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MONITORING OF GROUND SURFACE TEMPERATURES IN VARIOUS BIOPHYSICAL MICRO-ENVIRONMENTS NEAR UMIUJAQ, EASTERN HUDSON BAY, CANADA

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Abstract

We measured ground surface temperatures (1995-1996) on a number of land types representative of all the terrain conditions encountered in a study area in order to establish interpretation keys for permafrost regional mapping. Continuous soil surface temperature data were obtained using 15 micro-dataloggers set 5 cm deep in various biophysical micro-environments located in the Umiujaq area, on the eastern shore of Hudson Bay. Analysis of the mean temperatures and the ratio between the freezing and thawing indexes, combined with the cumulative degree-day curves and the frost and thaw penetration curves, allowed us to predict the existence of permafrost at 7 of the 15 sites monitored. Sites affected by permafrost are located only under low vegetation stands, independent of surficial deposit types. Except at some herbaceous sites, the minimum annual snow depth needed to prevent permafrost development in the study area is about 50 cm.

Introduction

In Canada, several studies have concerned the relationships between snow cover, surface materials, vegetation and ground surface temperature and therefore permafrost distribution (e.g., Brown, 1966, 1975; Brown and Péwé, 1973). More specifically in Subarctic Quebec, fieldwork by Brown (1979), Lévesque et al. (1988), Allard et al. (1993) and Michaud et al. (1994), among others, has made it possible to draw regional permafrost maps that take into account the relationships between surface variables that have a bearing on permafrost. Given the large land areas covered by these studies and the type of instrumentation used in them, however, maps had to be drawn on the basis of field temperature data that covered only parts of the study areas, sometimes non-continuously.

The aim of this study is to monitor ground thermal profiles in relation to surface conditions in order to establish interpretation keys to map permafrost distribution and soil thermal regime within a discontinuous permafrost region. Ground surface temperatures were measured and recorded in micro-dataloggers for a full year cycle at 15 sampling sites, in various biophysical settings. Instrumented sites were spread over the entire study area, allowing a good spatial representation. These data allowed the calculation of soil surface freezing and thawing indexes, which in turn were used to calculate freezing and thawing depths and to determine the presence or absence of permafrost.

Regional setting

The Umiujaq region (56° N, 76° W) is located on the east coast of Hudson Bay (Figure 1) in the widespread

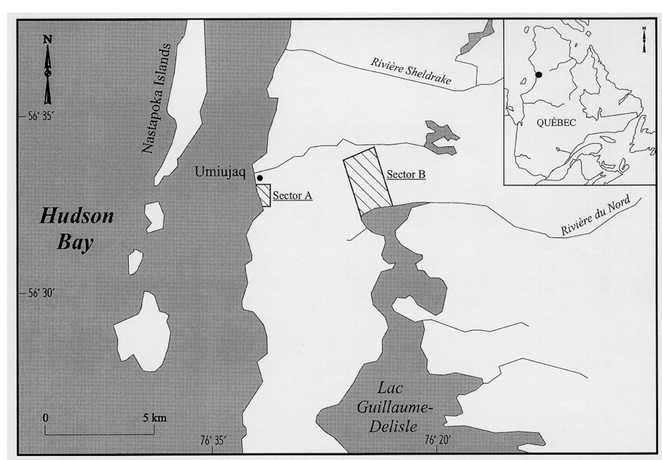

Figure 1.Location of the two sectors of the study area.

discontinuous permafrost zone (Allard et al., 1993). The study area is divided into two sectors: a small sector (1 km^2) on the eastern shore of Hudson Bay near the village of Umiujaq (sector A) and a second one (sector B) in the deep inland valley (Vallée-des-Trois) near the northern end of Lac Guillaume-Delisle. Sector A is characterized by raised sandy beaches and a dune field in which the bedrock outcrops at several places. In sector B, the valley (1 km by 4 km) is floored by a complex sequence of Holocene sediments and landforms including till, glaciofluvial gravels, raised beaches, gullied silts and fens. Permafrost mounds are found in fine sediments (fine sand, silt and clay) deposited in the Tyrrell Sea. They are characterized by a flattened shape and a diameter of approximately 50 m. They are about 3 m above the surrounding terrain. Thermokarst lakes and small active layer failures affect the slopes of the mounds.

The region's climate is subarctic with cool, damp summers and relatively dry, very cold winters. Interpolation of climatic data from Kuujjuarapik (55˚ 28' N) and Inukjuak (58˚45' N) weather stations yields an estimated mean annual temperature of -5.5˚ C (Fortier, 1991). Annual precipitation is 550 mm, and nearly 40% of this is snow. In the winter, the prevailing westerly and northwesterly winds affect the snow distribution and much snow accumulates in deep gulleys and wherever the shrub or tree cover is dense. On hilltops and on permafrost mounds, however, the snow cover is almost absent (1996 and 1997 winter field observations).

Because Hudson Bay influences the climate, the treeline, represented by the contact between the shrub-tundra to the west and the forest-tundra to the east, cuts through the region in a north-south direction (Payette, 1983). The shrub-tundra comprises krummholz vegetation made up of black spruce (*Picea mariana* (Mill.) BSP.) and various shrubs (*Betula glandulosa* Michx, *Salix* sp. and *Alnus crispa* (Ait.) Pursh) only in protec-ted areas. In the forest-tundra, woodland forest appears in valleys and sheltered areas.

Selected sites

Fifteen measurement sites were chosen after aerial photo-interpretation and biophysical mapping. The mapping units, at a scale of 1: 10,000, are homogeneous units similar to "ecological types" in biophysical land classification (Jurdant et al., 1977). They are defined by a series of parameters such as topography, surficial material, soil organic layers and vegetation cover. These map units recur across the region and form the mosaic that composes the landscape. The selected sites cover all the possible combinations of relief, surficial deposits and vegetation types (e.g., sand under lichen layer, silt under moss layer, sand under shrub layer, silt under tree layer, etc.) present in the study area, thus making it possible to analyze how these deposits and vegetation types interact in the occurrence of permafrost (Luthin and Guymon, 1974; Wright, 1995; Ménard et al., 1997).

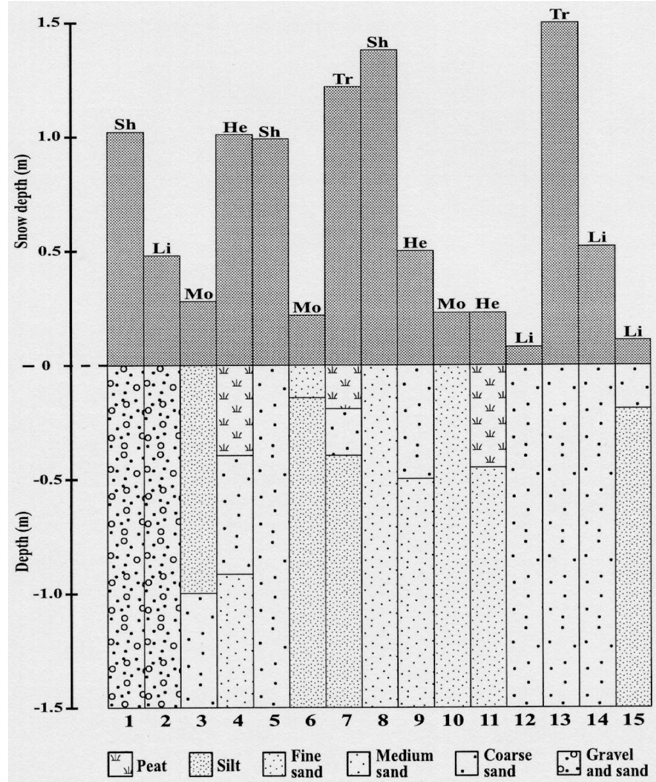

Figure 2.Stratigraphy, snow depth (April, 16 1996) and vegetation cover of the 15 sampling sites. The vegetation cover is divided into five groups: tree layer (Tr), shrub layer (Sh), herbaceous layer (He), Lichen layer (Li) and moss layer (Mo).

Sites 12, 13, and 14 are located near the village of Umiujaq (sector A) whereas all of the other sites are in the Vallée-des-Trois (sector B). Figure 2 shows the stratigraphy (down to 1.5 m), the vegetation cover, and the snow depth, as measured in the field on April 16, 1996. Snow depths varied from 0.08 m in lichenic areas to over 1.5 m in forested areas. By this date, 83% of the snowfall in the winter of 1995-96 had fallen at the Kuujjuarapik weather station, i.e., 221 of the total 268 cm (Environment Canada, 1996). The mean density of the snow for all of the 15 sites was calculated at about 0.43 g/cm^3 in April.

Instrumentation

Ground surface temperatures were recorded (Sept. 1995 to Sept. 1996) with miniature dataloggers (Optic StowAway Temp, WTA32) programmed to record at a regular interval of 4 hours 48 minutes (maximum interval of the device). These waterproof loggers operate in a temperature range from -40˚C to 75˚C with an accuracy of ±0.2°C. Most of the loggers were placed immediately under the moss or lichen cover at about 5 cm depth. In the case of sites 4, 7, and 11, the loggers were placed in peat at the same depth.

Results

Air Temperature

From 1992 to 1995, the mean annual air temperature in Vallée-des-Trois was -4.8°C (automatic meteorological station) whereas the freezing and thawing indexes were 2850 and 1200 degree-days respectively. For 1995, the mean annual temperature was -4.2°C with a maximum of 24°C and a minimum of -33°C. The thawing index was 1220 degree-days calculated between May 17 and October 29. The freezing index (1995-96) was 2889 degree-days for a total of 200 frost days spread out between October 30 and May 14. Figure 3 shows the air temperature record between September 1995 and September 1996. Note that swings in daily temperatures are much larger during the winter months than during the fall when Hudson Bay is still ice-free.

Ground Surface Temperatures

Table 1 combines the ground surface temperature data measured at all of the sites. Data were recorded over a 12-month period and covered a complete freezing cycle, thus enabling the freezing indexes to be charted continuously. The thawing indexes are approximate because they have been calculated from the end of one thaw season and the beginning of the next one. However, they should still be reasonable estimates (Taylor, 1995). Figure 4 shows examples of records of ground surface temperatures at lichen covered site 12 and forested site 13.

The n-factor is defined as the ratio between the seasonal freezing (or thawing) index at the ground surface and the seasonal freezing (or thawing) index of the air. It is a parameter that globally quantifies heat transfer at the atmosphere-soil interface through various processes affected by the vegetation and the snow cover (Lunardini, 1978; 1981). The n-factors calculated from

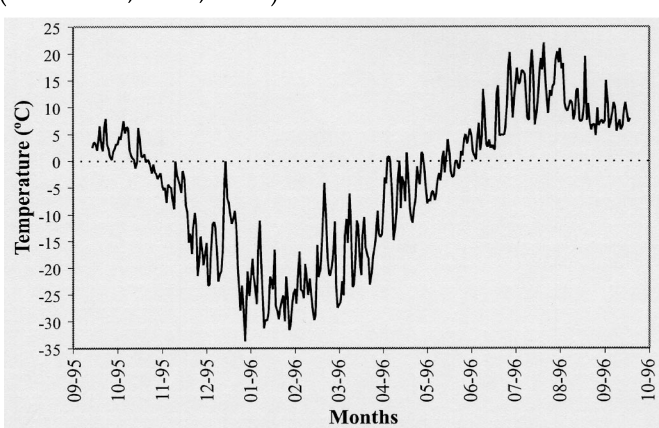

Figure 3.Profile of daily mean air temperatures recorded at weather station in the Vallée-des-Trois.

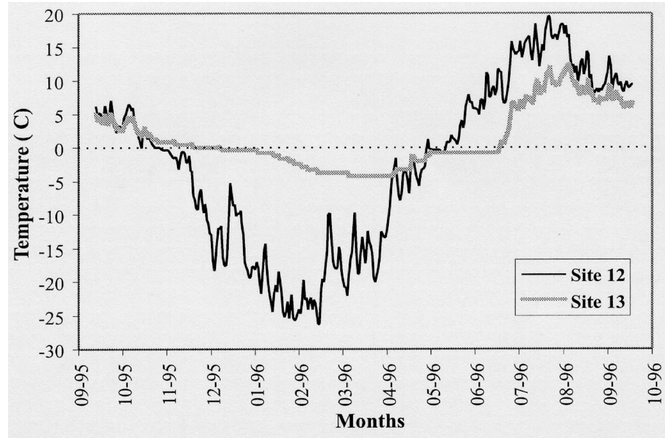

Figure 4.Profiles of daily mean ground surface temperatures for two sites located near village of Umiujaq.

the 15 sites are similar to those obtained by Taylor (1995) along the Mackenzie River (Northwest Territories) for similar terrain. Results show that the more the n-factor falls below 1.0, the more the snow cover and the vegetation reduce the impact of air temperature on ground surface temperature. Freezing n-factors are not as high as thawing n-factors, since the snow has an attenuating effect.

It was possible to measure how much the snow cover correlates with the ground surface temperatures by using the snow depths measured on April 16, 1996 (Figure 5). The correlation coefficient of 0.49 shows a general positive tendency. The graph, however, clearly indicates just how much the vegetation cover affects snow cover and, thus, surface temperatures. The points on the graph fall into two groups. The first group is represented mainly by moss and lichen covers (low temperatures, low snow depth) and the second group is represented by shrub and tree covers (high temperature, high snow depth).

Shape of Cumulative Degree-Day Curves

The shape of cumulative freezing degree-day curves (Figure 6a) at each of the sites clearly show that the freezing curve is much more pronounced in the moss- and lichen-dominated sites. The slope of the curves

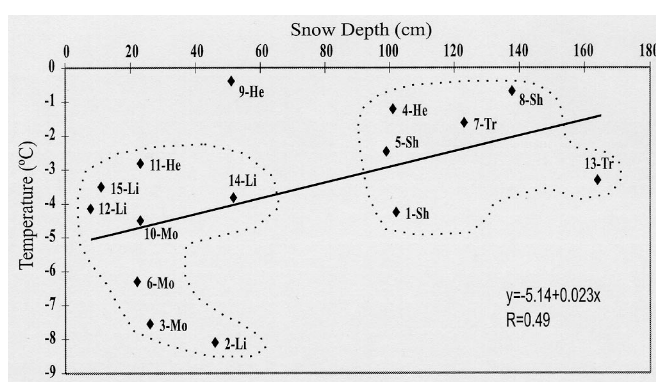

Figure 5.Relationships between ground surface temperatures and snow depth (April, 16 1996).

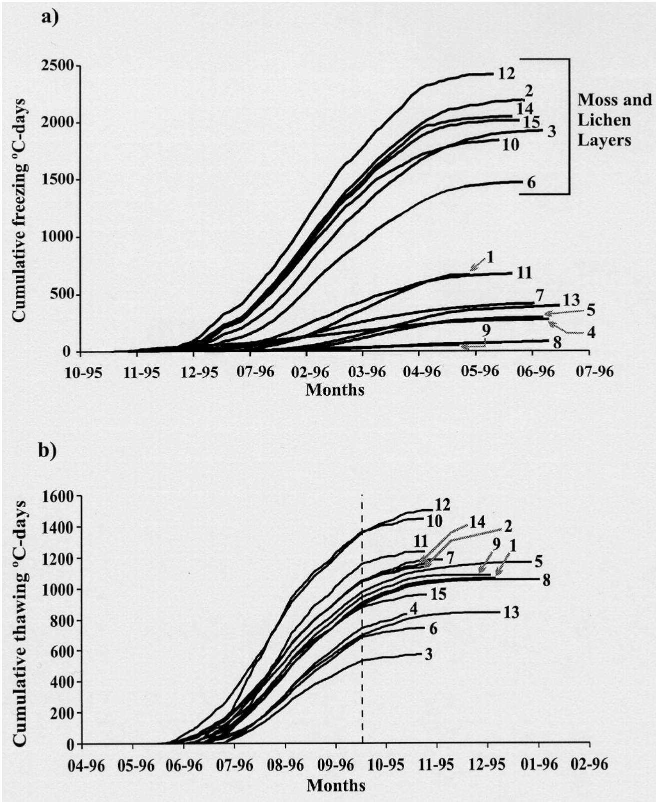

Figure 6.Cumulative degree-day curves (a) below and (b) above 0°C at the surface, for the 15 sampling sites

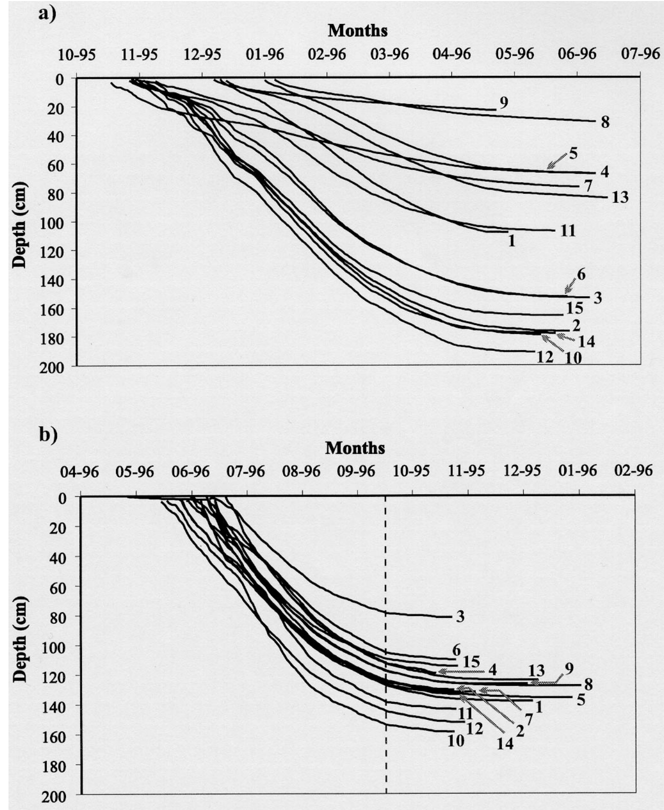

Figure 7.Predicted curves of seasonal depth of (a) frost and (b) thaw penetration for the 15 sampling sites.

shows that freezing keeps intensifying from January to early April. Cumulative thawing degree-days (Figure 6b) produce similar types of curves but the thaw period differs from one site to another, with refreezing coming later in areas of dense vegetation cover. The different low-lying vegetation sites exhibit heterogenous degree-day values, with moss sites insulating the ground far more than at lichen-covered sites (Brown, 1966)

Using the cumulative degree-day data, the depths of underground frost and thaw penetration were calculated for the 15 sites over the entire period under study (Figure 7a and 7b) by applying the modified Berggren equation (Johnston, 1981):

$$x = \lambda \left(48kI / L\right)^{1/2} \qquad [1]$$

where:

x is depth of freezing or thawing in centimetres;

λ is a coefficient determined from a nomogram (Sanger 1963, p. 254) taking into account the mean ground surface temperature, freezing and thawing period, heat capacity of the ground, and latent heat of fusion of the water contained in the pore spaces

k is ground thermal conductivity (cal h^{-1} cm^{-1} $°C^{-1}$);

I is value of freezing and thawing degree-days at the ground surface;

L is latent heat of fusion of the water contained in the pore spaces (cal cm^{-3}).

Value for k, λ and L were chosen from Johnston (1981) and Andersland and Ladanyi (1994) for the types of soil materials found in the study area. The results, while approximate (Sanger, 1963), can be used to estimate the maximum depth of freezing and thawing for the year under study. The practical advantage of using this equation and these units is the ease of reference to parameter tables that have proven to be accurate in the literature. Thaw values are similar to the depths of thaw (about 1 m) measured in late summer in pits over permafrost mounds. The curves have shapes similar to the cumulative degree-day curves (see Figure 6) with some differences due to the variable soil thermal parameters

Permafrost occurrence

By processing data on surface temperatures and surface conditions, an estimate may be made on the presence or absence of permafrost. Analysis of the mean temperatures and the ratio between the freezing and thawing indexes (Table 1), combined with the cumulative degree-day curves (Figures 6a and 6b) and the frost and thaw penetration curves (Figures 7a and 7b) allow us to predict the presence of permafrost at 7 of the sites.

The sites affected by permafrost all have a low-lying lichen and moss vegetation and snow depths less than 50 cm. They show negative temperature means with Fi/Ti ratio > 1. The non perennially-frozen sites exhibit positive temperature means and Fi/Ti ratio < 1. It is

Table 1. Location and summary of ground surface temperatures data of 15 sampling sites

SITE	DESCRIPTION	X COOR. UTM	Y COOR. UTM	MEAN TEMP.	FREEZING INDEX (Fi)	MEAN FREEZING	THAWING INDEX (Ti)	MEAN THAWING	RATIO Fi/Ti	N-FACTOR, FREEZING	N-FACTOR, THAWING
1	Plateau	408549	6270361	1.1	666	-4.6	1066	4.8	0.6	0.23	0.86
2	Plateau	408577	6270720	-2.9	2187	-10.0	1134	7.7	1.9	0.76	0.91
3	Permafrost mound	409150	6269101	-3.7	1923	-8.4	572	4.2	3.4	0.67	0.46
4	Fen	409332	6269089	1.5	278	-1.2	839	6.6	0.3	0.10	0.68
5	Salix layer	409143	6268862	2.4	296	-1.8	1167	5.7	0.3	0.10	0.94
6	Permafrost mound	410046	6268000	-2.0	1473	-6.8	744	5.0	2.0	0.51	0.60
7	Forest	409890	6267592	2.1	416	-2.0	1182	7.6	0.4	0.14	0.95
8	Bottom of gulleys	410229	6267832	2.7	85	-0.5	1056	5.1	0.1	0.03	0.85
9	Tidal marsh	412083	6266772	2.8	53	-0.4	1086	4.7	0.0	0.02	0.88
10	Small permafrost mound	411967	6266933	-1.1	1841	-9.0	1446	8.9	1.3	0.64	1.17
11	Fen	411323	6267329	1.6	673	-3.2	1239	7.8	0.5	0.23	1.00
12	Raised beach	405087	6268098	-2.5	2419	-12.5	1500	8.7	1.6	0.84	1.21
13	Depression between bedrock	406252	6267647	1.2	397	-2.1	844	4.8	0.5	0.14	0.68
14	Dune	406122	6267177	-2.5	2049	-9.9	1153	7.3	1.8	0.71	0.93
15	Plateau	408680	6270772	-2.9	2014	-9.5	959	6.3	2.1	0.70	0.77

thus possible to differentiate sites affected by permafrost from those affected only by seasonal freezing. The difference between the depths of frost and thaw penetration confirms this interpretation. Sites where frost penetration is deeper than thaw penetration correspond to sites of low-lying vegetation with shallow snow. Sites potentially subject to permafrost (2, 3, 6, 10, 12, 14, 15) are found in all types of surficial deposit. At the surface, virtually no cryogenic morphology can be observed in the coarse sediment sectors, in contrast to the fine sediment sectors where the presence of segregation ice leads to frost heave and the development of permafrost mounds. Support for the interpretation of permafrost distribution is given by deep borehole measurements in the area. A thermistor cable located close to site 6 shows that permafrost may be quite thick (Figure 8), a conclusion reached by Fortier (1991) who estimated a thickness of 22-25 m from borehole data. Characterized by a slight swelling of the ground, site 10 (fine sand under a moss layer) is a special case whose interpretation is more complex. The ratio between the freezing and thawing indexes is very low (1.3) and the ratio between mean freezing temperature and mean thawing temperature is 1.0 (Table 1). The maximum depth of frost penetration is estimated at 178 cm while thaw penetration is estimated at 158 cm. This site is probably affected by permafrost, but it may be undergoing aggradation or may be simply in equilibrium near the freezing point.

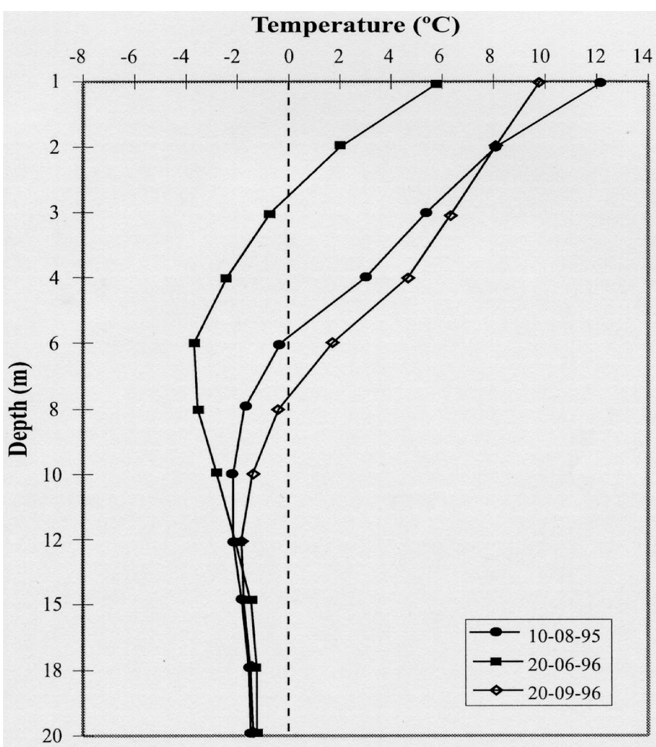

Figure 8.Temperature profiles from the thermistor cable located in bedrock near the village. Dates given as day/month/year.

Ground surface temperatures at shrub and forest sites stands show that permafrost cannot be maintained in these sectors. The ratio between the freezing and thawing indexes is too low, and the mean soil surface temperatures are too high for permafrost to form. The large amounts of snow collected by the vegetation insulate the ground and prevent winter cooling (Goodrich, 1982). The sites covered with herbaceous vegetation also exhibit surface temperatures that are not conductive to the formation of permafrost. Warm temperatures maintained by this sedge-dominated herbaceous cover are attributed to water-logged conditions and therefore an important storage of latent heat. At these sites, vegetation height and density play a less significant role. This may explain why sites 9 (tidal marsh) and 11 are the only ones where a thin snow cover (< 50 cm) failed to yield negative values for mean surface temperature and a soil Fi/Ti ratio > 1.

Conclusion

The interaction between vegetation, snow cover, and ground surface temperatures was quantified and analyzed using a large volume of field data collected over a one-year period. Permafrost in mineral soil is found only under low-lying vegetation covers independently of surficial deposit types. It is worth noting that the different relationships between ground surface temperatures and biophysical micro-environments differ by region. In subarctic Quebec, wooded regions usually cover soils unaffected by permafrost. In the Northwest Territories, the opposite occurs: not much snow falls in the winter and branches block much of the solar radiation in the summer (Brown, 1966). The interpretations in this paper are thus valid only for subarctic Quebec where permafrost is discontinuous.

The use of micro-dataloggers provides an inexpensive means for collecting high quality measurements of ground surface temperatures to outline permafrost areas. The data are more continuous than those obtained by sporadic measurements as in the BTS method (Haeberli, 1973, Haeberli et al., 1993) and they lend themselves to thermal modelling.

Although monitoring work is still in progress, interpretations presented in this paper are based on sound information. When combined with topographic data, these monitoring sites will provide the baseline information for regional mapping of permafrost distribution and for the simulation of permafrost thermal regime across the region. These results will allow simulations and useful predictions regarding environmental and anthropogenic changes in permafrost areas.

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References

Allard, M., Tremblay, C., Pilon, J.A. and Frydecki, J. (1993). Quaternary geology and geocryology in Nunavik, Canada. In *Proceedings 6th International Conference on Permafrost, Beijing, China*. South China University of Technology Press, pp. 5-10.

Andersland, O.B. and Ladanyi, B. (1994). *An introduction to frozen ground engineering.* Chapman & Hall, ITP, New-York (352 pp.).

Brown, R.J.E. (1966). Influence of vegetation on permafrost. In *Proceedings Permafrost International Conference*. Research Paper no. 298, Division of Building Research, National Research Council Canada, Ottawa, pp. 20-25.

Brown, R.J.E. (1975). *Permafrost investigations in Quebec and Newfoundland*. NRC, Technical Paper no. 499 (85 pp.).

Brown, R.J.E. (1979). Permafrost distribution in the southern part of discontinuous zone in Quebec and Labrador. *Géographie Physique et Quaternaire*, **33**, 279-289.

Brown, R.J.E. and Péwé, T.L. (1973). The distribution of permafrost in North America and its relationship to the environment: A review, 1963-1973. In *Permafrost: The North America Contribution to the Second International Conference*. Washington, D.C., pp. 71-100.

Environment Canada (1996). *Unofficial Meteorological summary*. Environment Canada, Atmospheric Environment Branch, meteorological data of Kuujjuarapik (Sept. 95 to Sept. 96).

Fortier, R. (1991). *Étude d'une butte minérale de pergélisol à Umiujaq par diagraphies géophysiques.* Masters Thesis, Laval University, Department of Geology, Ste-Foy (229 pp.).

Goodrich, L.E. (1982). The influence of snow cover on the ground thermal regime. *Canadian Geotechnical Journal*, **19**, 421-432.

Haeberli, W. (1973). Die Basis-Temperatur der winterlichen Schneedecke als möglicher Indikator für die Verbreitung von Permafrost in den Alpen. *Zeitschrift für Gletscherkunde und Glaziologie.* Bd. IX, Heft 1-2, 1973, pp. 221-227.

Haeberli, W., Hoelzle, M., Keller, F., Schmid, W., Vonder Mühll, D.S. and Wagner, S. (1993). Monitoring the long-term evolution of mountain permafrost in the Swiss Alps. In *Proceedings 6th International Conference on Permafrost, Beijing, China*. South China University of Technology Press, pp. 214-219.

Johnston, G.H. (1981). *Permafrost. Engineering design and construction.* Associate Committee on Geotechnical Research. National Research Council of Canada, John Wiley & Sons. Toronto (540 pp.).

Jurdant, M., Bélair, J.-L., Gérardin, V. and Ducruc, J.-P. (1977). *L'inventaire du Capital-Nature*. Série de la classification écologique du territoire , no 2. Service des Études Écologiques Régionales, Direction Régionale des Terres, Pêches et Environnement Canada, Québec (202 pp.).

Lévesque, R., Allard, M. and Seguin, M.K. (1988). Regional factors of permafrost distribution and thickness, Hudson bay coast, Québec. In *Proceedings, 5th International Conference on Permafrost, Trondheim, Norway*. Tapir Publishers, pp. 199-204.

Lunardini, V.J. (1978). Theory of n-factors and correlations of data. In *Proceedings 3rd International Conference on permafrost, Edmonton, Alberta*. National Research Council of Canada, Ottawa, pp. 41-46.

Lunardini, V.J. (1981). *Heat Transfer in Cold Climates*. Van Nostrand Reinhold Company, Toronto (731 pp.).

Luthin, J.N. and Guymon, G.L. (1974). Soil moisture-vegetation-temperature relationships in central Alaska. J*ournal of Hydrology*, **23**, 233-246.

Ménard, É., Allard, M. and Michaud. Y. (1997). Essai de cartographie du pergélisol discontinu à l'aide d'un SIG: Détroit de Manitounuk, Québec nordique, Canada. *Permafrost and Periglacial Processes*, **8**, 237-244.

Michaud, Y., Allard, M., Parent, M., Paradis, S., Ménard, É., Fortin, M. and Bégin, C. (1994). *Cartographie préliminaire des zones pergélisolées dans le secteur du détroit de Manitounuk et de la Petite Rivière de la Baleine, Hudsonie*. Geological Survey of Canada, Open file 2845 (34 pp.).

Payette, S. (1983). The forest tundra and present tree-lines of the northern Quebec-Labrador peninsula. In *Proceedings of the northern Quebec tree-line conference, Québec*. Collection Nordicana, no. 47, pp. 3-24.

Sanger, F.J. (1963). Degree-days and heat conduction in soils. In *Proceedings International Permafrost Conference,* United States National Academy of Sciences and National Research Council of Canada, no. 1287, pp. 253-262.

Taylor, A.E. (1995). Field measurements of n-factors for natural forest areas, Mackenzie Valley, Northwest Territories. In *Current Research 1995-B*, Geological Survey of Canada, pp. 89-98.

Wright, J. F. (1995). *A hybrid model for predicting permafrost occurrence and thickness*. Masters thesis, Carleton University, Department of Geography, Ottawa (92 pp.).