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High Arctic permafrost observatory at Alert, Nunavut – analysis of a 23 year data set

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ABSTRACT: Ground temperatures up to depths of 60 m have been measured on a regular basis since 1978 in five boreholes at Canadian Forces Station Alert, Nunavut. A general increase in air temperature of 0.12°C per year since 1986 has been accompanied by an observed rise in permafrost temperature in the upper 30 m with the trend interrupted by a brief period of cooling in the early 1990s. Since the mid 1990s, permafrost temperatures in the upper 30 m have increased by 0.15°C per year. Cooling of air temperature from the 1950s to the early 1980s appears to have resulted in lower permafrost temperature at depths below 40 m. Snow cover is thin but exhibits high spatial and temporal variability which is reflected in the response of the shallow permafrost temperatures to changes in air temperature.

1 INTRODUCTION

General Circulation Models (eg. Flato et al. 2000) predict increases in mean annual air temperature of several degrees in the Canadian Arctic in response to a doubling of the concentration of atmospheric carbon dioxide. Variations in permafrost temperatures can be a sensitive indicator of climate change and climate variability (Lachenbruch et al. 1988). The ground acts as a natural low pass filter, so that only longer term trends reach to greater depths. Deeper ground temperatures contain a signal of past temperature changes at the ground surface that may be related to past climate change. This signal may be especially well preserved in the permafrost of the High Arctic because of the lack of complicating water movement and the shallow active layer.

The detection of the climate change signal in permafrost is expected to occur sooner in the High Arctic due to the predicted greater increase in air temperature compared to lower latitudes and the low surface buffering effect of the sparse vegetation and thin snow cover (Smith and Burgess 1998). Recent studies indicate that trends in climate over the last century have not been uniform throughout northern North America. A general increase in air temperature has occurred in the western Arctic over the last century (Environment Canada 2000a). Observations indicate that permafrost in Alaska is warming (eg. Osterkamp & Romanovsky 1999). Data from active layer monitoring sites in the Mackenzie Delta indicate that thaw depths and ground subsidence increased during the 1990s (Wolfe et al. 2000, Smith et al. 2001). Studies in northern Quebec indicate that permafrost temperatures decreased into the early 1990s (Allard et al. 1995). Very little however is known about recent trends in permafrost temperatures in the Canadian High Arctic.

Ground temperatures up to depths of 60 m have been measured manually since 1978 on a regular basis at five borehole sites on northern Ellesmere Island (Fig. 1) at Canadian Forces Station Alert, Nunavut (82.5°N, 62.4°W) in a collaborative project between the Department of National Defence (DND) and the Geological Survey of Canada (GSC). These boreholes

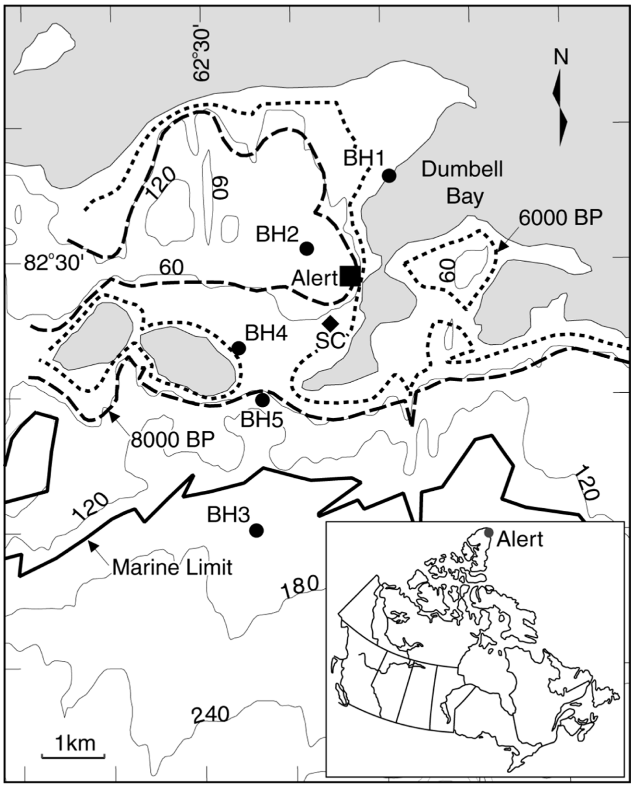

Figure 1. Location of permafrost monitoring sites at CFS Alert, Nunavut, Canada. The dashed lines labelled 6000 and 8000 BP indicate the approximate position of the shoreline 6000 and 8000 years ago (from England 1976). The contour interval is 60 m and SC refers to the location of Environment Canada's snow course.

represent the most northerly permafrost thermal monitoring site in the world and are an important contribution to the recently established Global Terrestrial Network for Permafrost (Burgess et al. 2000). The 23 year data set is one of the longest records of permafrost temperatures in Canada. An initial analysis of the first decade of the data record was conducted in 1991 by Freymond (1991). The site was upgraded with data loggers and air and ground temperature sensors at three boreholes in summer 2000.

This paper presents an analysis of the data collected at Alert over the 23 year period and documents recent trends in permafrost temperature. Although a limited one year data set of higher frequency logger data is now available from this site, this paper will focus mainly on the manually collected data.

2 DESCRIPTION OF STUDY SITE AND INSTRUMENTATION

The thermistors are calibrated to an absolute value of ±0.1°C but changes of ±0.01°C can be resolved. However, until 2001, frequent changes in the observers taking the measurements lowered the quality of the data and a resolution of ±0.1°C better reflects the precision of the measurements.

Snow depth is manually measured at four points at each site and an assessment is made of the proportion of the area around the borehole covered by snow during site visits. Air temperature and precipitation data are collected at the Environment Canada weather station at Alert.

In July 2000, air and ground surface temperature sensors were installed at BH3, BH4 and BH5. Thermistors were placed in radiation shields 1.5 m above the ground surface and connected to single channel data loggers to measure air temperature at four hour intervals. A similar sensor was placed just below the ground surface to measure ground surface temperature. Air and ground surface temperatures are recorded to an accuracy of ±0.5°C with a resolution of ±0.3°C. Eight channel data loggers with a resolution of better than ±0.01°C were connected to the temperature cables at these 3 boreholes to record ground temperatures at eight hour intervals. The first data retrieval from all data loggers occurred in August 2001. Continued collection and analysis of the higher frequency data will allow a better assessment of the local microclimate at each site.

The two dominant rock types encountered at the sites are a fine-grained varved argillite consisting of quartz and calcite and a coarser calcareous greywacke. An overburden layer of shattered rock up to 3.8 m thick and infilled with ice is also present. A more detailed description of geology is found in Taylor et al. (1982).

Permafrost is estimated to be over 600 m thick (Taylor et al. 1982, Freymond 1991). This area was subject to post glacial uplift and the marine limit has been estimated to be 135 m above sea level. All borehole sites except BH3 have emerged over the past 8000 years (Fig. 1). Permafrost thickness is therefore expected to vary with elevation with permafrost being thinnest at BH1 which emerged most recently.

The climate at Alert is cold and dry with a normal mean annual air temperature of −18.1°C (Environment Canada 1997). On average there are 77 days in which the maximum daily air temperature is above 0°C and the normal freezing degree day index is 6820. Total annual precipitation is 154 mm of which about 90% falls as snow. The maximum month-end snow cover of 37 cm occurs in April.

3 GROUND TEMPERATURE REGIME AT ALERT

3.1 *Spatial variation*

Ground temperature envelopes for 1997 at BH1, BH2, BH3 and BH5 are shown in Figure 2. Problems (remedied in 2000) with a cable connector at BH4 resulted in a suspension of data collection in 1988 and no data from this incomplete record will be reported here. Due to the moderate thermal conductivity (~3 W/mK) and lack of a surface buffer layer, the annual temperature wave propagates to a depth of 20 to 25 m. Ground temperatures are lowest at BH2 and BH5 and highest at BH1 which is closest to the ocean. Mean annual ground surface temperature has been determined by extrapolating the mean ground temperature below the level of zero annual amplitude to the ground surface. The mean annual ground surface temperature at BH1 is −13.7°C, at BH3 is −15.1°C and BH2 is −16.2°C. Temperatures are not measured below the level of zero annual amplitude at BH5. The mean annual surface temperature could not be extrapolated, but it appears

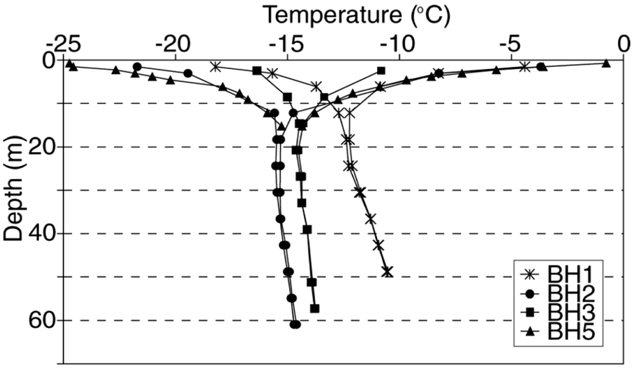

Figure 2. Ground temperature envelopes (annual maximum and minimum temperatures) for 1997 for four of the Alert boreholes.

to be similar to that of BH2. The largest annual range in shallow ground temperatures (upper 1 m) is observed at BH5 where it is about 24°C.

The shallowest sensor is within the permafrost at all sites. It is not possible to determine the active layer thickness from the manual data set. Probing is also not possible because of the coarse surface materials. The depth of the first sensor varies between sites but the shallowest sensor is at a depth of 0.76 m (BH5) and thus the active layer thickness is likely less than 0.76 m. A detailed analysis of the ground surface temperature data collected since 2000 together with the higher frequency shallow permafrost temperature data should enable better estimates of active layer thickness. In addition, a thermistor connected to a data logger was installed at a depth of 15–20 cm at BH3, BH4 and BH5 in August 2001. Data from these sensors should provide further information on development of the active layer.

The differences in ground temperatures between the sites are partly due to differences in snow cover and exposure. Snow cover is generally thin to absent in the Alert area but exhibits high temporal (Fig. 3) and spatial variability. Snow depth is shallowest at BH5 (Fig. 4) where it is often less than 10 cm throughout the winter. BH5 is situated on a north facing slope in a valley aligned with the prevailing wind. Redistribution of the snow by wind is the likely reason for the low snow cover conditions at this site (Taylor et al. 1982). The moderating effect of snow cover on winter ground temperature is illustrated in Figure 5 which shows daily ground surface temperatures between July 2000 and August 2001 for BH3 and BH5. Ground surface temperature during the winter was up to 12°C lower at BH5 than that at BH3. Ground surface temperatures also show greater variation during the winter at BH5 and tend to more closely track changes in air temperature. This difference in ground surface temperature is due to a difference in snow cover at the two sites (Fig. 4) with snow cover generally thicker at BH3. The presence of a thicker snow cover can also lead to a delay in warming of the ground in the spring. The ground surface warmed up to temperatures above 0°C at BH5 before BH3 where heat flow into the ground was restricted by the presence of the snow cover. This resulted in a thaw season at BH3 that was about one month shorter than that at BH5. The lack of a thick snow cover and associated lower winter ground temperatures at BH5 result in lower mean annual ground temperatures than those observed at BH1 and BH3 which tend to have thicker snow cover.

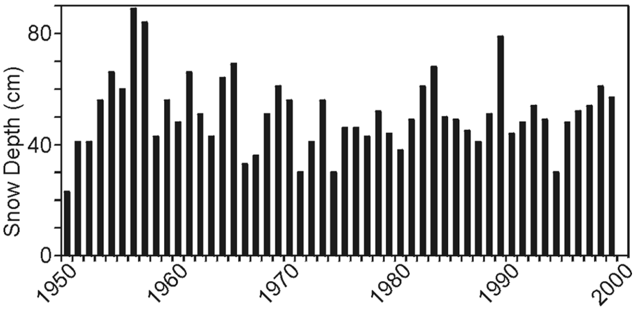

Figure 3. Maximum winter snow depth obtained from the Environment Canada weather station at Alert. Location shown in Figure 1. Data are from Environment Canada (2000b).

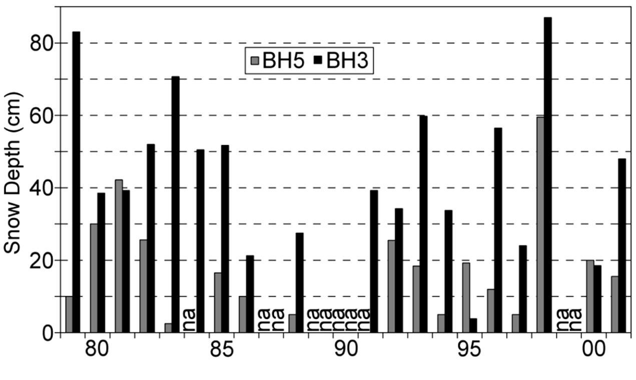

Figure 4. Maximum winter snow depth for boreholes 3 and 5 (na = data not available).

3.2 *Temporal variation*

Shallow ground temperatures to a depth of 15 m at BH5 are plotted along with mean monthly air temperature from the Environment Canada weather station in Figure 6. The amplitude of the annual wave decreases from greater than 20°C at 0.76 m to 1°C at 15 m. The progressive lag in the temperature wave as it propagates is also shown with changes in ground temperature at 15 m lagging behind those in air temperature by about 7 months. There is considerable inter-annual

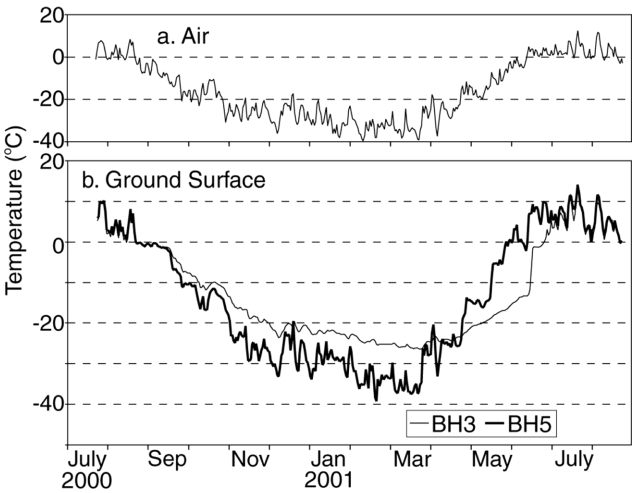

Figure 5. Mean daily air temperatures at BH3 (a) and ground surface temperatures between July 2000 and August 2001 for BH3 and BH5 (b).

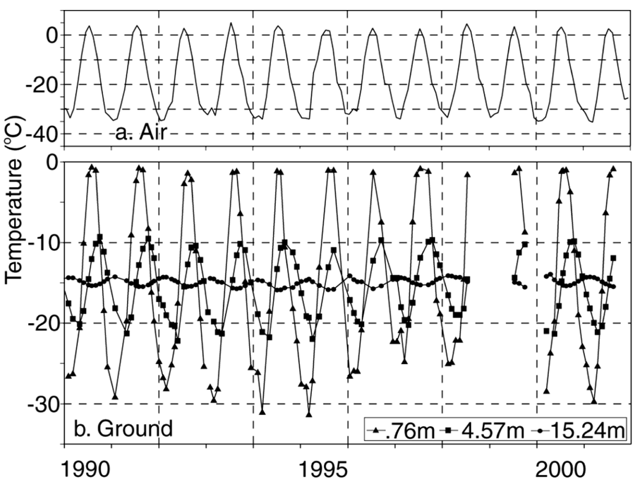

Figure 6. Shallow ground temperatures measured at BH5 between 1990 and 2001 and monthly air temperatures from Environment Canada weather station at Alert.

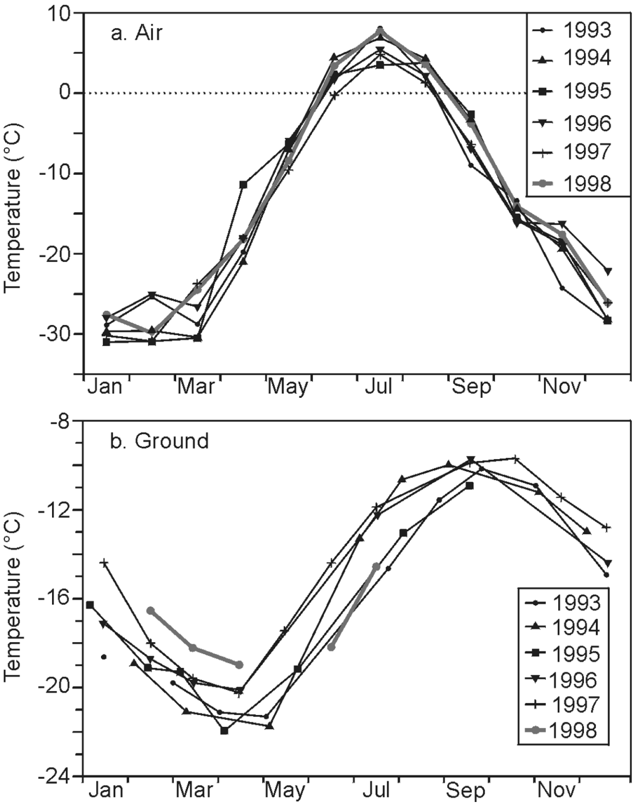

Figure 7. (a) Mean monthly air temperatures at Environment Canada weather station at CFS Alert for 1993–1998. (b) Ground temperatures measured at a depth of 4.5 m at BH5.

variation in ground temperature especially in the minimum annual temperature which is likely related to variations in snow cover as well as air temperature. This inter-annual variation in ground temperature at BH5 at a depth of 4.5 m during the 1990s is further illustrated in Figure 7. Higher shallow ground temperatures were observed during the winter months of 1998 (February to April) even though winter air temperatures were similar to those recorded during the rest of the decade (Fig. 7). Snow depths measured at BH5 indicate that the maximum snow depth during the winter of 1997–1998 was greater than 50 cm compared to the lower amounts of snow generally found at this location (Fig. 4). The deeper snow pack provided additional insulation resulting in a lower rate of heat loss from the ground during the winter (Smith et al. 2001). Limited summer data suggest that the presence of the thicker snow cover for a longer duration may have delayed the onset of active layer development and warming of the ground during the summer of 1998.

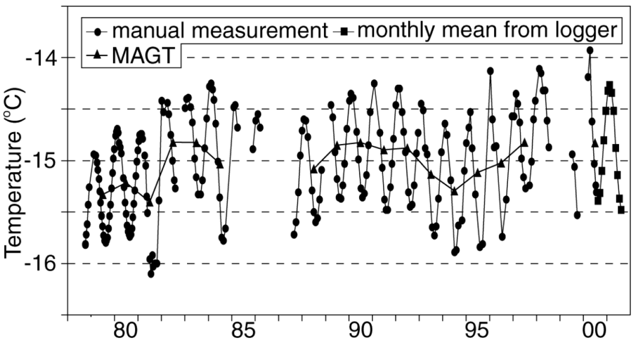

Figure 8. Observed and mean annual ground temperatures (MAGT) at a depth of 15 m at BH5 from 1978 to 2001. Note: monthly mean temperatures determined from data logger records are shown after July 2000.

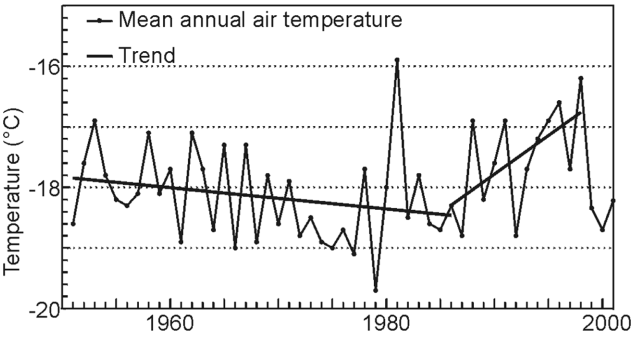

Figure 9. Mean annual air temperature (1951 to 2001) obtained from the Environment Canada weather station at Alert. Data are from Environment Canada (2000a). Data after 1999 have been extracted from Environment Canada's internet-based Canadian Climate Summary. General trends in air temperature for the periods 1951–1986 and 1986–1998 are also shown.

The observed and mean annual ground temperature at a depth of 15 m at BH5 is shown in Figure 8. The mean annual ground temperature was calculated where sufficient data were available to interpolate the annual wave. A large gap in the data record exists between 1985 and 1987. Air temperatures generally increased between 1986 and 1998 by about 0.12°C per year (Fig. 9) and this has not been accompanied by as distinct a rise in shallow permafrost temperature.

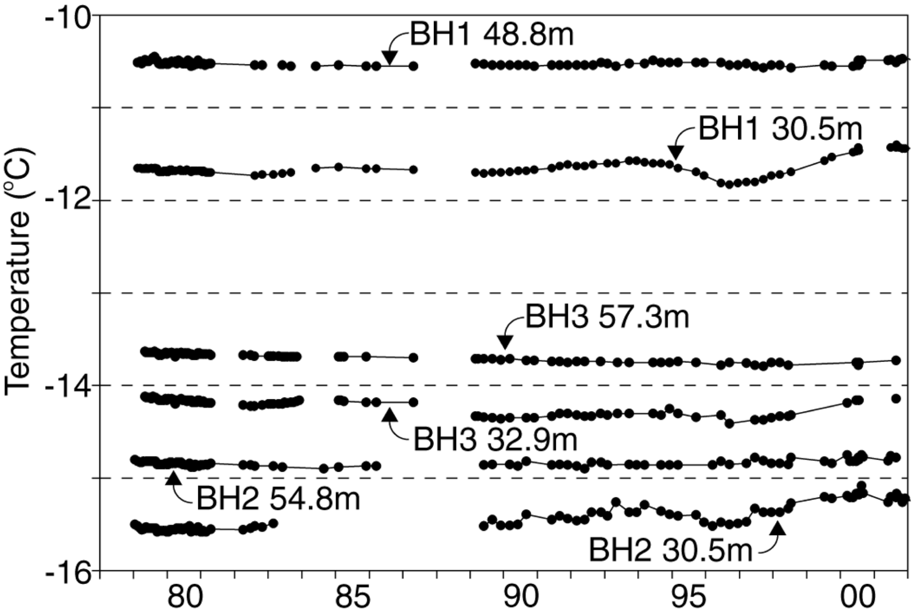

Figure 10. Observed ground temperatures between depths of 30 and 60 m at BH1, BH2 and BH3 from 1978 to 2001.

A brief cooling in the upper 15 m is observed in the early 1990s. From the mid to late 1990s, ground temperature at a depth of 15 m has shown a general increase of about 0.15°C per year. There has been a decrease in mean annual air temperature from 1999 to 2001 which has been accompanied by a levelling off of shallow ground temperature in 2000 and 2001.

A preliminary analysis of deeper ground temperatures indicates that at a depth of about 30 m, which is just below the depth of zero annual amplitude, ground temperatures have generally increased since at least 1989 with a short period of cooling between 1994 and 1995 (Fig. 10). Warming of about 0.06°C per year is observed from about 1996 onwards at BH1, BH2 and BH3. This warming trend at 30 m lags one to two years behind that at 15 m.

The cooling trend of about 0.017°C per year from the 1950s to the early 1980s in the mean annual air temperatures (Fig. 9) appears to have resulted in lower permafrost temperatures at depths below 40 m at BH1 and BH3 (Fig. 10) during the following decade. Analysis of ground temperatures between 48 and 60 m, indicate however that this decline in temperature is very small, about 0.01°C per year over a 15 year period at a depth of 57 m in BH3 for example. Temperature changes of this magnitude are not much greater than the resolution of the manual measurements making it difficult to detect trends of a smaller magnitude.

4 SUMMARY

This paper has focussed on an analysis of manual measurements of ground temperature made at Alert over a 23 year period. Analysis of the ground temperature data has allowed documentation of recent trends in permafrost temperatures in the Canadian High Arctic. The pattern in shallow ground temperature (upper 30 m) since the late 1980s is similar to that observed in the western Arctic by Osterkamp and Romanovsky (1999) and Romanovsky (2001) who observed a general increase since the mid 1980s in ground temperatures at 20 m depth at monitoring sites in Alaska. A decrease in permafrost temperatures was observed in the early 1990s in both regions. Ground temperatures in the upper 30 m at Alert have increased since the mid 1990s but this increase appears to have lagged behind that observed in Alaska by about one year.

The low frequency and lower quality manual measurements collected until 1999 do not allow a detailed assessment of short-term and/or low magnitude permafrost temperature trends such as those that might be present between depths of 30 to 60 m. The continued collection and analysis of improved precision and higher frequency temperature data will allow for better detection and interpretation of these trends.

Snow cover exhibits high spatial and temporal variability at Alert and this is reflected in the response of shallow ground temperatures to changes in air temperature. Snow cover measurements and the high frequency ground surface temperature data from BH3 and BH5 collected from July 2000 to August 2001 provided further insights into the role of the timing and thickness of snow cover. Long-term changes in snow cover that may accompany warmer air temperatures will be an important consideration when evaluating the impact of climate change on the permafrost environment in the High Arctic. Further analysis of high frequency air, ground surface and permafrost temperature data collected since July 2000, and the data to be obtained from snow sensors to be installed in summer 2002 will provide a better understanding of the role of the local microclimate in influencing the permafrost response to changes in air temperature.

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