less than 0.1°F); this is referred to as the "level of zero annual amplitude." Below this depth, influence of the annual air temperature cycle is not felt and ground temperatures change only in response to long-term changes extending over many centuries. Use of the present mean annual air temperature to predict the mean annual ground temperature at depths below the level of zero annual amplitude is complicated by the latter temperature being a reflection of both present and past climatic regimes (with possibly different mean annual air temperatures).

A change in mean annual air temperature can result, over a long time, in a significant change in the extent and thickness of permafrost. Observations from Canada, Alaska, and

the USSR show that the geothermal gradient can vary within wide limits (1°F/40 ft to 1°F/300 ft) depending on thermal properties of soil and rock, geological structure, and other factors. In the Mackenzie River delta, Canada, W. G. Brown [12] found a geothermal gradient of 1°F/53 ft. Misener [13] observed a geothermal gradient of 1°F/46 ft at Resolute, NWT, in the Canadian Arctic archipelago. At Point Barrow, Alaska, geothermal gradients of 1°F/42 ft and 1°F/53 ft were found in an oil well [14] and beneath a small lake [15], respectively. Geothermal gradients ranging from 1°F/72 ft to 1°F/324 ft, depending on rock type, were observed in the Lena River basin, Siberia [16].

The lower values observed in North America may be attributed partly to the proximity of large bodies of water in contrast to those in the USSR which were mostly in inland watersheds. Shpolyanskaya [17] reported values in the Transbaikal region of the USSR which are of the same order of magnitude as those cited from Canada and Alaska: 1°F/37 ft in sedimentary rock and 1°F/92 ft in dense crystalline rock. Therefore, a change of 1°F, for example, in the mean annual air temperature could result over a long time in a change of 1°F in the mean annual ground temperature. This would cause a change in permafrost thickness of approximately 40 to 300 ft, depending on the geothermal gradient.

MEAN ANNUAL AIR AND GROUND TEMPERATURES IN CANADA

At present, ground temperature observations are available from 17 locations in Canada's permafrost region (Fig. 1). The latitude, longitude, height above sea level, permafrost distribution and thickness, and mean annual air temperatures of these stations are listed in Table I. Information is given also for Ottawa which is south of the permafrost region. Ground temperature values are listed in Table II.

At some of these stations the records are either of short duration, contain gaps, or are of questionable reliability due to observer error or instrument difficulties; thus, only approximate mean annual ground temperature values can be given. In some cases, the ground temperatures may not have had time to return to their original values prior to disturbance by installation procedures. In addition, an excess of drilling wash water frozen around a temperature cable in a hole would change the thermal diffusivity of the ground being measured from the surrounding undistrubed ground sufficiently to affect ground temperature observations.

DISCUSSION

Results of Observations

Most of the temperatures reported were measured under difficult field conditions and are of questionable precision so that only general relationships can be deduced. These ground-temperature measurements suggest that there is not a constant difference between them and the mean annual air temperatures. There is no instance, however, of the latter being higher than the former. Some of the ground temperature observations are either single observations or averages for only part of a year. As a result, the values vary slightly from the mean annual ground temperatures, the difference decreasing with depth to the level of zero annual amplitude where the difference should be negligible. Variations in temperature with depth are, of course, greatly influenced by the geothermal gradient, the magnitude of which varies from place to place.

In view of these factors, it is difficult to obtain a precise correlation between mean annual air and ground temperatures. Because the problem concerns variations in the ground thermal regime over a year or more, it is best to make measurements at a depth where the influence of short-term weather cycles

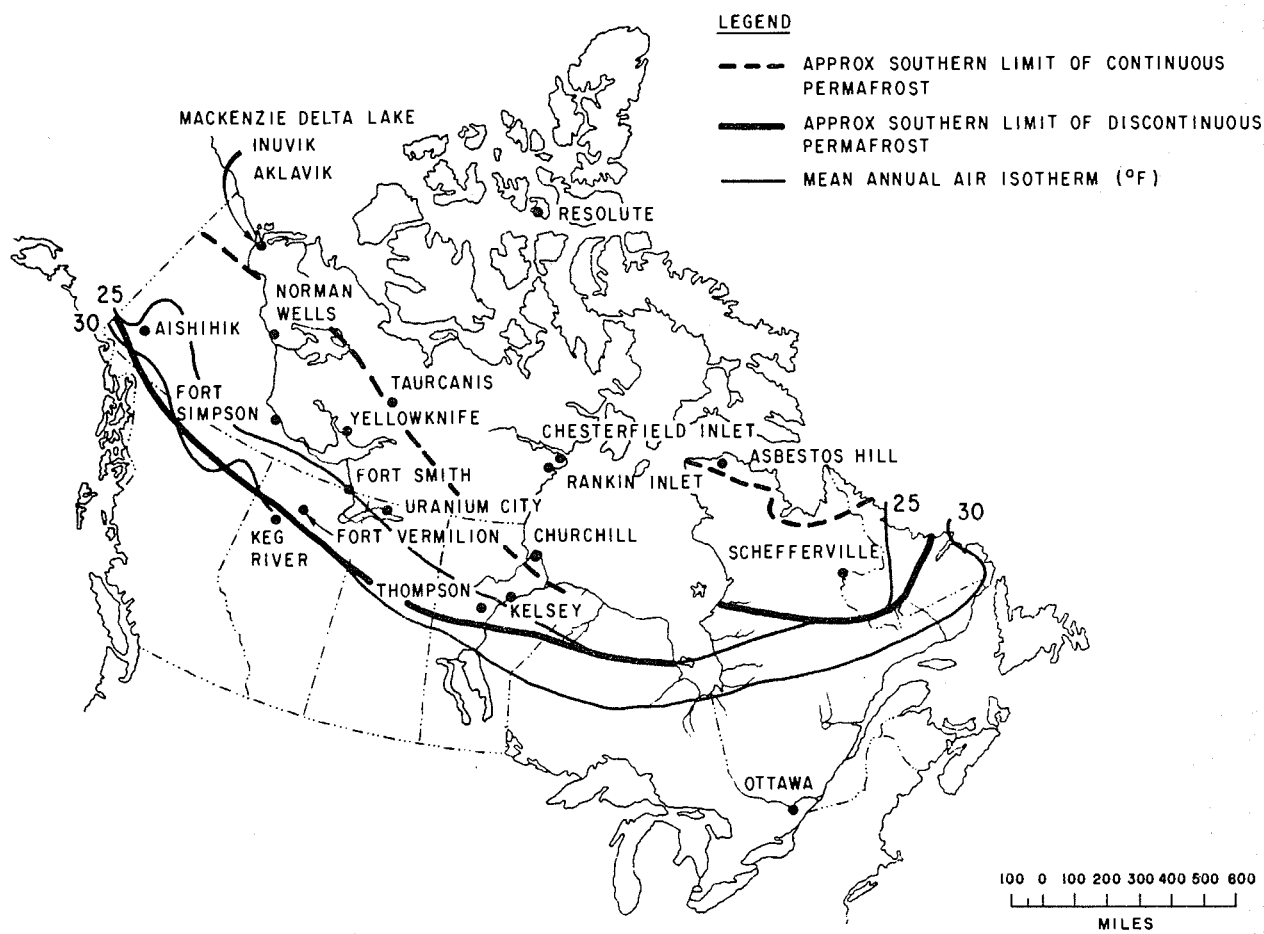

Fig. 1. Distribution of permafrost and ground temperature observation sites in Canada

will not be large (below about 2 ft). None of the ground temperature values (except Ottawa [38]) has been subjected to Fourier analysis because of the short duration of most of the observations and their uncertain accuracy. This type of analysis could be applied probably to the Fort Simpson and Fort Vermilion values.

Relation Between Air and Ground Temperatures

Air and ground temperature records show that the latter are warmer than the former by a wide range varying from about 1°F at Keg River, Alta., to 12°F at Taurcanis, NWT. Differences between mean annual air and ground temperatures are summarized in Table III.

Several factors complicate this situation: (a) Some individual ground temperature values above the level of zero annual amplitude may be higher or lower than the annual mean depending on the time of year and the depth. (b) Mean annual ground temperatures in permafrost decrease with depth from the ground surface to a depth of 50 to 100 ft and then steadily increase under the influence of the geothermal gradient. For example, the ground temperature in the Taurcanis mine of 29°F at the 325-ft depth is probably several degrees higher than the probable temperature at the level of zero annual amplitude.

Mean annual ground surface temperatures (1 cm depth) are available at three stations. Comparison with mean annual air temperatures showed differences of 8.0°F at Ottawa, Ont., 10.4°F at Fort Simpson, NWT, and 11.6°F at Fort Vermillion, Alta.

Differences between mean annual air and ground temperatures were examined in relation to the relative continentality of their location. Maritime stations include: Asbestos Hill, Que., Churchill, Man., and Rankin Inlet and Resolute, NWT. Differences at these stations did not appear to vary significantly from those at the other stations. Undoubtedly this is due to the lack of precision in computing the differences and the variable depths at which observations were made.

As already noted, the most southerly occurrences of permafrost with temperatures between 31° and 32°G, several tens of feet thick, and not restricted to a particular type of terrain, are found at such stations as Thompson, Man., Kelsey, Man., and Uranium City, Sask. All these locations have mean

Table I.

Location	Lat. N	Long. W	Ht, asl[a] (ft)	Permafrost Zone	Permafrost Thickness, (ft)[b]	Source	Mean Ann. Air Temp., (°F)
1. Aishihik, Y.T.	61°39'	137°29'	3170	Discontinuous (Widespread)	50 to 100	[18]	24.5
2. Asbestos Hill, P.Q.	61°50'	73°45'	1650	Continuous	>930	[19]	17
3. Churchill, Man.	58°46'	94°08'	80	Continuous	100 to 200	[18] [20]	19
4. Fort Simpson, NWT.	61°52'	121°21'	415	Discontinuous (Patchy)	about 40	[18] [21]	25.0
5. Fort Smith, NWT.	60°01'	111°58'	665	None	. . .	DBR[c]	26.2
6. Fort Vermilion, Alta.	58°23'	116°03'	950	None	. . .	[22]	28.2
(Keg River, Alta.)	57°47'	117°50'	1402	Discontinuous	about 5	[23]	31
7. Inuvik, NWT.	68°18'	133°29'	198	Continuous	>300	DBR[c]	. . .
(Aklavik, NWT.)	68°14'	135°00'	30	Continuous			15.6
8. Kelsey, Man.	56°02'	96°32'	600	Discontinuous (Patchy)	about 30	DBR[c]	25.5
9. Mackenzie Delta Lake, NWT.	68°19'	133°50'	35	Continuous	250 to 300	[24]	15.6 (Aklavik)
10. Norman Wells, NWT.	65°18'	126°49'	240	Continuous or Discontinuous (Widespread)	150 to 200	DBR[c] [25] [26]	20.8
11. Rankin Inlet, NWT.	62°49'	92°05'	. . .	Continuous	about 1000	[27]	. . .
(Chesterfield Inlet, NWT.)	63°21'	90°42'	13				11.2
12. Resolute, NWT.	74°41'	94°54'	56	Continuous	1300	[13]	2.8
13. Schefferville, P.Q.	54°49'	66°41'	1605	Discontinuous (Widespread)	>250	[28] [29]	23.9
14. Taurcanis, NWT.	64°02'	111°10'	. . .	Continuous	900	[30]	17
15. Thompson, Man.	55°36'	98°42'	700	Discontinuous (Patchy)	about 50	[31] [32]	24.9
16. Uranium City, Sask.	59°34'	108°37'	. . .	Discontinuous (Patchy)	about 30	DBR[c]	24
17. Yellowknife, NWT.	62°28'	114°27'	682	Discontinuous (Widespread)	200 to 300	[27]	22.2
18. Ottawa, Ont.	45°28'	75°38'	180	None	. . .	. . .	41.6

[a] Height above sea level
[b] Permafrost thicknesses based on information reported to 1963
[c] Division of Building Research, Canada

Table II.

Location	Depth (ft)	Mean Ann. Ground Temp. (°F)	Ground Temp. (°F)	Observation Dates	Source
1. Aishihik, Y.T.	20	28.3	. . .	1953-1959 (weekly)	DTC[a]
2. Asbestos Hill, P. Q.	50	. . .	19.6	Average of two readings 15 Apr. '62 and 8 July '62	DBR[b]
	100	. . .	19.6		
	200	. . .	19.6		
3. Churchill, Man.	25	. . .	27.5	July 1955	[33]
	54	. . .	28.9		
4. Fort Simpson, NWT.	1 cm	35.4	. . .	1959-1962 (daily)	[34]
	10 cm	34.9	. . .		
	20 cm	34.1	. . .		
	50 cm	34.6	. . .		
	100 cm	33.7	. . .		
	150 cm	33.2	. . .		
5. Fort Smith, NWT.	about 15	about 32	. . .	1950's	DBR[b]
6. Fort Vermilion, Alta.	1 cm	39.8	. . .	1959-1962 (daily)	[34]
	10 cm	38.9	. . .		
	20 cm	38.8	. . .		
	50 cm	38.9	. . .		
	100 cm	38.9	. . .		
	150 cm	38.9	. . .		
Keg River, Alta.	about 5	a few tenths below 32	. . .	Sept. 1963	DBR[b]
7. Inuvik, NWT.	47	25.9	. . .	1955-1958 (weekly)	[35]
townsite	25	26.8	. . .	1961-1963 (weekly)	DBR[b]
	50	26.6	. . .		
	100	26.7	. . .		
road to Hidden Lake	22	. . .	23.9	22 Sept. '62	DBR[b]
	47	. . .	24.5		
	97	. . .	25.4		
8. Kelsey, Man.	down to 30	30.5 to 31.5		1958-1963 (weekly)	DBR[b]
9. Mackenzie Delta Lake, NWT.	50	. . .	25.4	6 May 1961	DBR[b]
	75	. . .	25.9		
	100	. . .	26.5		
	150	. . .	28.0		
	200	. . .	29.2		
	surface	23.8 (calc.)	. . .		[12]
10. Norman Wells, NWT. 900 ft from river	60	. . .	28.6	1947-1948	[26]
	100	. . .	28.6		
	180	. . .	31.7		
	200	. . .	32.0		
100 ft from river	50	. . .	26.0	1958-1962	DBR[b]
	100	. . .	28.5		
11. Rankin Inlet, NWT.	about 100		about 15 to 17	1960	[27]
12. Resolute, NWT.	50	10.0	. . .	1954-1957 (weekly)	[13]
	100	8.5	. . .		[36]
13. Schefferville, P. Q.	25	30.7	. . .	1962 (weekly)	MSRL[c]
	50	30.2	. . .		
	100	30.3	. . .		
	140	30.6	. . .		
	190	31.7	. . .		
14. Taurcanis, NWT.	325	. . .	29	1961	[30]
15. Thompson, Man.	down to 25	31 to 32	. . .	1961-1963 (weekly)	[31]
16. Uranium City, Sask.	down to 30	31 to 32	. . .	1954-1957 (weekly)	DBR[b]
17. Yellowknife, NWT.	2.3	33.0	. . .	1954-1957 (weekly)	[37]
	4.3	32.4	. . .		DBR[b]
	6.3	32.5	. . .		
	8.3	31.4	. . .		

Table II. (continued)

Location	Depth (ft)	Mean Ann. Ground Temp. (°F)	Ground Temp. (°F)	Observation Dates	Source
18. Ottawa, Ont.	1 cm	49.6	. . .	1959-1962 (daily)	[34]
	10 cm	49.0	. . .		
	20 cm	47.9	. . .		
	50 cm	48.5	. . .		
	100 cm	48.6	. . .		
	150 cm	48.6	. . .		

[a]Department of Transport, Canada
[b]Division of Building Research, Canada
[c]McGill Subarctic Research Laboratory

annual air temperatures of about 24° to 25°F. An exception to this is Aishihik, Y.T., whose mean annual air temperature of 24.5°F is comparable, but the mean annual ground temperature of 28.3°F at the 20-ft depth is several degrees lower than the ground temperatures at the other three stations. However, a mean annual air temperature of, say 25°F or less, is almost certain to indicate a permafrost condition in the vicinity.

The question arises again as to what is the maximum mean annual air temperature at which permafrost can exist. Permafrost, albeit only a few feet thick, is found at Keg River, Alta., which has a mean annual air temperature of 31°F. It does not occur in the vicinity of Fort Vermilion, Alta. (28.2°F), nor at Fort Smith, NWT (26.2°F), nor even at the Experimental Farm at Fort Simpson, NWT (25.0°F). Clearly vegetation plays a dominant role in this situation. Permafrost at Keg River is confined to a few small scattered spruce-Sphagnum peat bogs. No such bogs occur in the Fort Vermillion area. Permafrost exists also in similar bogs in the fort Smith and Fort Simpson areas.

The origin of permafrost in these bogs, particularly in Keg River, could be attributed to one or more of the following causes:

(a) It could be a remnant from the cooler climatic regime of the Pleistocene;
(b) It could be short-lived permafrost of perhaps several decades duration which formed as a result of slightly lower air temperatures than those prevailing at present; and
(c) It could be short lived as in the second case but formed as the result of terrain changes such as snow cover or drainage which were conducive to initiation of permafrost without a change in mean annual air temperature.

In all three cases the permafrost is protected by moss and peat cover; it would probably disappear and not re-form if this cover were removed.

Thermal Mechanisms

Mechanisms which allow formation of permafrost in these bogs are associated with variations in heat exchange at the surface of the moss and peat. When dry, peat has a low thermal conductivity, equivalent to that of snow. When wet, its thermal conductivity is greatly increased; when frozen its thermal conductivity is many times that of dry peat. During summer, a thin surface layer of dried peat having a low thermal conductivity would prevent warming of the underlying soil. During the cold part of year, the peat is saturated from the surface; when it freezes, its thermal conductivity greatly increases. Because of this the amount of heat transferred in winter from the ground to the atmosphere through the frozen ice-saturated peat is greater than the amount transmitted in the opposite direction through the surface layer of dry peat and underlying wet peat in summer. A considerable portion of heat is also required during the warm period to melt the ice and to

Table III.

Location	Mean Ann. Air Temp. (°F)	Ground Temp. (°F)	Approx. Air-Ground Difference (°F)
1. Aishihik, Y.T.	24.5	28.3 (20 ft)	4
2. Asbestos Hill, P.Q.	17	19 to 20 (50 ft to 200 ft)	2 - 3
3. Churchill, Man.	19	27.5 to 28.9 (25 ft to 54 ft)	8 - 10
4. Fort Simpson, NWT.	25.0	35.4 (surface) to 33.2 (150 cm)	8 - 10
5. Fort Smith, NWT.	26.2	About 32 (about 15 ft)	6
6. Fort Vermilion, Alta.	28.2	39.8 (surface) to 38.9 (150 cm)	10 - 11
(Keg River, Alta.)	31	A few tenths degree below 32 (about 5 ft)	1
7. Inuvik, NWT.	...	About 26 (25 ft to 100 ft)	10
(Aklavik, NWT.)	15.6		
8. Kelsey, Man.	25.5	30.5 to 31.5 (down to 30 ft)	5 - 6
9. Mackenzie Delta Lake, NWT.	15.6 (Aklavik)	23.8 (surface) to 26.5 (100 ft)	8 - 11
10. Norman Wells, NWT.	20.8	About 26 to 28.5 (50 ft to 100 ft)	5 - 8
11. Rankin Inlet, NWT.	...	About 15 to 17 (about 100 ft)	4 - 6
(Chesterfield Inlet, NWT.)	11.2		
12. Resolute, NWT.	2.8	10.0 (50 ft) to 8.5 (100 ft)	6 - 7
13. Schefferville, P.Q.	23.9	About 30 to 31.5 (25 ft to 190 ft)	6 - 8
14. Taurcanis, NWT.	17	29 (325 ft)	12
15. Thompson, Man.	24.9	31 to 32 (down to 25 ft)	6 - 7
16. Uranium City, Sask.	24	31 to 32 (down to 30 ft)	7 - 8
17. Yellowknife, NWT.	22.2	33.0 (2.3 ft) to 31.4 (8.3 ft)	9 - 11
18. Ottawa, Ont.	41.6	49.6 (surface) to about 48 (150 cm)	6 - 8

warm and evaporate the water. The net result is a negative imbalance of heat and conditions conducive to the formation of permafrost.

Snow Cover

The influence of snow cover on the variation between mean annual air and ground temperatures warrants separate consideration. This is illustrated by comparing mean annual air and ground temperatures at Fort Simpson, NWT; Fort Vermilion, Alta., and Ottawa, Ont., all located at Dominion Experimental Farms of the Canadian Department of Agriculture. Despite similarities in vegetation and soils, differences between mean annual air and ground surface temperatures (1 cm depth) for the period 1959 to 1962 vary among the three stations—Fort Simpson, 11.2°F; Fort Vermilion, 9.7°F; and Ottawa, 7.0°F.

Significant differences in snow cover could account for these variations. Average monthly snow cover depths for October to December when winter frost penetration is initiated are 5.9, 3.2, and 1.3 in. for Fort Simpson, Fort Vermilion, and Ottawa, respectively.

Average monthly snow cover depths for April and May when air temperatures rise above 32°F and initiate thawing of the frozen ground are 11.2, 2.9, and 0.0 in., respectively. Therefore, the snow cover would have the greatest effect at Fort Simpson and the least at Ottawa. It is difficult to estimate, however, the net effect of the relative amounts of snow cover during the freezing and thawing periods on mean annual ground temperatures.

Snow cover reduces the amount of solar radiation received at the ground surface thus affecting the differences between mean annual air and ground temperatures. Observations are available for Fort Simpson and Ottawa, and annual amounts of radiation received at both stations have about the same effect when considered in relation to snow cover. During May to September (1959 to 1962) when the ground was free of snow, the daily average incoming solar radiation was about 470 g cal/sq cm at Ottawa and 425 g cal/sq cm at Fort Simpson—a difference of only 10%. During October to April (1959 to 1962) when the ground was snow covered at Fort Simpson and Ottawa for most of the period, solar radiation at Ottawa was about 225 g cal/sq cm and at Fort Simpson about 130 g cal/sq cm—a difference 1f 42%. The effect of this large difference would be practically nullified, however, by the snow cover at both sites.

CONCLUSION

It appears that an accurate prediction of mean annual ground temperature and the occurrence of permafrost at a site solely from the mean annual air temperature is subject to variations caused by other climatic and terrain factors already noted. Many more observations are required before anything more than a broad relation can be established. This is a formidable but, hopefully, not impossible task.

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