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Short Communication

A Field Survey of Late-Summer Depths to Frozen Ground at Two Study Areas near Mayo, Yukon Territory, Canada

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ABSTRACT

A field survey of late-summer depths to frozen ground within 1.5 m of ground surface was performed in July and August of 1994, in support of the Cryospheric System programme of the Earth Observing System. This project's stratified sampling technique was devised to be a simple and efficient means to sample a very large number of sites over two areas of interest, within a relatively short period. The successful completion of the 1994 field season resulted in the compilation of a large and representative dataset of depths to frozen ground near Mayo, Yukon Territory. The survey suggests that most late-summer depths to frozen ground cluster within a narrow depth range in the main study area, while a much smaller proportion of this study area's dataset extends deeper to the 1.5 m depth limit of this study. Furthermore, the results of the survey suggest that considerable differences can exist between closely spaced study areas with regard to predominant depths to frozen ground, as well as relations between surface variables and depths to frozen ground. This implies that computer-based models designed to map active layer thicknesses through correlation with landcover and topographic imagery must be supported by field measurements made in all areas being mapped. The extrapolation of correlations measured between active layer conditions and surface variables from one study area to an unsurveyed study area cannot be assumed to be valid. The mapping of active layer thickness over large regions (e.g. central Yukon) will therefore require a considerable field effort if reliable correlative mapping products are to be generated.

RÉSUMÉ

Des mesures (jusqu'à 1.5 m) sur le terrain de la profondeur du sol dégelé à la fin de l'été ont été réalisées en juillet et août 1994 dans le cadre du programme 'cryosphère' de l'observation de la terre. La technique d'échantillonnage préconisée par le projet est apparue comme une méthode simple et efficace pour étudier un très grand nombre de sites en un temps relativement court. Le succès des travaux de terrain 1994 résulte du rassemblement de nombreuses données représentatives près de Mayo dans le Yukon. Les données recueillies suggèrent que la majorité des profondeurs du sol gelé se groupent dans une gamme étroite dans la région principale étudiée, tandis que pour un nombre beaucoup plus limité d'observations, la couche dégelée s'étend plus profondément que la profondeur étudiée, soit 1.5 m. En outre, les résultats du léve suggérent que des différnces considérables peuvent exister entre des régions proches en ce qui concerne la profondeur du sol gelé ainsi que en ce qui concerne les relations entre les variables de surface et les profondeurs du sol gelé. Ceci implique que les modèles utilisés par les ordinateurs pour cartographier les épaisseurs de la couche active en considérant la couverture du sol et de la topographie doivent être étayées par des mesures de

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terrain dans toutes les régions cartographiées. L'extrapolation des corrélations obtenues entre la couche active et les variables de surface depuis une région étudiée vers une autre région ne peut pas à l'avance être supposée valide. La cartographie des épaisseurs de la couche active dans de grandes régions (par exemple le centre du Yukon) demandera de ce fait un nombre considérable de travaux de terrain si on veut obtenir des cartes fiables.

KEY WORDS: active layer; Mayo; CRYSYS

INTRODUCTION

A field survey of depths to frozen ground within 1.5 m of ground surface was performed in late July and August of 1994, at two study areas in the vicinity of Mayo, Yukon Territory. Using a sampling procedure developed during a 1993 reconnaissance visit, depths to frozen ground were measured in all of the primary geological, landcover, and topographic environments found within the study areas. The survey was performed in late summer in order to measure the virtually fully thawed active layer. During the survey, 325 and 100 field sites were visited in study areas 1 and 2, respectively. The collected data indicate that differences in topographic and subsurface properties between study areas can lead to very different characteristic values and distributions of depth to frozen ground, even when these areas are close to each other. This implies that active layer mapping models (see e.g. Leverington and Duguay, 1995) used to correlate between active layer conditions and surface variables can be employed only in areas that have been fully surveyed. The extrapolation of correlations measured between active layer conditions and surface variables from one area to an unsurveyed area cannot be assumed to be valid.

This work is part of the Cryospheric System research programme of the Earth Observing System (CRYSYS, 1991). The data generated by this project and other work in the Mayo region have been used to test the utility of digital classification procedures in the prediction and mapping of depth to frozen ground from topographic and remotely sensed imagery (see Leverington, 1995; Leverington and Duguay, 1994; Leverington and Duguay, 1995).

FIELD LOCATION

Mayo (63°35′N, 135°35′W) is located within the zone of widespread discontinuous permafrost, and within the Boreal Northern Cordilleran Ecoclimatic Region (Ecoregions Working Group, 1989). The village of Mayo is located in the Central Yukon Basin, a region with a continental climate. The mean annual air temperature is −4°C, mean annual rainfall is 185 mm, and mean annual snowfall is 131 cm (Wahl *et al.*, 1987).

Both study areas used in this research are part of the Selwyn Fold Belt of the Cordilleran Orogen. The study areas are underlain by quartzite, argillite, shale, and phylite (Bostock, 1946; Gabrielse *et al.*, 1980; Roots and Murphy, 1992). Quaternary sediments thickly blanket much of Stewart River valley, and bedrock exposures are common only on especially steep hillslopes. Soil development in the region is generally weak, owing to the youthfulness of the surface materials and the dry climate (Brown, 1967; Tarnocai *et al.*, 1985).

Regional topographic effects associated with the mountains of the western Cordillera maintain the severe winter temperatures and low winter snowfall that favour the maintenance of permafrost in the valleys of southern and central Yukon and the upper Mackenzie District (Burn, 1994). Burn (1991) found permafrost thickness in alluvial sediments near Mayo to be ~20 m. A summary of recent borehole measurements associated with construction at Mayo indicates that depth to the permafrost table can range from 0.6 to 13.5 m at sites near the settlement, while permafrost thickness at the Mayo Group Home, east of Mayo, is 37 m (Burn, 1991). September active-layer depths measured at forest sites located ~3 km south-west of Mayo in glaciolacustrine silty clay are known to range from 35 cm to ~100 cm (Burn and Friele, 1989). Measurements made by Burn and Smith (1990) indicate that near-surface permafrost in glaciolacustrine sediments near the Mayo airport and 3 km south-east of Mayo are ice-rich, with measured volumetric ice contents of up to 80%.

Study area 1 is 18 by 18 km in dimension, and includes within its boundaries the village of

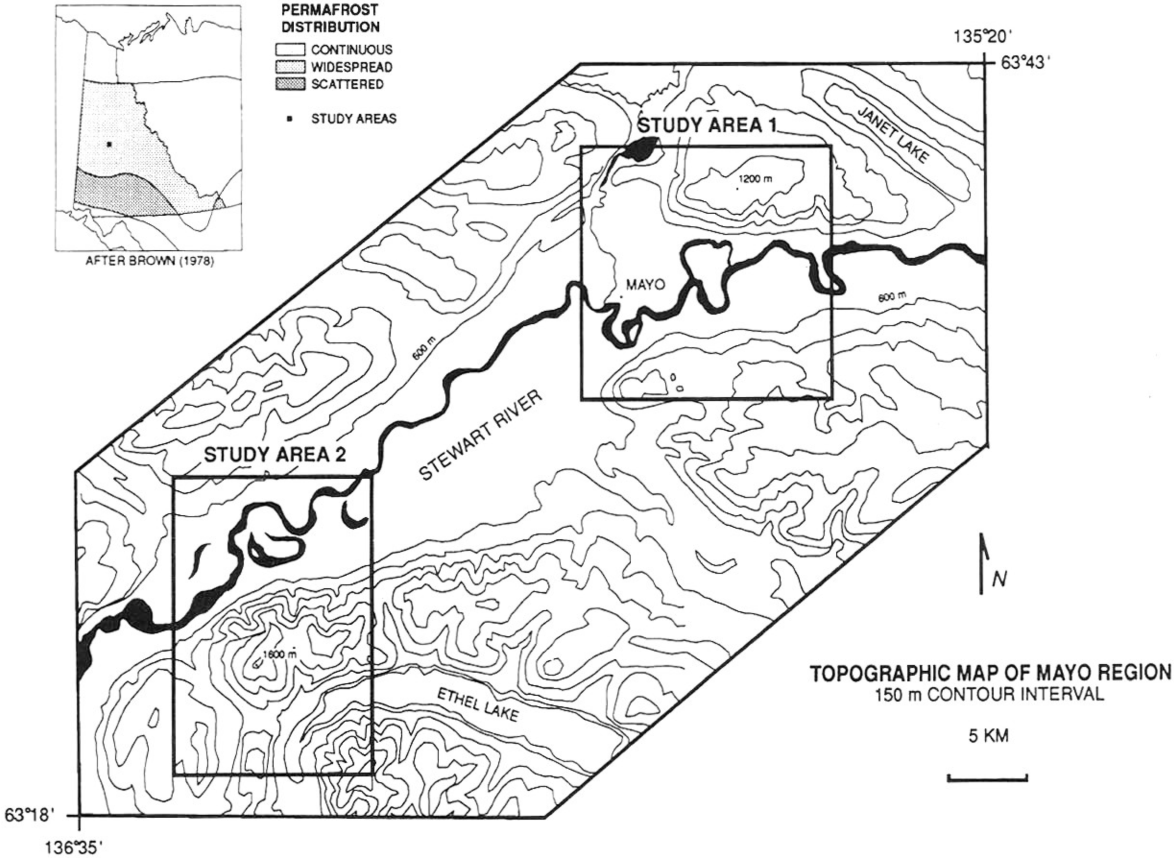

Figure 1 Topographic map of Mayo region.

Mayo itself. The area is bounded along its northern and southern limits by east–west oriented hills (see Figure 1). These hills enclose the valley of the Stewart River, which runs west across the centre of the study area. Elevations range from ~500 m ASL in the Stewart River valley to ~1200 m ASL at the peaks of the hills to the north. The study area is within the limits of the Late-Wisconsin Reid and McConnell advances of the Pleistocene Cordilleran Ice Sheet (Bostock, 1966; Burn, 1985; Hughes *et al.*, 1989). Valley deposits are primarily a luvial and glaciolacustrine in origin, while hillside deposits are primarily colluvial and morainic (Hughes, 1979).

Study area 2 is 13 by 20 km in dimension, and its eastern boundary is ~15 km west of study area 1. The Stewart River meanders in a south-west direction across the northern half of the area, while hills dominate the southern half (see Figure 1). Elevations range from ~500 m ASL in the Stewart River valley to ~1600 m ASL at the peak of Hungry Mountain, located at the centre of the study area. Tundra conditions occur on the summit areas of numerous southern hills. The study area is within the limits of the Reid advance of the Cordilleran Ice Sheet, but outside the limits of the more recent McConnell advance (Bostock, 1966; Burn, 1985; Hughes *et al.*, 1989). Valley deposits consist primarily of loose alluvial sands, while hillside materials are composed largely of colluvial deposits and exposed bedrock.

METHODOLOGY

In general, depths to frozen ground in the Mayo area approach maxima by mid to late July (C. R. Burn, personal communication, 1994). As a result, the 1994 field measurements were made between 19 July and 29 August, allowing measured values of depth to frozen ground to approximate active layer thicknesses. Most areas believed to be characterized by thick (>1.5 m) active layers were sampled first, permitting areas with a thinner active layer (those most sensitive to premature measurement) to be sampled as late as possible in the field season.

Although general site selections were made in advance of the 1994 field season, based upon air photography and 1993 field experience, the precise location and distribution of sites were necessarily determined while in the field. A sampling procedure stratified by predominant landcover, topography, and surface geology was used. It was critical to sample each environment in study area 1 to an extent sufficient to allow for the generation of accurate frozen ground class signatures for the prediction and mapping purposes of CRYSYS (CRYSYS, 1991). The survey of study area 2 was therefore less complete than that of study area 1.

All sites in the survey were selected in accordance with the following rules: (1) all sites must be identifiable on airphotos or locatable using a handheld 'global positioning system' (GPS) unit; (2) all sites must be generally homogeneous with regard to depth to frozen ground, slope, aspect, and vegetation over a 30 by 30 m site area; and (3) all landcover classes must be represented by as many sites as possible, and these sites should be distributed throughout each area. At each site, the following information was measured or estimated: (1) landcover/forest species type, (2) slope, (3) aspect, (4) surface exposure, (5) depth to frozen ground (measured using pits and a 1 m steel probe), and (6) site coordinates (using high-resolution airphotos, satellite imagery, or a GPS unit).

The pits were used as the primary tool for the measurement of depth to frozen ground. It was found in the preliminary (1993) field season that most measurements made by probe in the Mayo area cannot be considered valid without confirmation by a pit. This is due to the inability of the field worker to identify with certainty the nature of any particular ground feature that may obstruct the passage of the steel probe through the ground. Ground features that may be confused with a frost table include tree roots, pebble and cobble strata, and firm clay units.

At least one pit was dug at each site. Exceptions to this rule were made at a small number of sites located in low black spruce (*Picea mariana*) areas characterized by thick organic layers and shallow frozen ground. It was found in 1993 (and confirmed in 1994) that probing was sufficient for frozen ground measurement at these sites and that the digging of pits would have been unnecessarily time consuming and damaging to the local environment.

At most sites, pits were dug to 1.5 m or to the frost table, whichever was reached first. At a minority of sites where digging was especially difficult, pits were dug only to 1 m if ground temperatures were found to exceed 6°C at this depth (temperature measurements were made at these sites by horizontally inserting a temperature probe into the pit wall at 1 m, and allowing temperature readings to stabilize). The vast majority of pits at these particular sites had temperatures of 8–10°C at 1 m; the high thermal conductivity of solidly packed pebbly and cobbly materials probably caused the strong relation with deeply thawed areas. At some sites characterized by loose sandy sediments, pits were dug to 1 m and further probed the additional 50 cm, to expedite field procedures.

Probing was performed to supplement pit measurements, as depth to frozen ground can vary within an individual site. Ground probing was performed at those sites where it was deemed, based upon pit stratigraphy, that the probe measurements would be valid measurements of depth to frozen ground. The majority of sites at which frozen ground was encountered within 90 cm of the ground surface were successfully probed. At such sites, three individual probings were made at 5 m intervals in each of the four cardinal compass directions, centred upon the main site pit. Thus, 12 probe values supplemented the central pit measurement at these sites. This probing methodology was devised for efficiency and simplicity in field implementation.

RESULTS

Upon return from the field, each site was assigned a single 'best-estimate' depth to frozen ground value: either the pit value or, where available, the average of the pit and probe measurements. Depth to frozen ground at any given site almost always clusters around a narrow range of values (with occasional outliers due to drainage differences, for example). Those sites where frozen ground was not found within 1.5 m of the ground surface were given a best-estimate num-

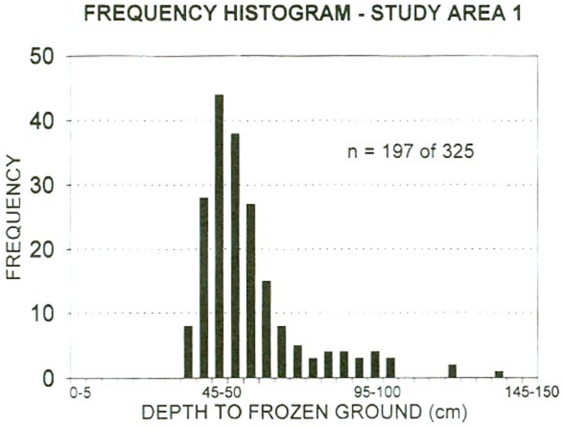

Figure 2 Histogram of depths to frozen ground in study area 1.

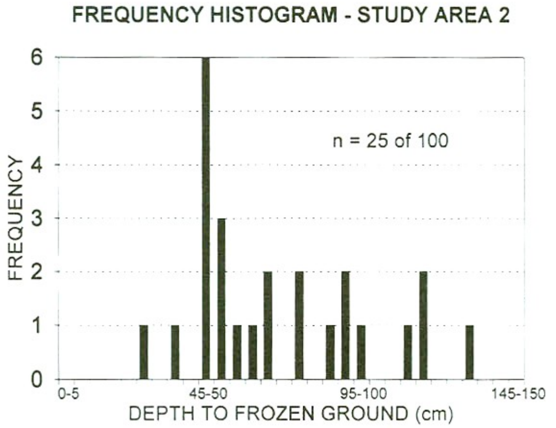

Figure 3 Histogram of depths to frozen ground in study area 2.

ber of >1.5 m. This label does not imply that frozen ground necessarily underlies the site.

A good association exists in study area 1 between landcover, topography, and late-summer near-surface frozen ground conditions. For example, nearly all flat or north- and north-west-facing sites vegetated by spruce (*Picea mariana* and/or *Picea glauca*) were found to be underlain by shallow (<~70 cm) frozen ground. The most shallow frozen ground conditions in study area 1 were consistently found to be correlated with sites vegetated by low and widely spaced ('open') black spruce forest (this type of forest is often associated with scattered willows (*Salix* spp.) and carpeted by thick surface aggregations of moss). The deepest frozen ground conditions are usually associated with mature spruce forests. Frozen ground was not encountered at any site dominantly vegetated by deciduous forest. Only one mixed forest site was found to be underlain by frozen ground within 1.5 m of the ground surface.

The associations that exist in study area 2 between landcover, topography, and late-summer near-surface frozen ground conditions are not as strong as those found in study area 1. For example, there is an inconsistent relationship between spruce stands and frozen ground conditions in the area; some sites vegetated by low and open spruce forest are underlain by both shallow and deeper frozen ground, and yet others are not underlain by near-surface frozen ground at all. Grassy clearings in study area 1 are never associated with near-surface frozen ground, while grassy clearings located at high elevations in study area 2 were sometimes associated with shallow frozen ground.

Based upon earlier 1993 mid-summer measurements of depth to frozen ground, a wide variation in 1994 late-summer measured depths was expected to characterize both areas. Instead, it is evident from the frequency histogram presented in Figure 2 that the depths to frozen ground of study area 1 cluster around approximately 55 cm, with a standard deviation of ~10 cm being associated with the main distribution curve. A tail of depths derived from a much lower proportion of sites extends to the 1.5 m depth limit of this study, even though effort was made during the 1994 field season to sample areas with depths to frozen ground greater than 1 m (e.g. those sites vegetated by deciduous, mixed, and mature spruce forest). Thus, rather than being characterized by a gradation of classes, the dataset suggests that frozen ground in study area 1 tends to be present in late summer within a narrow range of shallow depths, or does not exist at all, within 1.5 m of ground surface.

Despite the fact that the landcover properties of the two study areas are similar, the depths to frozen ground of study area 2 were found to vary somewhat more than those of study area 1 (see Figure 3). The frequency distribution for study area 2 peaks at the same point as the distribution for study area 1, but extends to greater proportions across all depths considererd in this study. Differences in surface geology, drainage conditions, and topography are likely prime causes of the difference in distributions of depths to frozen ground between the two study areas.

DISCUSSION

The differences between the two study areas' associative relationships and datasets of depth to frozen ground are notable with regard to the use of such datasets in the prediction and mapping of frozen ground classes over large areas using correlative methods (e.g. maximum likelihood, evidential reasoning, or neural networks; see Peddle, 1991; Leverington, 1995; Leverington and Duguay, 1994; Leverington and Duguay, 1995). For example, it is apparent from the simple relations between surface conditions and frozen ground (described above) that the application of correlative techniques toward prediction of depths to frozen ground in a given area can only be made with reasonable confidence using a training dataset derived from the area in question (this is confirmed by classification results presented by Leverington 1995, produced using the dataset described here). The correlation between surface characteristics and depth to frozen ground cannot be assumed to be constant across different areas, even when these areas are essentially identical with regard to general climatic conditions and location. Differences in subsurface and topographic properties more subtle than those found in the Mayo datasets would nevertheless complicate the portability of training data in mapping projects. The mapping of large regions (e.g. central Yukon) will require a considerable field effort if reliable correlative mapping products are to be generated, and the costs of such a field effort solely for the purposes of projects such as EOS-CRYSYS may be prohibitively high.

Further surveys of depth to late-summer frozen ground should be performed in other regions of Canada's north; very few areas have been thoroughly sampled with regard to depth to frozen ground, and more datasets (representing a range of northern environments) are required in order to further determine the utility of correlative procedures for active layer prediction. The establishment of an accepted methodology for such field efforts may aid in the application of correlative prediction procedures over larger areas, and could result in new permafrost insights owing to direct data comparability between diverse study areas.

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REFERENCES

Bostock, H. S. (1946). *Mayo, Yukon Territory*. Map 890A, Geological Survey of Canada.

Bostock, H. S. (1966). *Notes on Glaciation in Central Yukon Territory*. Geological Survey of Canada, Paper 65–36 (18 pp.).

Brown, R. J. E. (1967) *Permafrost Investigations in British Columbia and Yukon Territory*. Division of Building Research, National Research Council of Canada, Technical Paper 253 (55 pp.).

Brown, R. J. E. (1978). Permafrost. In *Hydrological Atlas of Canada*. Fisheries and Environment Canada, Ottawa, Plate 32.

Burn, C. R. (1985). *Guidebook to the Surface Geology and Environmental History of the Silver Trail*. Silver Trail Tourism Association, Mayo, Yukon (38 pp.).

Burn, C. R. (1991). Permafrost and ground ice conditions reported during recent ice-wedge development at Mayo, Yukon Territory. *Permafrost and Periglacial Processes*, **1**, 3–14.

Burn, C. R. (1994). Permafrost, tectonics and past and future regional climate change, Yukon and adjacent Northwest Territories. *Canadian Journal of Earth Sciences*, **31**, 182–191.

Burn, C. R. and Friele, P. A. (1989). Geomorphology, vegetation succession, soil characteristics and permafrost in retrogressive thaw slumps near Mayo, Yukon Territory. *Arctic*, **42**, 31–40.

Burn, C. R. and Smith, C. A. S. (1990). Development of thermokarst lakes during the Holocene at sites near Mayo, Yukon Territory. *Permafrost and Periglacial Processes*, **1**, 161–176.

CRYSYS (1991). *Science Report on the CRYSYS Workshop for University Investigators*. Institute for Space and Terrestrial Science, University of Waterloo (71 pp.).

Ecoregions Working Group (1989). *Ecoclimatic Regions of Canada*. Ecological Land Classification Series no. 23, Canada Committee on Ecological Land Classification, Environment Canada (118 pp.).

Gabrielse, H., Tempelman-Kluit, D. J., Blusson, S. L. and Campbell, R. B. (1980). *MacMillan River: Yukon, District of Mackenzie, Alaska*. Map 1398A, Map Sheet 105–115, 1:1 000 000 Geological Atlas, Geological Survey of Canada.

Hughes, O. L. (1979). *Janet Lake, Yukon Territory: Surficial Geology and Geomorphology*. Map 4-1982, Geological Survey of Canada.

Hughes, O. L., Rutter, N. W. and Clague, J. J. (1989). Yukon Territory (Quaternary stratigraphy and history, Cordilleran Ice Sheet). In Chapter 1 of Fulton, R. J. (ed.), *Quaternary Geology Canada and Greenland*. Geological Survey of Canada, Geology of Canada, no. 1, pp. 58–62.

Leverington, D. W. (1995). *Prediction of Depth to Late-Summer Frozen Ground Using Satellite Imagery and Digital Topographic Data, Mayo, Yukon Territory*. MSc thesis, Department of Geology, University of Ottawa (139 pp.).

Leverington, D. W. and Duguay, C. R. (1994). Prediction of depth to frozen ground using satellite imagery and digital topographic data: Mayo, Y. T. In *Proceedings: International Association for Mathematical Geology Annual Conference*. Mont Tremblant, Quebec, pp. 218–222.

Leverington, D. W. and Duguay, C. R. (1995). Application of a neural network toward mapping near-surface active layer thickness. In *Proceedings: 17th Canadian Symposium on Remote Sensing*. Saskatoon, Saskatchewan, Vol. 1, pp. 47–51.

Peddle, D. R. (1991). *Evidential Classification of Landcover and Permafrost from Multisource Remote Sensing Imagery in Mountainous Terrain, Yukon*. MSc thesis, Department of Geography, University of Calgary (163 pp.).

Roots, C. F. and Murphy, D. C. (1992). New developments in the geology of Mayo map area, Yukon Territory. In *Current Research, Part A*, Geological Survey of Canada, Paper 92-1A, pp. 163–171.

Tarnocai, C., Smith, S. and Hughes, O. L. (1985). Soil development on Quaternary deposits of various ages in central Yukon Territory. In *Current Research, Part A*, Geological Survey of Canada, Paper 85-1A, pp. 229–238.

Wahl, H. E., Fraser, D. B., Harvey, R. C. and Maxwell, J. B. (1987). *Climate of Yukon*. Environment Canada, Atmospheric Environment Service (323 pp.).