LONG-TERM AIR AND GROUND TEMPERATURE RECORDS FROM THE CANADIAN CORDILLERA AND THE PROBABLE EFFECTS OF MOISTURE CHANGES

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Abstract

Long-term (up to 14 year) measurements of air and ground temperature records from three stations in permafrost in the Canadian Cordillera show that variations in apparent trends of ground temperature at different depths in the ground are relatively common and are often unrelated to variations in air temperature. They are not confined to the upper part of the permafrost zone as suggested previously in the literature and appear to be due to changes in the moisture content with time. They imply (1) that studying climatic change by monitoring ground temperatures will normally be unsuccessful unless an arid area is chosen; (2) that basing engineering designs on measurements of ground temperatures alone will be hazardous; and (3) that the ground-temperature profile with depth is an unreliable indicator of past climatic changes.

Résumé

Des mesures à long terme (jusqu'à 14 ans) de la température de l'air et du sol relevées à trois stations dans le pergélisol dans la Cordillère canadienne révèlent que les variations de température à différentes profondeurs dans le sol sont relativement fréquentes et que, souvent, elles ne sont pas liées aux variations de la température de l'air. Elles ne sont pas confinées à la partie supérieure du pergélisol comme le suggère la littérature, et elles semblent attribuables aux variations de la teneur en eau en fonction du temps. L'auteur conclut (1) que l'étude du changement climatique basée sur le suivi des températures du sol sera vraisemblablement peu concluante sauf dans les sites secs; (2) qu'il serait dangereux de concevoir les ouvrages de génie uniquement selon les températures du sol; et (3) que le profil des températures du sol en fonction de la profondeur n'est pas un indicateur fiable des changements climatiques passés.

Introduction

It has long been recognized that climatic parameters might be used to predict permafrost occurrence and properties, and there are currently many research projects and working groups studying the problem. In general, it seems to be accepted that air temperature and ground temperature are closely linked and can be modelled, and that one can readily be used to predict the other. In practice, there are significant exceptions to this rule, for example, Burn and Smith (1988) found that the mean ground temperature in the active layer at Mayo showed a "thermal offset" away from the mean ground temperature in the permafrost. This was earlier predicted to occur by calculations by Gold et al.(1972), Gilpin and Wong (1975) and Goodrich (1978, 1982 & 1983). Similarly, Judge (1973) reported a 3.3°C warmer mean annual temperature at the depth of zero amplitude than the mean annual air temperature for 38 sites in Canada, but there was a standard deviation of ±1.5°C, indicating substantial variability. The National Academy of Sciences (1974, p. 40) claimed that the mean ground temperature and the temperature at the depth of zero amplitude were the same, although Grave (1967, p.1341, Table 1) showed considerable variation (1.5° to 9.3°C).

Since 1974, the author has been measuring ground and air temperatures at a number of permafrost sites in the Cordillera, the early work being in collaboration with the late R. J. E. Brown of the former Building Research Division, National Research Council of Canada. It soon became apparent that the relationship between the air and ground temperatures is far more complex than previously believed, and this paper summarizes the results of 14 years of work on the problem.

Study Sites and Methods Used

In this paper, results will be given for three of the ten sites studied so far, viz.: Plateau Mountain, Marmot Basin, and Summit Lake (Fig. 1). Table 1 provides basic climatic data for the sites. In addition, some data will be used from north of Tuchitua, Yukon.

The Plateau Mountain site was the one originally used to establish the presence of permafrost in the mountains of southwestern Alberta (Harris & Brown, 1978, 1982). PM#2 was the first thermistor cable used in the work and was emplaced in the drill-hole with the conventional thermocouple cable for comparison. The YSI 44033 thermistors

Table 1. Climatic conditions at the three main study sites based on actual measurements.

Location	Elevation (m)	Years of Data	Mean Winter Snow Cover Nov-May (cm)	Mean Annual Temperature (°C)	Aspect	Mean Freezing Index * (°C days)	Mean Summer Thawing Index (°C days)
Plateau Mountain #2	2499	13	12	-1.97	W	1533	995
Marmot Basin #1	2286	9	5	-1.76	S	1735	1190
Summit Lake #A	1524	6	12	-3.85	N	2269	965

* Winter Freezing Index = Freezing Index derived by the summation of all the negative values of mean daily temperature (°C) between the frost free period.

\# Summer Thawing Index = Thawing Index derived by the summation of all the positive values of mean daily temperature (°C) between the time of continuously below zero mean daily temperatures of one year and that of the next.

gave results an order of magnitude more precise than the thermocouples, so that all future work was carried out using thermistors. The site is at 2499 m elevation on patterned ground developed in 120 m of felsenmeer on the flat top of the mountain under tundra vegetation. A recording 3-level Lambrecht soil thermograph continuously records both air temperature and near surface ground temperature, while seven thermistors at various depths to 15.3 m are read approximately once a month. The sensor measuring air temperature is at 1.5 m above the ground and is both shielded from direct insulation and ventilated.

The Marmot Basin site lies on top of a ridge in Jasper National Park at 2286 m elevation. Instrumentation is similar to that of the Plateau Mountain site, the deepest thermistor being at 17.4 m. depth. The borehole is drilled through about 50 cm of till overlying bedrock under a tundra vegetation. Mean soil moisture in summer is considerably greater at this site (Table 2) and the permafrost in the underlying shaly bedrock is probably icy.

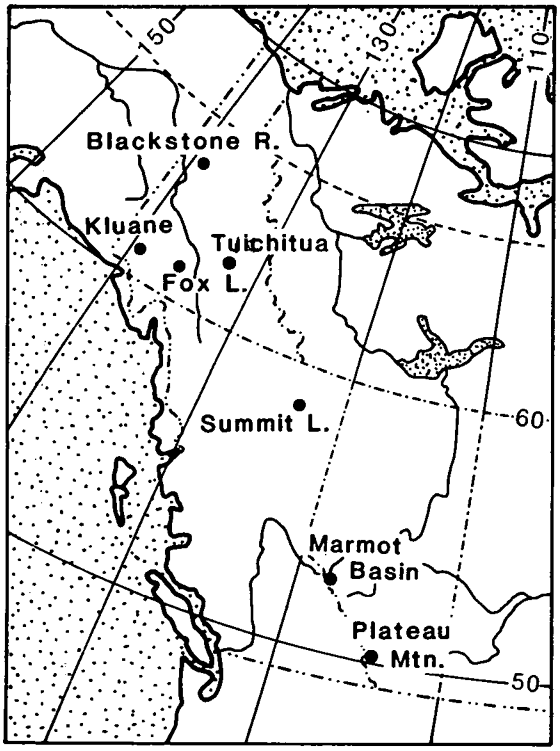

Figure 1. Location of the study sites in the Cordillera.

By 1979, the writer had become doubtful about the simplicity of the relationship between climate and ground temperature for detailed study. The Stefan equation indicates that the depth of freezing is dependent on the thermal conductivity of the frozen soil, the latent heat of water in the soil, and the freezing index. Since the thermal conductivity of the frozen soil varies with the H_20 content, any changes in the H_20 in the ground will alter the vertical temperature profile at a given site under a given constant freezing index.

Throughflow of H_20 in layers of higher permeability under the influence of gravity is widespread in soils, and could obviously also occur in permafrost where the pores are not totally filled with ice. At Plateau Mountain, the felsenmeer is very porous and would need a high ice content to become impermeable. Furthermore, H_20 can move in response to thermal gradients (see Harris, 1989) and this can also occur in icy permafrost (Mackay, 1983; Cheng & Chamberlain, 1988). Thus changes in H_20 content must also be examined if possible.

Attempts to put in an access tube for a soil moisture probe at Marmot Basin were unsuccessful, but when A. Heginbottom, Terrain Sciences Division, Geological Survey of Canada, sponsored the research at Summit Lake, this was finally achieved.

The Summit Lake A site in northern British Columbia is located at 1524 m on a bench composed of till. The bottom thermistor is at 19.5 m while the adjacent moisture access tube only goes down to 6 m. The site is more moist than Marmot Basin (Table 20 and supports a lichen tundra vegetation. The instrumentation for measuring air and ground temperature is the same as at the other two sites.

Table 2. Maximum and mean summer moisture contents and mean winter snow cover for three main study sites.

	SITE		
	Plateau	Marmot	Summit
Mean winter snow cover (cm)	12	5	12
Maximum moisture content (% by volume) in top 1m of the active layer in summer	15	32	48
Mean moisture content (% by volume) in top 1 m of the active layer in summer	8	22	26

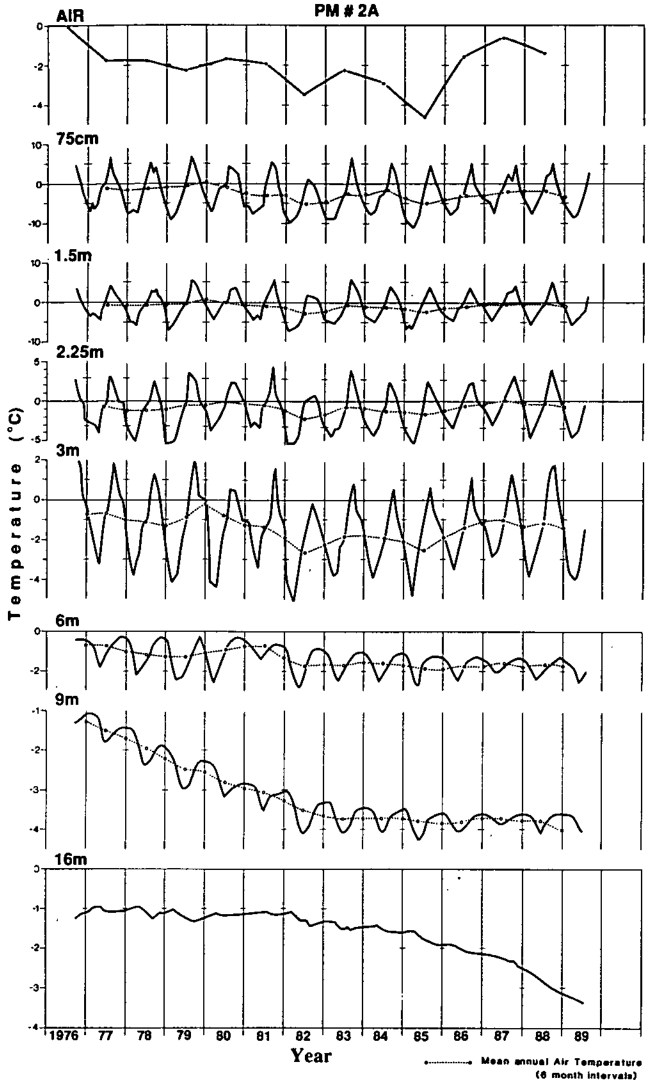

Figure 2. Ground temperatures measured at Plateau Mountain #2 by the thermistors since 1976 compared with the mean monthly air temperature. Means at 6 month intervals are used to smooth some of the curves.

The Tuchitua site is at km 161.7 on the Robert Campbell Highway between Watson Lake and Ross River, Yukon Territory (Fig. 1). It consists of access tubes for both ground temperature cables and the soil moisture probe drilled into a classic mature peat plateau. Black spruce trees on the plateau have up to 220 annual rings, showing the mechanical stability of the peat plateau. The instrumentation is the same as at the other sites.

The ground temperatures were measured using a Biddle Wheatstone Bridge with resistances reproducible between machines to 1 ohm. The neutron moisture probe was a Campbell Pacific Nuclear Model 503, and the results are based on dividing the actual neutron probe count at a given depth by the mean standard count. This was calibrated by using soil samples for which both density and water content were determined. The initial results represent the moisture content by volume until corrected for the density of the substrata.

Results

Figure 2 shows the results of long-term monitoring of air and ground temperature at Site #2, Plateau Mountain. The air temperature shows a variable but slight reduction over the 14 years, with some abrupt peaks and troughs to use as markers. When these are compared with the ground temperatures, it will be seen that there is not a very good correlation of these markers with temperatures in the top 3 m of the ground. In detail, each level changes independently of the others.

The problem becomes far worse at depth. The thermistor at 9 m showed a steady decline in temperature from 1976 to 1982, but relatively consistent temperatures since then. The thermistor at 16 m showed consistent temperatures until 1982, but the ground temperature then started getting colder.

When the thermistor readings are checked against the thermocouple readings, the two sets of readings match within the accuracy permitted by the thermocouples (±0.1 °C).

In 1978, a 150 m hole was drilled 5 m from TC#2, and the temperatures encountered a year later are shown in Figure 3. It will be apparent that the sequence of temperatures with depth is both complicated and quite unlike that described from the Arctic coast of Alaska (see Lachenbruch & Marshall, 1969; Gold & Lachenbruch, 1973).

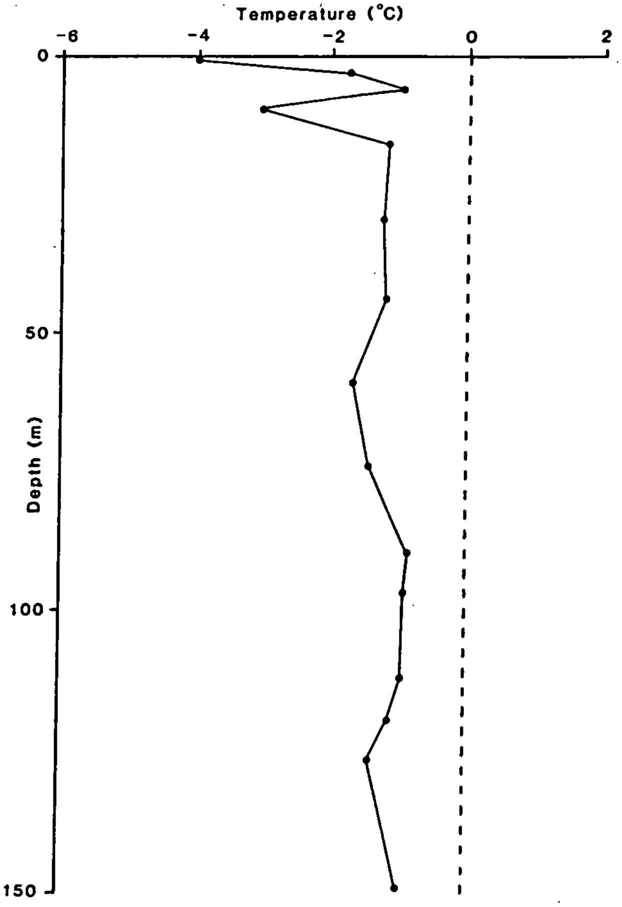

Figure 3. Ground temperatures measured at Plateau Mountain #2A on a 150 m thermistor cable.

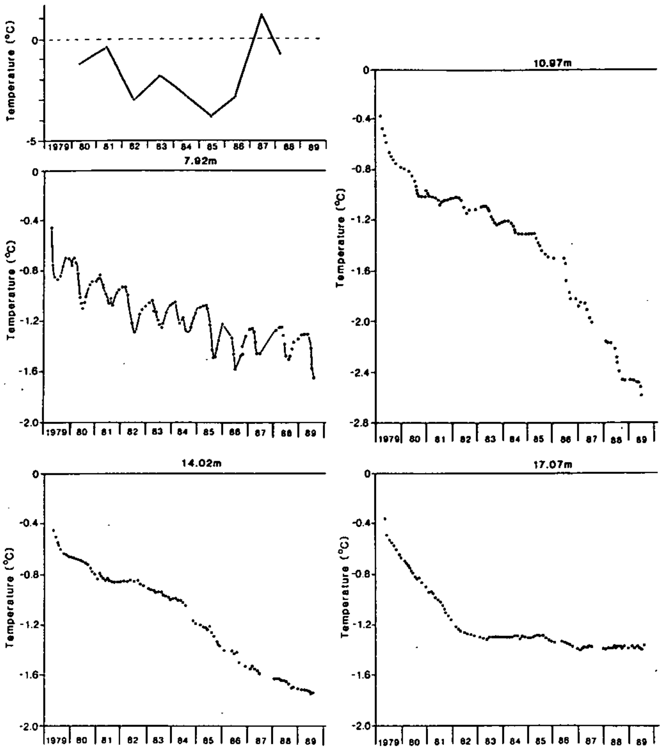

Figure 4. Ground temperatures measured at Marmot Basin #1 by the thermistors since 1979, compared with the mean annual air temperatures.

Similar results for 17 m holes are encountered at other sites. Thus, at Marmot Basin Ski Area, Jasper National Park, the upper site (MB#1) has produced the data in Figure 4. The changes in air temperature are not reflected clearly in ground temperatures, while the latter exhibit different trends with time at the various depths. Thus the thermistor at 17 m shows a steady drop in temperature for several years followed by steady temperatures, while a more gentle but relatively continuous drop in temperature is occurring higher in the ground.

Summit Lake site #A is different again. There the running means of the air temperature from 1982 to 1988 showed rising temperatures but these are not directly reflected in the ground temperatures in the top 1.5 m (Fig. 5). The problems become greater at depth (Fig. 6) with the ground temperatures at 5.5 m, 7.5 m and 19.5 m showing declining ground temperatures. Of particular interest are the ground temperatures at 3.5 m which show an increase until late 1986 and then suddenly change to decreasing temperatures.

When the moisture content of the ground is examined (Fig. 7), there are significant changes in the top 6 m between 1984 and 1989. The peaks of moisture content that were present in 1984 appear to be moving downwards with time so that the moisture content adjacent to the thermistors will be changing. Greatest changes occur near the surface, and the downward movement appears to decrease with depth, as suggested by Harris (1989). Although there is insufficient data for a direct correlation, there are indications that the thermistors showing declining ground temperatures are in zones of higher moisture content.

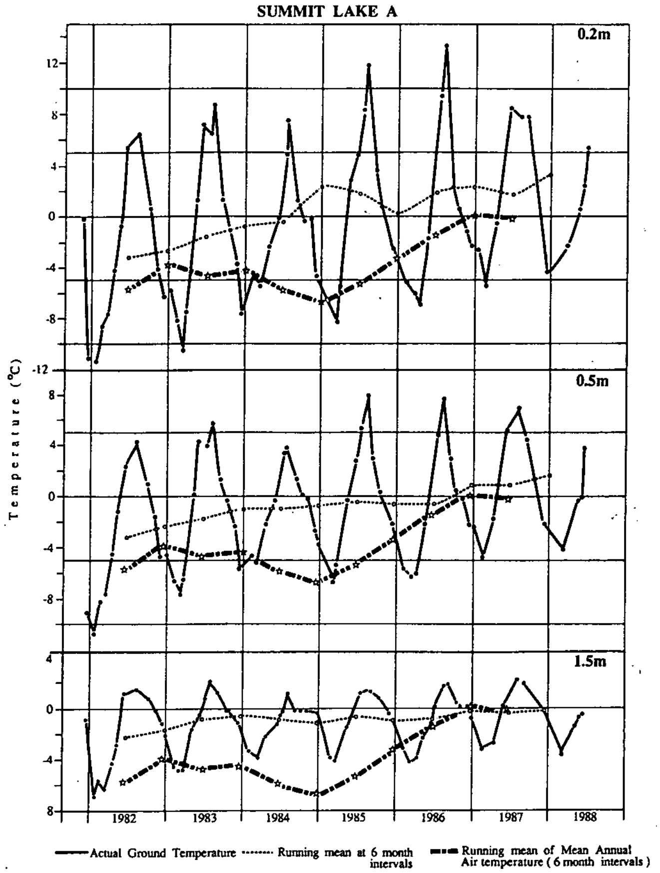

Figure 5. Ground temperatures measured in the upper 1.5 m at Summit Lake #A, compared with the mean monthly air temperatures.

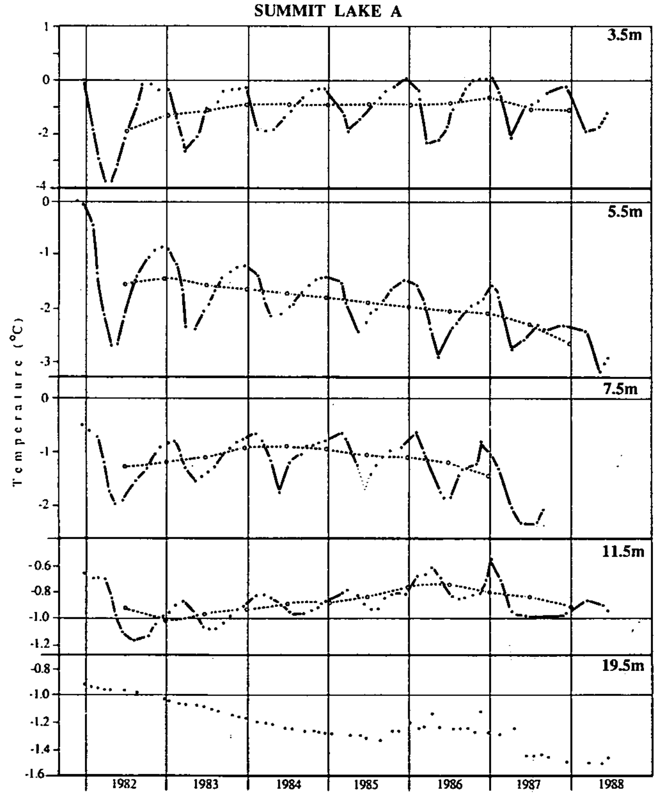

Figure 6. Ground temperatures measured below 3.5 m at Summit Lake #A.

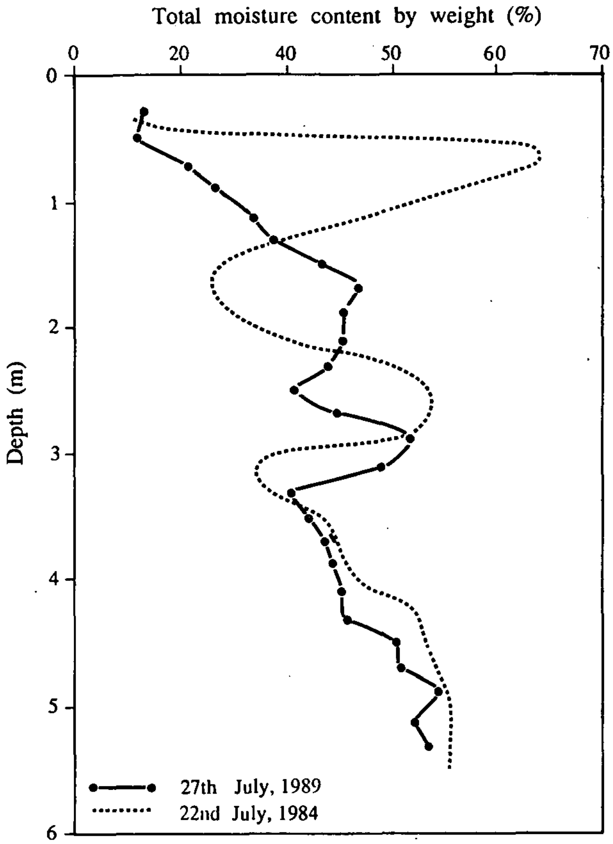

Figure 7. Moisture content at Summit Lake #A as measured in July 1984 and again in July, 1989.

One of the quickest ways of checking on the effectiveness of moisture content in modifying the thermal conductivity in the upper layers of the ground is by monitoring the "thermal offset" in the active layer of a profile on a peat plateau. Figure 8 shows the range of temperatures encountered in the upper 3 m of the peat plateau studied at km 161.7 along the Robert Campbell Highway north of Tuchitua, Yukon Territory. This site is reasonably close to Mayo where Burn and Smith (1988) reported up to a 1.5° offset. At km 161.7, the mean ground temperature measured by thermistors at 10 cm is 5.6°C, while at 110 cm, it is -0.12°C. The peat plateau appears to be in equilibrium with its present-day environment, and the permafrost has an ice content of between 84% and 91% by volume (measured gravimetrically). This is much higher than at Mayo and so is the offset. Mean winter snow cover over 2 years is 67 cm, therefore the source of the enhanced offset at km 161.7 must lie in the differences between the thermal conductivity of the dry soil in summer and the soil with high moisture content in winter in the peat (as suggested by Kudriavtsev & Melamed, 1972; Goodrich, 1978, 1982; and Mackay, 1983).

POSSIBLE INTERPRETATIONS

Circuit Deterioration

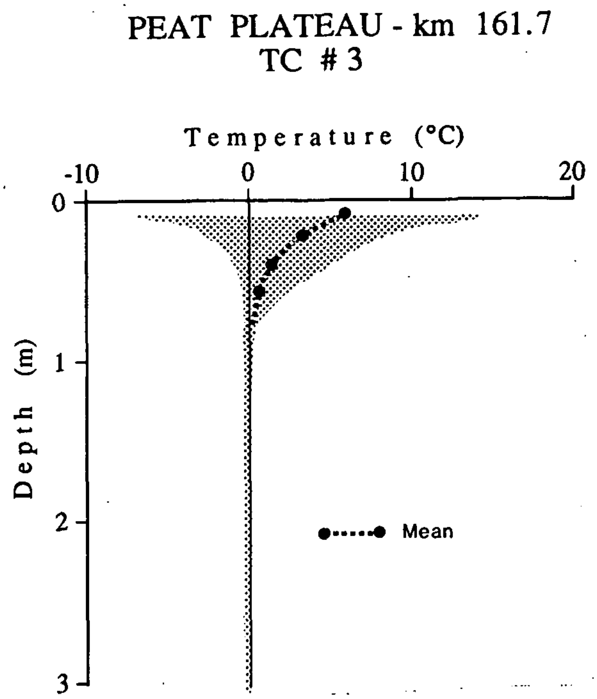

Figure 8. Ground temperature envelope in the upper 3 m of the peat plateau at km 161.7, Robert Campbell Highway.

There are a number of possible causes of differences in thermistor readings with time. Deterioration of a thermistor bead produces an apparently rapidly dropping ground temperature indicated by increased resistances, so that the apparent measured temperature becomes colder than -100°C in two or three months. This has not occurred with any of the thermistors used here.

Minor deterioration of thermistors may cause a slow systematic drift, and this would presumably affect all the thermistors of a particular batch. No such general drift is apparent, but this can be checked later if the cables can be recovered intact.

A third source of problems could be the corrosion of one or more wires in the cables. This should produce increasing apparent resistance of the thermistor in the circuit with the deteriorating wire which, once started, will be continuous and substantial. No such changes have been observed.

Comparison of the actual mean temperatures at each depth along a thermistor string provides a reasonable idea of the accuracy of calibration of the thermistors, together with any modifications of their response due to the soldering process.

Air and Near-Surface Temperatures

If the circuits are working properly, then the discrepancies between mean annual air and near-surface (0–3 m depth) ground temperatures must be due to other causes. Examination of the mean annual air temperatures suggests that the longer term (14-year) data does not approximate a sine-wave. Instead, there appears to be minor cooling with considerable variability from year to year.

The differences between mean annual air and near-surface ground temperatures must be due to changes in the surface with season. Of these, the variations in winter snow cover from year to year are probably the most significant, while changes in H_20 content of the surface layers obviously could alter the seasonal heat-flow at the peat plateau site north of Tuchitua. At Marmot Basin and at Summit Lake, the surface of the active layer may be wet enough in summer for variations in evaporation to modify the temperatures of the ground surface (Table 2).

Ground Temperatures

These show the normal increasing delay in penetration of the colder and warmer seasonal waves into the ground. At Plateau Mountain, these take approximately 12 months to penetrate to 16 m (Fig. 2).

Superimposed on this pattern are some rather obvious fluctuations and variations between layers. The most marked of these is the apparent cooling of the thermistor at 9 m depth at Plateau Mountain between 1976 and 1982. It occurred independently of the surrounding thermistors, indicating a separate cause. From 1983, this thermistor has indicated a constant temperature, which must mean that the results are not caused by circuit deterioration. The magnitude of the observed changes, together with the consistent trends for a period of several years rules out errors of measurement as a cause. Obviously there was a six-year period of greater heat loss in this layer that reached a steady-state equilibrium in 1982. This implies either a change in thermal properties towards a higher thermal conductivity in this layer compared with the others or else a source of lateral heat flow affecting only this layer for the six-year period of time. One of the few remaining possible causes would be the movement of moisture into the layer to form more ice and to provide a higher thermal conductivity. Other smaller discrepancies between the apparent ground temperatures at the different levels in the records for all three cables indicate that this is not an isolated case.

At Summit Lake, the thermistors at different depths show opposite trends of cooling and warming of the ground simultaneously. Furthermore, the thermistors that show the apparent warming trends can change to indicating a cooling trend with time, this change occurring when there is the probability of increased moisture input into that layer. While it has not been possible to actually measure the moisture content and ground temperature at exactly the same depth and time to conclusively prove this correlation, the circumstantial evidence is highly suggestive.

Thermal offsets and variations in apparent trends of ground temperatures at different depths in the ground are relatively common in the permafrost of alpine regions. They are apparently not confined to the upper part of the permafrost zone and to the active layer, as suggested previously (cf. Goodrich, 1978, 1986; Burn & Smith, 1988) and appear to be due to changes in the moisture content with time within the permafrost zone. If this interpretation is correct, ground temperatures tend to become more negative with time as H_20 accumulates in the profile until an equilibrium H_20 content is reached. The increased H_20 appears to increase thermal conductivity at depth, resulting in more efficient cooling of the permafrost.

The theory of predicting equilibrium temperatures in relation to air temperature was eloquently developed by Terzaghi (1952) and the effects of changes in that equilibrium were further developed by Lachenbruch (1968). What their models and calculations assume is that the thermal properties are unchanging. In practice, this cannot normally be true. Substantial changes in H_20 content have been demonstrated by many workers around the world for both the active layer and for the permafrost (see Harris, 1988, 1989). This moisture inevitably causes changes in the thermal properties of the layers it moves from and to, while there will be further complications in the thermal regime caused by the phase changes involving latent heat. Since moisture can move in any direction in the profile, given the right conditions of temperature gradients (see Harlan, 1974) or gravity, any realistic modelling allowing for the changes in moisture will be difficult to achieve. If moisture changes are not the cause, then the origin of the discrepancies between temperatures in successive layers in the ground remains and clearly has serious implications for users of ground temperature measurements.

Given these results, the typical temperature profiles can only reasonably be interpreted in terms of past climate where the changes in H_20 are small relative to the other factors, e.g. the North coast of Alaska. In other areas, the trends in the ground temperatures are likely to be somewhat at variance with the air temperature, and logging of the changes in the total moisture content of the ground and the variations in overall snowfall would be the only way to improve the predictive ability of such measurements. Given the difficulties in regular measurements of moisture in the ground at an adequate range of depths, this will only be feasible at a few selected sites and then only with considerable effort.

For the present time, engineers would do well to be cautious in using limited numbers of short-term readings of ground temperature cables to design foundations. Similarly, climatologists and paleoclimatologists would do well not to expect too much from long-term ground temperature measurements as a means of studying climatic change unless they are able to monitor the distribution of moisture in the ground adjacent to the thermistors on a regular basis and establish their interrelationship. Even then, the seasonal changes in the upper layers of the active layer may prove to be a formidable problem since the neutron depth-moisture probe cannot normally be used above 30 cm depth.

Acknowledgements

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