VOL. 41, NO. 2 (JUNE 1988) P. 99-104

Observations of the "Thermal Offset" in Near-Surface Mean Annual Ground Temperatures at Several Sites near Mayo, Yukon Territory, Canada

C.R. BURN[1] and C.A.S. SMITH[2]

(Received 20 May 1987; accepted in revised form 25 November 1987)

ABSTRACT. Temperature profiles in the surface layers of the ground were measured frequently over a 12-month period beginning in May 1984 at seven sites near Mayo, Yukon Territory. Permafrost is present at six of the sites. The mean annual ground temperature profile at each site displays a thermal offset, with measured mean annual temperatures in the active layer up to 1.7°C higher than in permafrost. Similar mean annual soil temperature profiles are presented from other stations in northern Canada and the U.S.S.R. Such near-surface inflections are not included in conventional models of the thermal regime of permafrost. The data indicate that equilibrium or aggrading permafrost may be present at sites where the mean annual ground surface temperature is above 0°C.

Key words: permafrost, soil temperature

RÉSUMÉ. On a mesuré fréquemment les profils de température dans les couches de surface du sol, sur une période de 12 mois commençant en mai 1984, à sept sites près de Mayo dans le Yukon. Le pergélisol est présent à six de ces emplacements. Sur tous, les profils des moyennes annuelles de température du sol montrent un décalage thermique: les moyennes annuelles de température mesurée dans la couche active sont de jusqu'à 1,7°C supérieures à celles du pergélisol. On décrit aussi des profils semblables de moyennes annuelles de température du sol, provenant d'autres stations situées dans le Grand Nord canadien et soviétique. Les modèles conventionnels du régime thermique du pergélisol ne tiennent pas compte de telles inflexions proches de la surface. Les données indiquent que le pergélisol stable ou alluvionnant peut être présent aux emplacements où la moyenne annuelle de la température de la surface du sol est supérieure à 0°C.

Mots clés: pergélisol, température du sol

Traduit pour le journal par Nésida Loyer.

INTRODUCTION

As part of an investigation into the origin of near-surface ground ice in permafrost terrain (Burn, 1986), the thermal regimes of seven sites near Mayo, Yukon Territory, were monitored at frequent intervals between 29 May 1984 and 1 June 1985. At each site, soil temperatures were measured on thermistors (YSI 44004), calibrated to ±0.1°C, at intervals of 15 cm to a depth of 2 m. The uppermost thermistor was installed 10 cm below the soil surface. Measurements were made twice weekly between 29 May and 3 September, at weekly intervals until 1 December and subsequently every fortnight until 1 April. Readings were taken twice weekly in April and twice in May 1985.

Mean temperature profiles were computed for the year at each site from these data. In each profile, a "thermal offset" of increasing temperature with proximity to the surface was noticed in the active layer, similar to that calculated by Gold *et al.* (1972), Gilpin and Wong (1975) and Goodrich (1978, 1982, 1983). The purpose of the present paper is to discuss the form of these profiles, to compare them with other examples and to comment briefly upon the significance of the observations. In particular, attention is drawn to differences between these profiles and those commonly used to describe the thermal regime of permafrost.

SITE CONDITIONS

Mayo (63°35′N, 135°35′W) has a mean annual air temperature of –4.0°C (Atmospheric Environment Service, 1982) and is in the widespread permafrost zone (Brown, 1978; Fig. 1). Equilibrium permafrost in the area is approximately 70 m thick (Smith and Burn, 1986). The village lies in the Stewart River valley, about 20 km east of the late-Wisconsinan, McConnell glacial limit (Hughes, 1983).

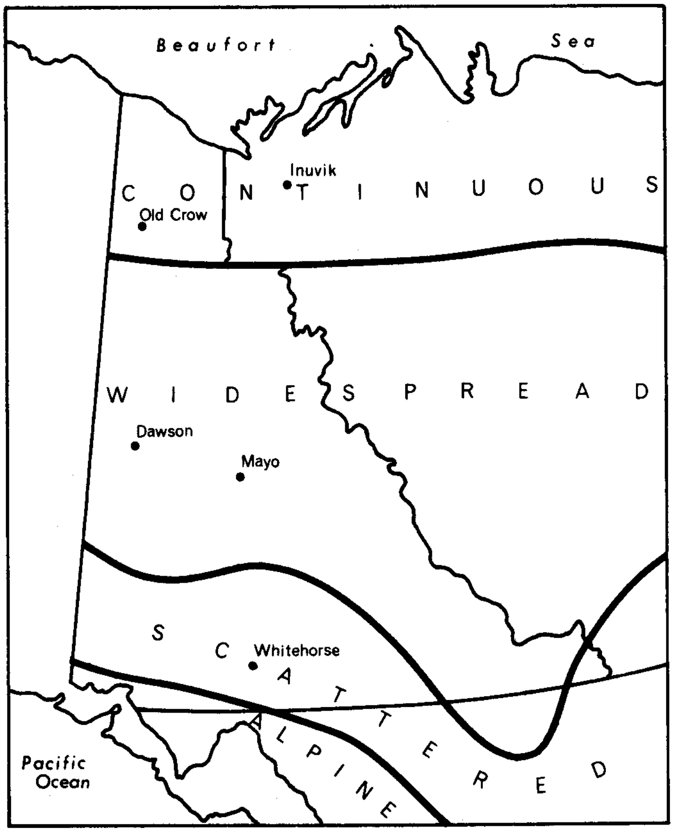

FIG. 1. Permafrost map of the Yukon Territory (after Brown, 1978).

The study area is located in a body of ice-rich glaciolacustrine sediments 3 km southeast of Mayo (see Burn *et al.*, 1986). Five

[1]Geotechnical Science Laboratories, Department of Geography, Carleton University, Ottawa, Ontario, Canada K1S 5B6; present address: Department of Geography, University of British Columbia, 217 - 1984 West Mall, Vancouver, British Columbia, Canada V6T 1W5
[2]Agriculture Canada, Land Resource Research Centre, P.O. Box 2703, Whitehorse, Yukon Territory, Canada Y1A 2C6

of the seven sites are located in this silt loam material (on average 2% sand, 74% silt, 24% clay); the sixth is in alluvial silt loam deposits of the Stewart River flood plain (20% sand, 70% silt, 10% clay); and the seventh is in the medium-textured, colluvial loam-silt loam (40% sand, 50% silt, 10% clay) of a recently (1952) drained lake, which is only frozen seasonally.

Geotherm plots of the annual ground thermal regime at sites 1 and 3, the sites with coldest and warmest winter temperatures, are presented in Figure 2. Site 3 is located in sediments

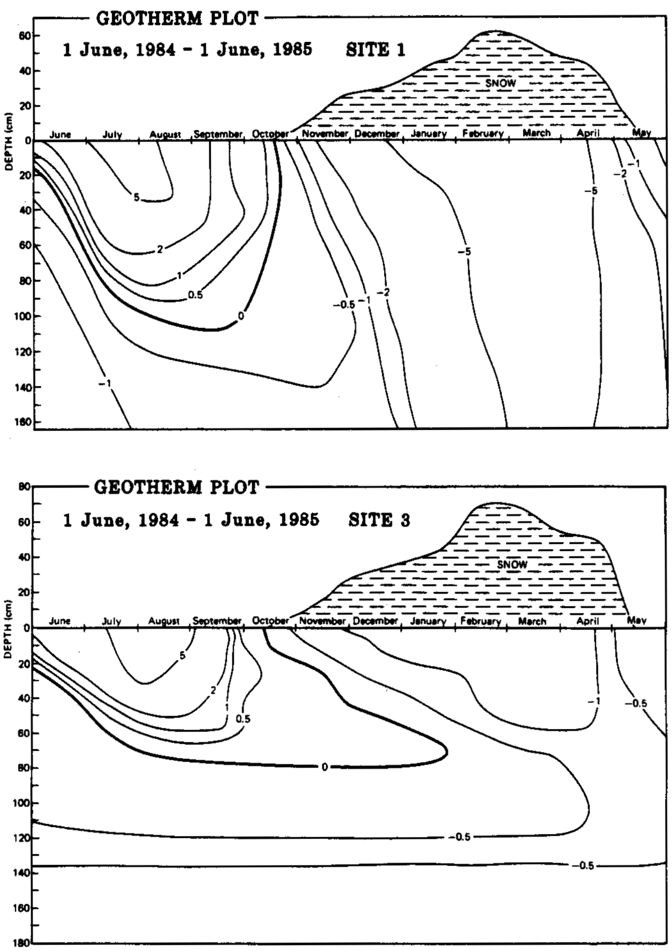

FIG. 2. Soil thermal regime, 1 June 1984 to 1 June 1985, at Mayo sites 1 and 3. Geotherms in °C.

emerging from a thermokarst lake, where permafrost is aggrading. A characteristic feature at all study sites was the slow freezing of pore water below 50 cm, which extended the −0.5°C geotherm past late November. The slower cooling rate coincided with snow accumulation at the sites. Table 1 contains a summary of the surface conditions at each site.

A majority of the sites (1, 2, 4, 5, 6) are located in the white spruce forest that dominates the study area. At these locations, up to 25 cm of *Hypnum* spp. peat-moss covers the mineral soil. However, site 3 is grass-covered and surrounded by willow bushes 2 m high, which act as a snow trap in winter. Site 7 is located in a clump of birch trees, where the ground surface is covered with leaf litter.

Mean monthly temperatures and total precipitation recorded at Mayo during the period were close to normal, except in

TABLE 1. Surface conditions at study sites, Mayo, Yukon Territory

Site	Soil texture	Organic matter (cm)[a]	Mean active layer moisture content ($cm^3 \cdot cm^{-3}$)[b]	Maximum snow depth (cm)[c]
1	Silty clay	10	0.38	60
2	Silt loam	10	0.33	50
3	Silty clay/loam	4	0.39	70
4	Silt loam	25	0.40	75
5	Silt loam	20	0.35	46
6	Silt loam	10	0.34	38
7	Loam	10	0.28	57

[a] Thickness of surface organic layer.
[b] Data from drill core samples collected in July 1983.
[c] 2 March 1985.

January 1985, when the mean air temperature was 19.6°C higher than the long-term mean. However, the freeze-back period (October to December) was slightly cooler than normal (2°C each month) and the snow cover at the sites moderated the effect of such warming on ground temperatures. At 10 cm, these were within 3°C of those recorded in January 1984 at all sites. In terms of the ground thermal regime, therefore, the year probably conformed reasonably to normal conditions.

MEAN ANNUAL GROUND TEMPERATURES

Mean annual ground temperatures and the maximum active layer depth at each site are presented in Figure 3. Mean temperatures were calculated by averaging values recorded over the year, with appropriate weight attached to each value to accommodate the varying intervals between observations. A "thermal offset," consisting of higher mean annual temperatures in the upper portion of the active layer than in permafrost, is observed at all sites. Kudriavtsev and Melamed (1972) and Goodrich (1978, 1982) have suggested that the offset may be due to the higher thermal conductivity (λ) of moist soil when frozen than when thawed (see Farouki, 1981) and that the offset may be enhanced by the moderating influence of snow cover on ground temperatures in winter (Smith, 1975; Goodrich, 1982). In addition, any drying of the soil in summer will augment the seasonal change in λ further, and both downward movement of "warm" active-layer water in summer and upward movement in winter (Mackay, 1983) may reinforce the asymmetry of seasonal ground temperature profiles. The offset is compatible with conditions of thermal equilibrium or, neglecting the geothermal flux, zero net annual heat flux. Similar near-surface mean annual ground temperature profiles have been reported by Goodrich (1983: Figs. 9-11) from a section of the Mackenzie Highway near Wrigley, N.W.T.; others are described below.

The data presented here indicate the magnitude of the offset at relatively undisturbed sites under a "natural" thermal regime. Between 10 cm and the base of the active layer the offset varies from 0.4°C (site 2) to 1.7°C (site 4). These extremes represent dry and wet soil conditions, where the seasonal change in λ should be relatively small and relatively large. If the mean annual temperature curve is extrapolated to the surface, these offsets increase to 0.5 and 2.1°C. Projected values for the mean annual ground surface temperature (T_s) at each site are included in Figure 3.

The profiles in Figure 3 indicate that the offset terminates a short distance below the base of the active layer, at which depth there is little seasonal change in λ (Goodrich, 1978, 1986). At

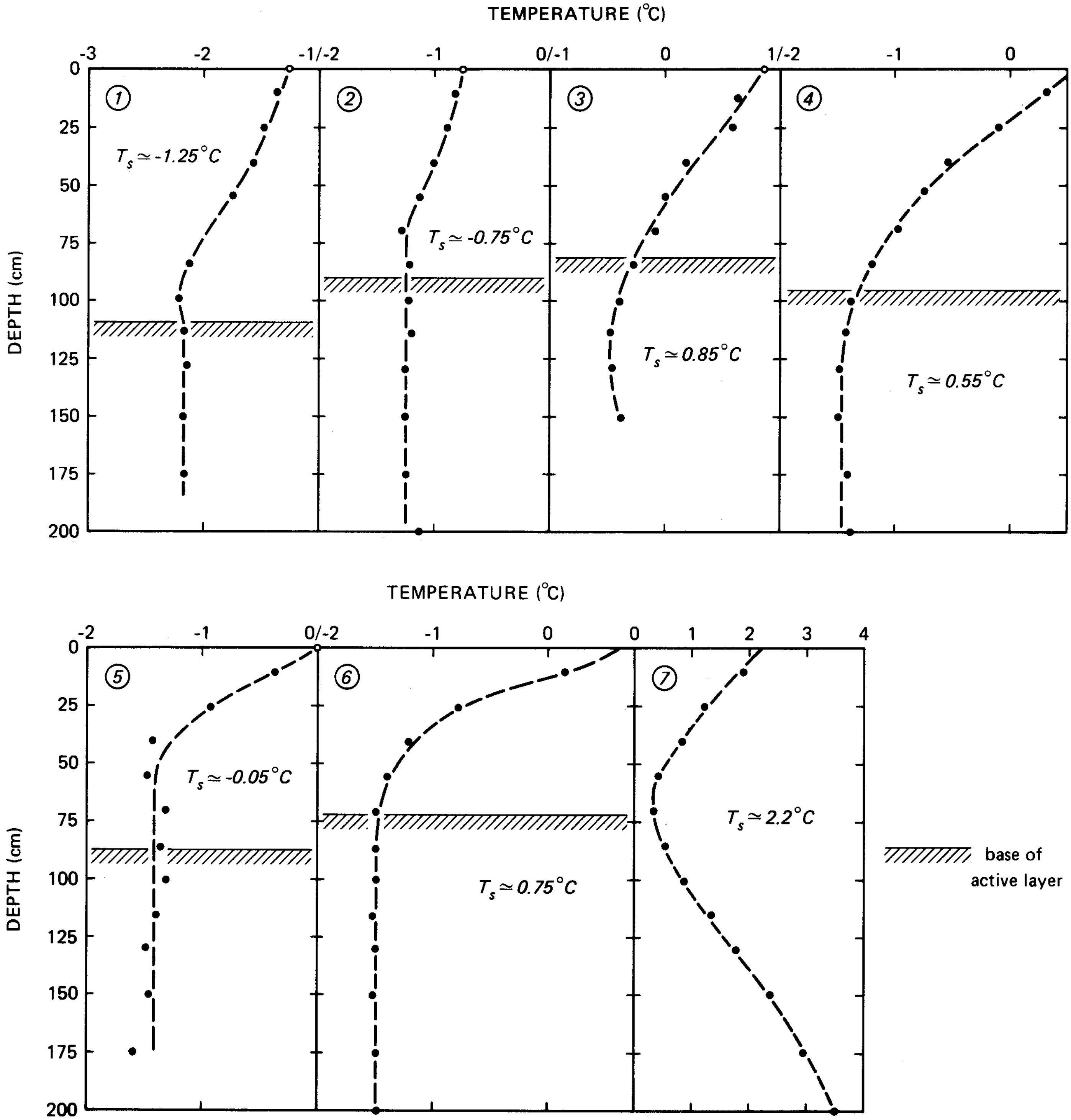

FIG. 3. Mean annual temperature profiles at Mayo sites 1-7, with active layer depths and projected values for T_s at each site. Active layer depths were determined from thermistor readings in late-September and October 1985.

site 3 the offset continues into permafrost, since the temperature range — e.g., –0.65 to –0.08°C at 85 cm — leads to considerable seasonal variation in soil thermal properties (see Kay *et al.*, 1981). The offset is also observed in the seasonally frozen layer at site 7. The mean annual temperature gradient below the offset at this site is 2.7°C·m^{-1}, two orders of magnitude greater than the geothermal gradient in the region (0.023°C·m^{-1}; Burgess *et al.*, 1982). This suggests that the warm temperatures are a residual feature of the lake talik.

It is important to note that the thermistors were read in the morning and early afternoon (PDT). The time lag, with depth, for the propagation of a sinusoidal surface temperature wave is

$z\sqrt{(\frac{1}{2}\kappa\omega)}$, where z is the depth (m), κ is the thermal diffusivity of the layer ($m^2 \cdot s^{-1}$), and ω is the angular velocity of the wave (s^{-1}). In this case, the time lag of the diurnal surface temperature wave at 0.1 m is over 5 hours, since $\omega = 7.27 \times 10^{-5} \cdot s^{-1}$, and $2.5 \times 10^{-7}\ m^2 \cdot s^{-1}$ may be a reasonable value for κ (unfrozen) of peat at the study sites (Riseborough, 1985). Twenty-four hourly measurements of (shielded) air temperature 4 cm above the ground surface made on 25/26 June 1982 under clear conditions indicated that mean diurnal surface temperature may be reached about 1030 PDT. Since thermistor readings were always completed by 1500 PDT in summer, the measurements, at depths of 10 cm and below, underestimated mean daily ground temperatures. Therefore, the thermal offsets presented in Figure 3, and the associated estimates of mean annual ground surface temperature, are conservative approximations of these phenomena.

OTHER OBSERVATIONS

Tarnocai (1984) has presented mean annual soil temperatures from eight sites near Inuvik, N.W.T., all of which indicate higher mean annual temperatures at the ground surface than at depth. Differences of up to 2.8°C between mean annual soil temperatures at a depth of 2.5 cm and lower in the profile (50 or 100 cm) were recorded. Brown (1973) and Nicholson and Granberg (1973) presented mean annual ground temperature profiles from several sites in northern Canada, but thermal offsets are not ubiquitous in these profiles, in part because the measurements closest to the surface are at depths of 0.5 or 1 m, where the offset may not be apparent (cf. Fig. 3). At some sites temperatures increased with depth in the upper layers of permafrost, perhaps because of local factors, such as a particularly thin snow cover. In addition, the interval between observations (one month for Brown's [1973] data, but not mentioned by Nicholson and Granberg [1973]) may have been too great to include brief, particularly warm summer periods in the annual mean. We may also note that mean annual soil temperature profiles, such as these, which are derived from short periods of observation, may not display a thermal offset. During a winter with particularly low air temperatures or snowfall, for instance, near-surface soil temperatures may decrease more than usual and reduce, or even eliminate, the offset.

Shamshoora (1959) has also presented asymmetric mean annual soil temperature profiles indicating either warming or cooling with depth, and Mills *et al.* (1977) reported mean annual soil temperatures from Manitoba with similar trends near the surface.

Mean annual soil temperature profiles from other sites in northern Canada and the U.S.S.R. are presented in Table 2. The profiles in Table 2 compiled from Atmospheric Environment Service (AES) (1984) records represent the annual means of daily temperature series; other profiles from sites in the Yukon Territory were compiled from readings made on a fortnightly or monthly basis under the auspices of the Canada-Yukon Soil Survey Unit. These stations were installed in summer 1984: the means are for the period September 1984 to September 1986.

A thermal offset is apparent at a majority of the sites in Table 2. At others, no offset can be detected. This may be due to dry soil conditions, which would result in a small seasonal change in λ. The AES records in Table 2, except for Haines Junction, Yukon, were acquired at airfields, under grass cover, where sensors are often buried in well-drained, coarse-textured materials. The soil temperature cable at Whitehorse, Yukon, is located under mature coniferous forest, in rapidly drained glaciofluvial outwash sands and gravels.

A comparison of the temperatures at 10 cm and at the base of each profile in Table 2 indicates that only the offsets from the Takhini Valley, Yukon, Fort Simpson and Resolute, N.W.T., Kuujjuaq, Quebec, and Vorkuta, U.S.S.R., are in the same range as those observed at Mayo. The wetness of forest soils at Mayo may lead to greater offsets at the sites. As noted above, the Mayo sites are in "natural" settings and represent conditions in the boreal forest, while many of the sites listed in Table 2 are at dry or disturbed locations. This suggests that the offset may be a more widespread phenomenon than inspection of published soil temperature records might indicate.

TABLE 2. Mean annual soil temperatures (°C) at stations across northern Canada and in the U.S.S.R.

Station	Depth (cm) 5	10	20	50	100	150	Source
Eagle Plains Lodge, Y.T.	−1.3	−1.8	−2.1	—	−2.1	—	1
Eagle River Bridge, Y.T.	−3.3	−3.6	−3.5	—	−3.4	—	1
Haines Junction, Y.T.	2.2	2.0	2.0	2.0	2.0	2.0	2
Takhini Valley Site 1, Y.T.	1.4	0.8	0.5	0.1	0.2	—	1
Takhini Valley Site 2, Y.T.	1.0	0.3	0.1	−0.1	−0.1	—	1
Liard River Bridge, Y.T.	0.8	0.8	0.8	1.0	1.5	—	1
Watson Lake, Y.T.	3.9	3.8	3.8	3.7	3.9	4.0	2
Whitehorse, Y.T.	1.1	1.1	1.2	1.2	1.2	—	1
Fort Simpson, N.W.T.	—	2.0	1.4	1.5	0.9	0.7	2
Mould Bay, N.W.T.	−14.2	−14.4	−14.2	−14.3	−14.3	−14.3	2
Resolute, N.W.T.	−9.9	−10.8	−11.3	−11.2	−11.5	−11.4	2
Baker Lake, N.W.T.	−7.7	−8.7	−8.6	−7.5	−6.9	−7.0	2
Cree Lake, Saskatchewan	1.8	2.0	1.8	2.4	2.8	3.3	2
Thompson, Manitoba	3.7	3.6	3.3	3.6	2.8	3.3	2
Kuujjuaq, Quebec	−1.9	−2.3	−2.5	−2.3	−2.4	−2.9	2
Yakutsk, Siberia	—	−2.5	−2.6	−2.7	−2.5	−2.2	3
Igarka, NE U.S.S.R.	—	1.7	1.6	1.4	1.3	1.4	3
Vorkuta, NE U.S.S.R.	—	0.9	0.9	0.8	0.5	0.3	3

Sources: (1) This paper; (2) Atmospheric Environment Service (1984); (3) Pavlov (1975:163-166).

DISCUSSION

Most discussions of the thermal regime of permafrost terrain do not treat the thermal offset in detail (e.g., Gold and Lachenbruch, 1973; Judge, 1973a; French, 1976; Johnston, 1978; Washburn, 1979; Lunardini, 1981). Indeed, the simple model of the annual ground thermal regime presented by Brown (1970) commonly accompanies such discussions (Fig. 4). This model portrays the mean annual temperature increasing monotonically with depth throughout the profile. The calculations of Goodrich (1978, 1983) and the data presented here indicate that such a model is an over-simplification of field conditions.

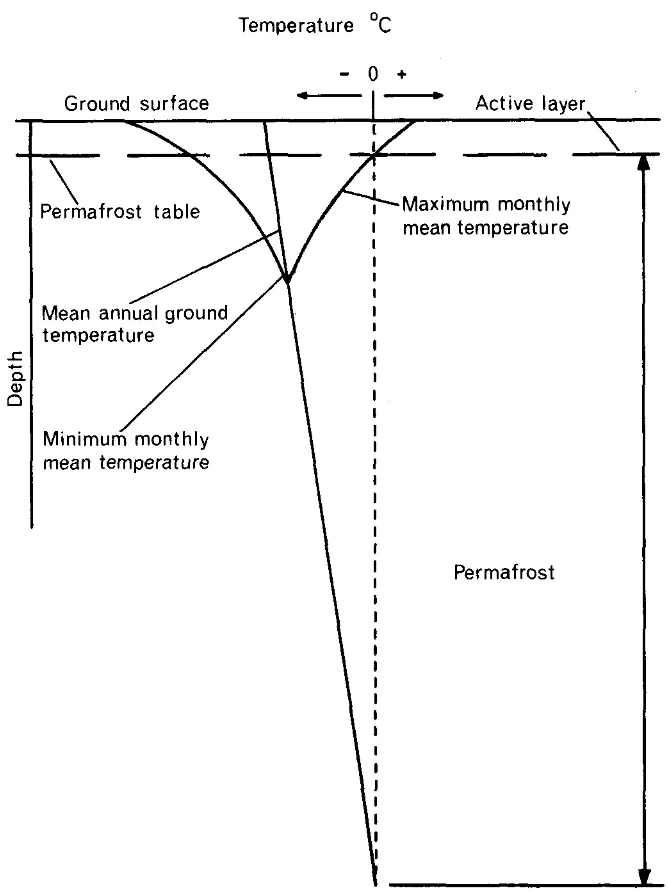

FIG. 4. Thermal regime of permafrost as portrayed by Brown (1970: Fig. 6).

In addition, the notion that T_s must be less than 0°C in order for permafrost to exist (Judge, 1973b:2; Williams, 1982:164) should be modified, since the observations of Tarnocai (1984) and Mills *et al.* (1977) and the data from Mayo sites 3, 4 and 6 support Goodrich's (1978:Fig. 2) demonstration that permafrost may be in equilibrium, or even aggrading, in environments where the mean annual surface temperature is above 0°C. Furthermore, since the magnitude of the offset is not constant between sites, T_s *per se* is not a diagnostic indicator of the presence or absence of permafrost.

The data also suggest that the critical mean annual ground temperature governing the thickness of equilibrium permafrost is that which exists below the thermal offset, rather than T_s. Indeed, the presence of an offset implies that permafrost thickness cannot be determined from any temperature measurements made within the active layer. Instead, the most accessible *informative* ground temperature measurements for the determination of permafrost thickness should be made several decimetres below the base of the active layer, some distance below the thermal offset.

The term permafrost was first used by Muller (1945) to refer to ground (soil or rock) that remains below 0°C for a number of years. The data presented here indicate that the mean annual ground surface temperature does not rigorously define the presence or thickness of permafrost. The offsets reported in this paper indicate that the ground temperatures diagnostic of permafrost conditions are those in permafrost itself, which, after all, are the criteria used to define it.

ACKNOWLEDGEMENTS

This note represents part of a Ph.D. thesis supervised by M.W. Smith of the Geotechnical Science Laboratories, Carleton University. His support and encouragement in all aspects of the work are greatly appreciated. The field work was supported through the good offices of A.S. Judge, Earth Physics Branch, Energy, Mines and Resources, Canada, and by the Arctic Institute of North America, the Canadian Commonwealth Scholarship Committee and the Natural Sciences and Engineering Research Council. Some winter field readings were taken by Michael Mason-Wood of Mayo. The research would not have been possible without the generous hospitality of Jim and Shann Carmichael of Mayo.

The manuscript has benefitted from the comments of J.R. Mackay, I.G. McKendry, M.D. Novak and C. Tarnocai. This note was written during the tenure of a Killam Post-doctoral Fellowship at the University of British Columbia.

REFERENCES

ATMOSPHERIC ENVIRONMENT SERVICE. 1982. Canadian climate normals, Temperature and precipitation, The North-Y.T. and N.W.T. Ottawa: Environment Canada. 55 p.

______. 1984. Canadian climate normals. Vol. 9: Soil temperature, Lake evaporation, Days with blowing snow, hail, fog, smoke or haze, frost. Ottawa: Environment Canada. 109 p.

BROWN, R.J.E. 1970. Permafrost in Canada: its influence on northern development. Toronto: University of Toronto Press. 246 p.

______. 1973. Influence of climate and terrain factors on ground temperatures at three locations in the permafrost region of Canada. Proceedings, Second International Permafrost Conference, North American Contribution. Washington, D.C.: National Academy of Sciences. 27-34.

______. 1978. Permafrost. In: Hydrological Atlas of Canada. Ottawa: Fisheries and Environment Canada. Plate 32.

BURGESS, M.M., JUDGE, A.S., and TAYLOR, A.E. 1982. Yukon ground temperature data collection — 1966 to August 1981. Earth Physics Branch Open File 82-1. Energy, Mines and Resources Canada, Ottawa, Ontario. 138 p.

BURN, C.R. 1986. On the origin of aggradational ice in permafrost. Ph.D. thesis, Carleton University, Ottawa, Ontario. 222 p.

______, MICHEL, F.A., and SMITH, M.W. 1986. Stratigraphic, isotopic and mineralogical evidence for an early Holocene thaw unconformity at Mayo, Yukon Territory. Canadian Journal of Earth Sciences 23(6):794-803.

FAROUKI, O. 1981. Thermal properties of soils. U.S. Army Cold Regions Research and Engineering Laboratory Monograph 81-1. 136 p.

FRENCH, H.M. 1976. The periglacial environment. London: Longman. 309 p.

GILPIN, R.R., and WONG, B.K. 1975. The ground temperature regime and its relationship to soil properties and ground surface cover. American Society of Mechanical Engineers Paper 75-WA/HT-98.

GOLD, L.W., and LACHENBRUCH, A.H. 1973. Thermal conditions in permafrost — a review of North American literature. Proceedings, Second International Conference on Permafrost, Vol. 1. Washington, D.C.: National Academy of Sciences. 3-25.

GOLD, L.W., JOHNSTON, G.H., SLUSARCHUK, W.A., and GOODRICH, L.E. 1972. Thermal effects in permafrost. Proceedings of the Canadian Northern Pipeline Conference, National Research Council Associate Committee for Geotechnical Research Technical Memorandum 104. 25-45.

GOODRICH, L.E. 1978. Some results of a numerical study of ground thermal regimes. Proceedings, Third International Conference on Permafrost, Vol. 1. Ottawa: National Research Council. 29-34.

______. 1982. The influence of snow cover on the ground thermal regime. Canadian Geotechnical Journal 19(4):421-432.

______. 1983. Thermal performance of a section of the Mackenzie Highway. Proceedings, Fourth International Conference on Permafrost, Vol. 1. Washington, D.C.: National Academy of Sciences. 353-358.

______. 1986. Field measurements of soil thermal conductivity. Canadian Geotechnical Journal 23(1):51-59.

HUGHES, O.L. 1983. Surficial geology and geomorphology, Janet Lake, Yukon Territory. Geological Survey of Canada Map 4-1982.

JOHNSTON, G.H., ed. 1978. Permafrost engineering design and construction. Toronto: Wiley. 540 p.

JUDGE, A.S. 1973a. The prediction of permafrost thickness. Canadian Geotechnical Journal 10(1):1-11.

______. 1973b. The thermal regime of the Mackenzie Valley: observations of the natural state. Report 73-38, Environmental-Social Program, Task Force on Northern Oil Development. Ottawa: Information Canada. 177 p.

KAY, B.D., FUKADA, M., IZUTA, H., and SHEPPARD, M.I. 1981. The importance of water migration in the measurement of the thermal conductivity of unsaturated frozen soils. Cold Regions Science and Technology 5(1):95-106.

KUDRIAVTSEV, V.A., and MELAMED, V.G. 1972. Asymmetry of the enveloping curves of temperature fluctuations in soil in relation to the calculations of depths of seasonal and perennial freezing. Permafrost Research 12:3-8. Moscow State University. In Russian.

LUNARDINI, V.J. 1981. Heat transfer in cold climates. New York: Van Nostrand Reinhold. 731 p.

MACKAY, J.R. 1983. Downward water movement into frozen ground, western arctic coast, Canada. Canadian Journal of Earth Sciences 20(1):120-134.

MILLS, G.F., TARNOCAI, C., and SHAYKEWICH, C.F. 1977. Characteristics and distribution of soil temperature regimes in Manitoba, Canada. Proceedings, 21st annual Manitoba Soil Science Meeting. 56-85.

MULLER, S.W. 1945. Permafrost or perennially frozen ground and related engineering problems. United States Geological Survey Special Report, Strategic Engineering Study 62. 231 p.

NICHOLSON, F.H., and GRANBERG, H.B. 1973. Permafrost and snow-cover relations near Schefferville. Proceedings, Second International Conference on Permafrost, North American Contribution. Washington, D.C.: National Academy of Sciences. 151-158.

PAVLOV, A.V. 1975. Heat transfer of the soil and atmosphere at northern and temperate latitudes. Hanover, New Hampshire: U.S. Army Cold Regions Research and Engineering Laboratory Technical Translation 511. 298 p.

RISEBOROUGH, D.W. 1985. Modelling climatic influences on permafrost at a boreal forest site. M.A. thesis, Carleton University, Ottawa, Ontario. 172 p.

SHAMSHOORA, G. Ya. 1959. The effect of snow cover on the thermal regime of soil in the Tamirsk Tundra. Research on the Principles of Ground Freezing. Moscow: Academy of Sciences. 186-201. In Russian.

SMITH, M.W. 1975. Microclimatic influences on ground temperatures and permafrost distribution, Mackenzie Delta, Northwest Territories. Canadian Journal of Earth Sciences 12(8):1421-1438.

______ and BURN, C.R. 1986. Instrumentation of long-term monitoring of permafrost temperatures in relation to climatic change, near Mayo, Yukon. Contract Report 5114-4320-00001-113-1160(J0055). Downsview, Ontario: Atmospheric Environment Service, Environment Canada. 36 p.

TARNOCAI, C. 1984. Characteristics of soil temperature regimes in the Inuvik area. In: Olson, R., ed. Northern Ecology and Resource Management. Edmonton: University of Alberta Press. 19-37.

WASHBURN, A.L. 1979. Geocryology. London: Arnold. 406 p.

WILLIAMS, P.J. 1982. The surface of the earth: an introduction to Geotechnical Science. London: Longman. 212 p.