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EFFECT OF ATMOSPHERIC TEMPERATURE INVERSIONS ON GROUND SURFACE TEMPERATURES AND DISCONTINUOUS PERMAFROST, NORMAN WELLS, MACKENZIE VALLEY, CANADA

Al Taylor[1], Mark Nixon[2], Joe Eley[3], Margo Burgess[2], Paul Egginton[2]

1. 9379 Maryland Drive, Sidney, BC V8L 2R5 Canada
e-mail: altaylor@kcorp.com

2. Terrain Sciences Division, Geological Survey of Canada
601 Booth St., Ottawa, ON K1A 0E8 Canada

3. Atmospheric Environment Service, Environment Canada,
11 Innovation Blvd., Saskatoon, SK S7N 3H5

Abstract

Atmospheric temperature inversions, measured during weather balloon ascents, are particularly frequent in the Arctic because of the negative radiation balance over snow and ice. To study the effect of persistent atmospheric inversions on discontinuous permafrost, we established paired air and ground surface temperature instrumentation on a 15 km transect over the elevation range 60-969 m ASL at Norman Wells, Canada. Measured surface air and ground temperatures reflect atmospheric temperature inversions on a mean annual basis. Permafrost thicknesses at elevations above the valley appear to have been limited by the persistent atmospheric inversions of this region. Permafrost is 52-62 m deep in the valley bottom (~60 m ASL), thins to <45 m or is absent where the mean annual atmospheric inversion strength is the greatest (100-500 m ASL), and is estimated 200-300 m thick at the summit (969 m ASL). Numerous springs and icings 100-200 m ASL are geomorphic evidence for the thinning and perforation of permafrost.

Introduction

An atmospheric inversion is an increase in air temperature with height best observed during weather balloon (radiosonde) ascents. This is an atypical situation in the lower atmosphere, as temperatures normally decrease with altitude. Inversions are particularly frequent in the Arctic because of the negative radiation balance over snow and ice that prevails for much of the year, particularly during calm conditions of the arctic winter (Burns, 1973). In areas of large topographic relief, cold air drainage into a valley may also contribute (Harris, 1986). With such relief, upper air inversions will influence air and ground surface temperatures on the mountain slopes (e.g., Haugen and Brown, 1978), and, in regions of discontinuous permafrost, may influence the distribution and thickness of permafrost.

Norman Wells (65°17.5' N, 126°45.7' W, elevation 60-90 m ASL, Figure 1a) lies within the discontinuous permafrost zone of the Mackenzie River valley, northwestern Canada (Brown, 1965) and frequently experiences atmospheric inversions 300-1500 m above the surface on a winter day (Eley, 1974). The slopes of Mount Hamar (summit elevation 969 m ASL), some 10-15 km north of Norman Wells, provide an opportunity to study the impact of atmospheric inversions on the thickness and distribution of mountain permafrost. We have set up a 7-station air and ground temperature measuring transect from Norman Wells to the summit of Mount Hamar to assess the correlation between atmospheric inversions and the ground environment. This paper describes the transect and provides preliminary results and interpretation.

Permafrost thermal regime

There is probably no permafrost beneath the Mackenzie River, which is several kilometres wide (electromagnetic surveys in the Mackenzie Delta suggest thick taliks occur beneath major channels, e. g., Geophysicon, 1983). Temperatures were obtained in the 1940's by industrial logging of petroleum exploration wells on the banks and low-lying islands of the Mackenzie River (Judge, 1973). While the accuracy of these logs is unknown, the depth to 0°C or permafrost base appears to be 52-62 m at wells within 100 m of the shore (Figure 1a, b). More recently, precision tempera-

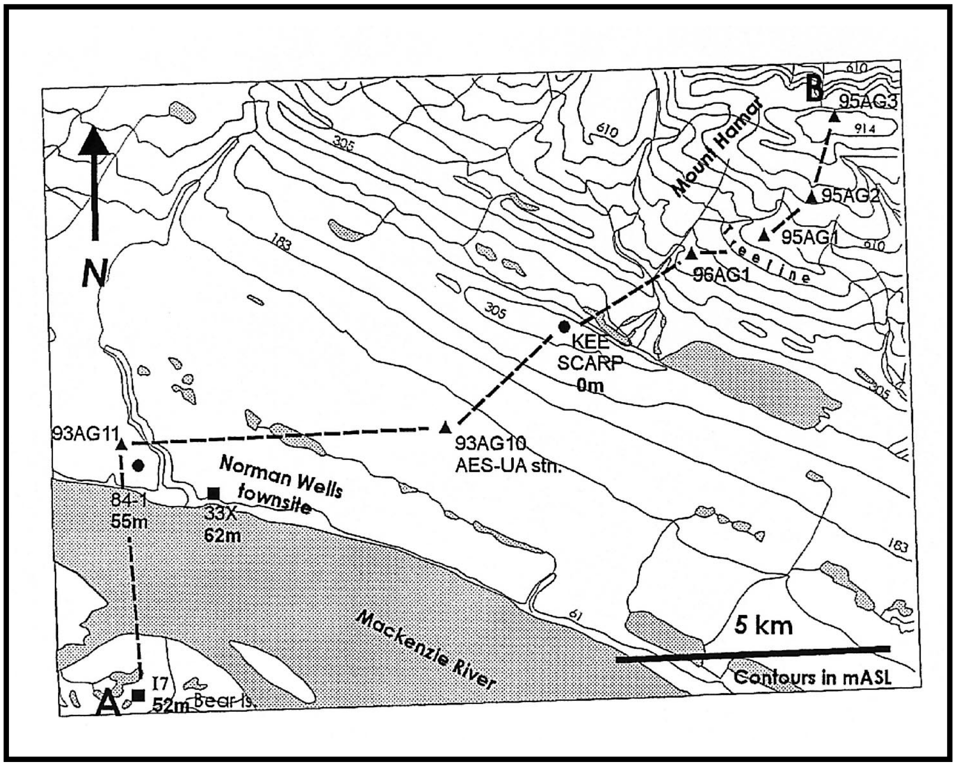

Figure 1 (a). Location of Norman Wells and Mount Hamar in the Mackenzie Valley, discontinuous permafrost zone, Canada. Sites are labelled, e.g., "95"= 1995, year of installation; "AG"=air and ground temperatures; "3"=site number; "84-1", Norman Wells pipeline monitoring site; "33X", "I7", deep petroleum wells. Depths to permafrost base are shown where measured (e.g. "52 m"). A-B is the instrumented transect studied here.

tures in specially drilled holes indicate that permafrost is the order of 50 m at sites along the Norman Wells oil pipeline about 1-3 km from the river (Burgess and Riseborough, 1990) and is absent at Kee Scarp (344 m ASL) at the base of Mount Hamar.

The authors have observed about 20 springs or regular major icings at elevations 100-200 m ASL between Gibson Gap (60 km west) and Vermillion Creek (35 km east). The timing, sizes and volumes of these icings suggests that they are not likely to arise solely from the active layer, and suggest the absence of permafrost elsewhere in this zone.

Instrumentation and sources of data

The Atmospheric Environment Service (AES), Environment Canada, maintains a weather and upper air station at Norman Wells (AES-UA, Figure 1a). Surface air temperatures and other parameters are measured hourly. Radiosonde releases are made twice a day, an early morning flight around 0500 MST (local time), and a late afternoon flight around 1700 MST; air temperatures are measured approximately every 60 m upward from about 100 m above the ground surface.

For this study, the Geological Survey of Canada (GSC) installed paired air and shallow ground temperature instruments in undisturbed, natural areas at four elevations on Mount Hamar (sites 95AG1, 95AG2, 95AG3 and 96AG1, Figure 1a,b), complementing sites established earlier in undisturbed forest in the valley bottom (93AG10, 93AG11) as part of a larger Mackenzie Valley permafrost and active layer monitoring network (Nixon et al., 1995; Nixon and Taylor, 1998). At these sites, air temperatures are measured with a thermistor in a 6-plate radiation shield at a height of 1.5 m, and ground temperatures are recorded at a depth of 3 to 7 cm, generally within a dense peat or mineral soil; inexpensive miniature data loggers are used to record the data at 2 to 6 hour intervals for a year.

Atmospheric temperature inversions at Norman Wells

At the Norman Wells AES weather and upper air station, inversions occur on 50-70% of early morning radiosonde releases throughout the year, on 59% of the late afternoon ascents December to February and on 5-22% of the daytime ascents from March to November (Burns, 1973). Mean upper air temperature profiles, 1961-1970, show strong inversions to about 1500 m ASL for early morning releases in January, April and October, and to 500 m in July (Fig. 10 in Eley, 1974).

Figure 2 shows mean annual upper air temperatures (MUAT) versus altitude for the 1996-1997 year, as derived from radiosonde data. For early morning flights, a strong inversion (+8°C increase per kilometre elevation) is present to 300 m elevation and a weak

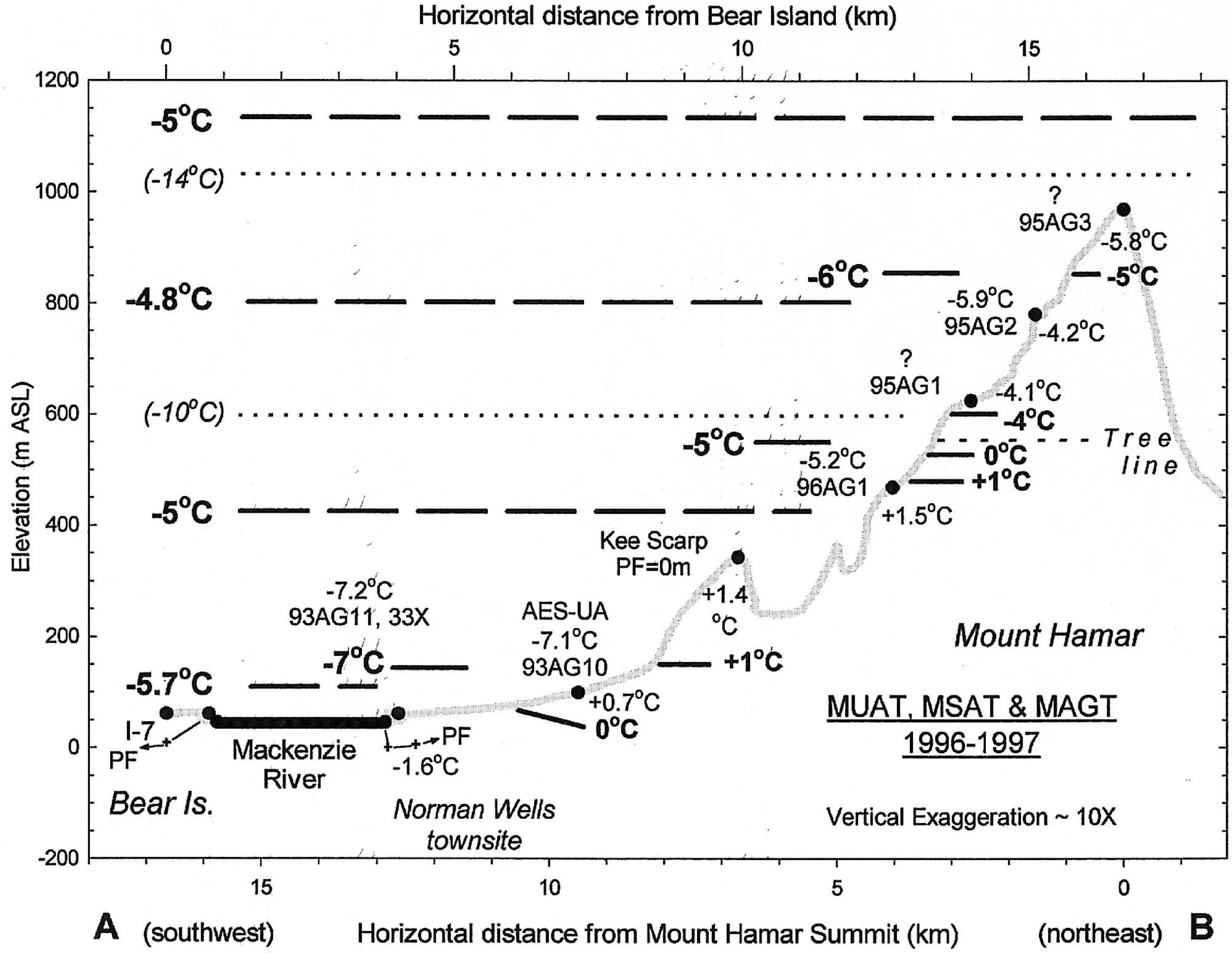

Figure 1 (b). Proposed generalized upper air, surface air and ground temperature structure for the topographic elevation transect through the instrumented sites (A-B, Fig. 1a); see text. Sites as in Figure 1a. + = measured permafrost base.

inversion (+1.6°C/km) from 300-1000 m; for the late afternoon releases, upper air temperatures decrease slightly with altitude. The mean annual temperature of both flight times shows an inversion centred at 600-900 m elevation. Note that such mean data is only an approximation, as twice daily measurements do not consider the duration of inversions adequately. However, these MUAT values represent a large departure from a "normal" atmosphere (lapse rate ~ -6.5°C/km, also shown in Figure 2).

Results and discussion

Considerable loss of data occurred at some of our surface air temperature sites during this period due to logger failures (particularly in mid-winter), and to loss of air screen due to wind at the summit; less than a year's air data are available at 95AG1 and 95AG3, and this limited the analysis.

Figure 3 is a bubble plot of the occurrence of inversion events of duration >18 h recorded with our surface air temperature instrumentation at 96AG1 (469 m ASL) relative to 93AG10 (95 m); the area of each "bubble" is proportional to the duration. These surface inversions often lasted for several days from fall 1996 to spring 1997. The mean inversion strength of the events selected is 4.7 +/- 0.3°C, and the mean duration is 3.0 +/- 0.5 days.

Returning to Figure 2, we note that the upper air inversions appear to be reflected in our surface-based measurements of mean annual surface air temperatures (MSAT) and mean annual ground temperatures (MAGT). MSAT at 469 m ASL (96AG1) are almost 2° higher than at the valley bottom, rather than some 3°C lower than valley bottom expected under a normal lapse rate. MSAT decrease at the next higher site (800 m ASL, 95AG2) but still remain about 1°C higher than in the valley bottom.

MAGT appear to follow MSAT but are higher due to effects of vegetation and snowcover, particularly below the treeline. The larger range in MAGT may be attributed to the sensitivity of ground temperatures to site variability (vegetation, snowcover, situation) and placement of the ground temperature sensor. The diagram presents the important conclusion that, on a mean

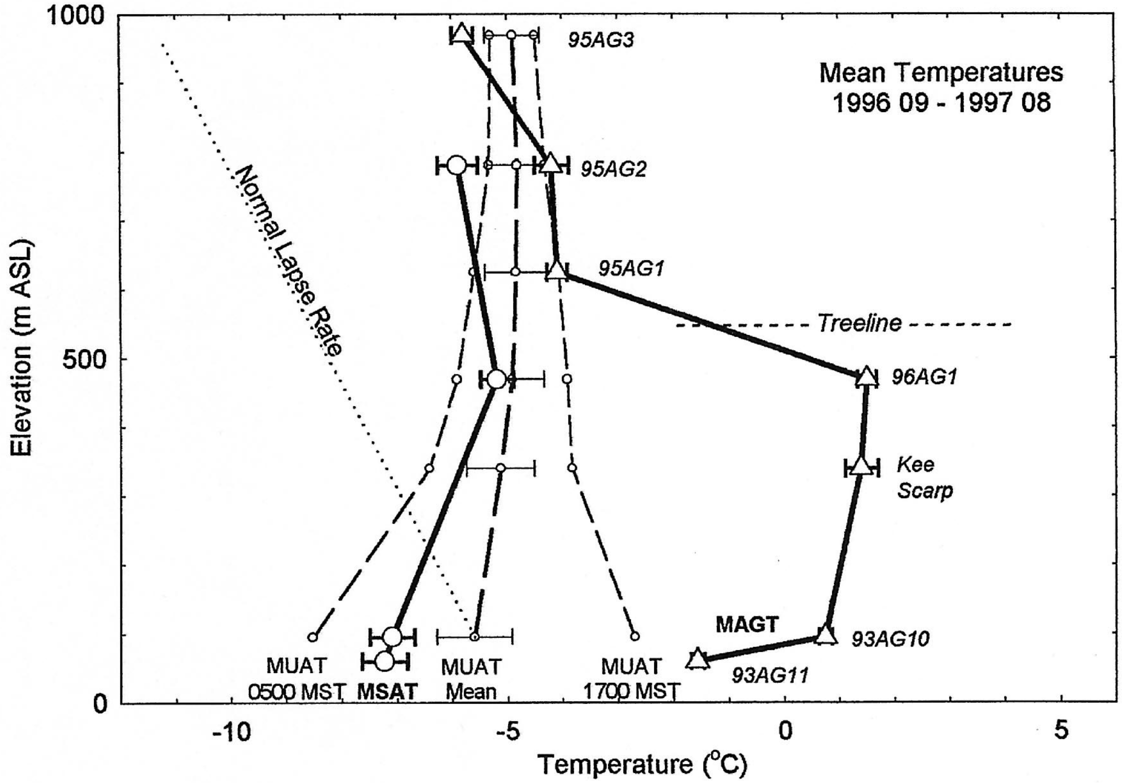

Figure 2. Mean annual upper air temperatures (MUAT) for early morning and late afternoon radiosonde flights, and the mean of data from both flights on an annual basis. The "normal" lower atmosphere lapse rate of -6.5oC/km altitude is shown for contrast. Mean annual surface air (MSAT) and ground temperatures (MAGT) from the topographic transect reported here. Error bars are standard errors.

annual basis, air temperature inversions are reflected in ground temperature inversions over our elevation range.

Kee Scarp experienced a fire in 1954 (P. Rivard, Government of the Northwest Territories Fire Office, personal communication 1997; Isaacs, 1974) and the destruction of forest cover and moss would lead to a modified surface temperature due to increased solar absorption and altered winter cooling. At present, the Kee Scarp area appears to be largely revegetated but is unlikely to have regained its pre-fire state, so the

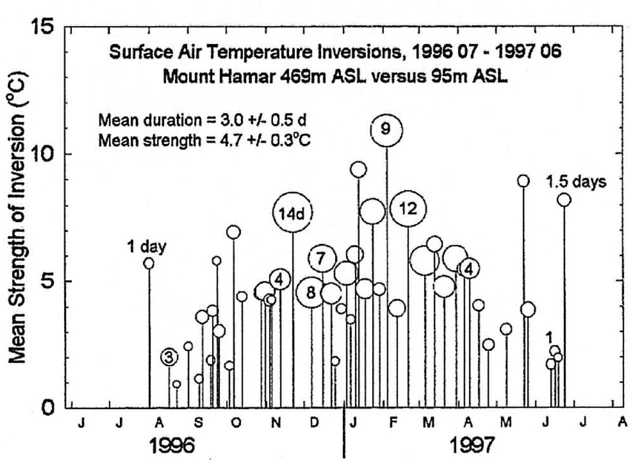

Figure 3. Bubble plot of the occurrence, mean strength and duration of inversion events longer than 18 hours observed at a mid-elevation site on Mount Hamar during the 1996-97 year. The area of each "bubble" is proportional to the duration, indicated in days in some of the circles.

MAGT shown in Figure 2 may reflect this disruption. As far as we know, the other sites are not located in recent burn areas.

Implications of atmospheric inversions

On Regional Surface Air and Ground Temperatures

Based on our observations of MSAT, MAGT and on AES's MUAT, we hypothesize the general nature of the air and ground temperature structure for the 1996-97 year in the study area (Figure 1b). MSAT and MAGT are shown as short, bold labelled contours on the "air" and "ground" side, respectively, of the topographic contour. MSAT decrease from -7°C near the valley bottom only to - 6°C near the summit. MAGT are <0°C in the valley bottom around Norman Wells. The 0°C boundary may lie along the gradual slope approaching the AES Upper Air Station, defining the lower limit of an elevation range of possibly 400 m where ground surface temperatures may be in general >0°C. Just above the treeline at approximately 500 m elevation, MAGT decrease to -4°C but do not fall below -6°C even at the summit. Qualitatively, this abrupt decrease in MAGT at the treeline can be attributed to the lack of vegetation, and reduced snowcover and windswept aspect observed by the authors at these higher sites.

MUAT (bold, long-dash atmospheric contours in Figure 1b) increase from -5.7°C in the valley bottom near the river to -4.8°C around 800 m elevation, then decrease with altitude, with the -5°C contour about 200 m above Mount Hamar summit. The atmospheric temperature structure expected under a "normal" lapse rate of -6.5°C/km altitude (light, short dashed lines) is in striking contrast, predicting mid-mountain temperatures of -10°C (rather than - 5°C) and summit temperatures of -13°C (rather than -6°C).

On Permafrost

This atmosphere temperature structure, if typical of the long term, will define the permafrost distribution and thickness in this region of discontinuous permafrost. It offers a plausible explanation, qualitative at present, for the observed thinning of permafrost several kilometres from the river and at Kee Scarp. It further suggests that permafrost may be thin (or absent) through a mid-elevation range 100-500 m ASL where MAGT are >0°C (and MSAT are higher than in the valley bottom). Springs and icings observed in this zone are strong geomorphic evidence of areas of permafrost absence, or of taliks that perforate the permafrost. The net effect of persistent inversions on this zone is to limit the thickening of permafrost with elevation and to allow taliks to exist.

At 500 m ASL (approximately the treeline), the abrupt decrease in MAGT suggests that permafrost may increase in thickness from the mid-elevation zone values. On the basis of the regional geothermal gradient, 20°C/km, obtained from bedrock temperatures (50-120 m deep) at Kee Scarp, a permafrost thickness of 200 m would be in equilibrium with today's conditions above the treeline where the MAGT is -4°C, and 300 m at Mount Hamar summit, where MAGT is -6°C. The net effect of persistent inversions above the treeline is to reduce the increase of permafrost thickness with elevation expected under a "normal" atmosphere.

Geothermal numerical modelling needs to be undertaken to fully consider the response of permafrost to the inversion structure identified here, in the context of the longer term and Holocene environments. This may be undertaken when more data are available from this transect.

Conclusions

We have examined radiosonde upper air temperatures, and surface air and ground temperatures from a 15 km instrumented transect extending northeast from Norman Wells (~60 m ASL) to the summit of Mount Hamar (969 m ASL) in the discontinuous permafrost of the Mackenzie Valley, Canada.

(1) Upper air radiosonde temperatures at Norman Wells for the decade 1961-70 and for 1996-1997 show that atmospheric temperature inversions are prevalent in seasonal to annual means, to altitudes above the summit of Mount Hamar.

(2) Air and ground temperatures measured along a surface transect from near the Mackenzie River (~60 m ASL) to the summit of Mount Hamar (969 m ASL) also exhibit an inversion with elevation. Mean annual air and ground temperatures at 500 m ASL are 2°C and at least 1°C higher, respectively, than in the valley bottom. These values are attributed to persistent atmospheric inversions and possibly to depressed valley temperatures due to cold air drainage. Mount Hamar summit air temperatures are some 7°C higher than predicted under normal lapse rate conditions.

(3) Permafrost thickness is 52-62 m in the valley bottom (~60 m ASL), and pinches out or is not likely to exceed 50 m at a mid-elevation zone between 100 m and 500 m ASL. In this forested zone, permafrost thickness appears to be reduced by the environment of persistent air temperature inversions. Permafrost thickness probably increases above the treeline, and may be 200-300 m on the summit. In this higher, sparsely vegetated zone of low snow accumulation, the growth of permafrost thickness with elevation appears to be limited by the persistent atmospheric inversions.

(4) Some 20 springs and icings observed around 100 m elevation in the region may be geomorphic evidence for taliks perforating thin permafrost in the mid-elevation zone.

Acknowledgments

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