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Observed recent changes in climate and permafrost temperatures at four sites in northern Canada

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ABSTRACT
Climate and ground temperature records 10 to 30 years in length from four widely separated permafrost monitoring sites were analyzed to assess the thermal response to recent climate warming, both seasonally and annually. The study sites are located in the tundra environments of Nunavut and the boreal forest of the Mackenzie Valley Northwest Territories. The timing and magnitude of the climate change varied regionally, and the response of the ground varied even more due to individual site conditions. Increases in winter air temperatures were significant and appear to be largely responsible for recent increases in ground temperature.

RÉSUMÉ
Les enregistrements du climat et des températures au sol ont été analysés sur une durée de 10 à 30 ans à quatre lieux de surveillance du pergélisol grandement éloignés, afin d'évaluer leur réaction thermique au réchauffement climatique récent, tant à l'échelle des saisons qu'à l'échelle des années. Les lieux d'étude sont situés dans des milieux de toundra du Nunavut et dans la forêt boréale de la vallée du Mackenzie, dans les Territoires-du-Nord-Ouest. Le moment et l'ampleur du changement climatique variaient à l'échelle régionale, et la réaction du sol variait encore davantage selon les conditions particulières du lieu. Les hausses des températures de l'air en hiver étaient importantes et semblaient être largement responsables des augmentations récentes des températures au sol.

1 INTRODUCTION

The ACIA (2005) and the IPCC (2007) both concluded that climate change, particularly changes in air temperature and precipitation, will be enhanced in the high latitudes over the next century. These climatic changes will affect permafrost conditions and its distribution across the polar and alpine regions of the world. During the twentieth century the arctic climate, between 60° and 90°N, warmed from the early 1900's until about 1940, cooled until the mid-1960's, then warmed again until present day (ACIA 2005). Recent warming has also been observed in permafrost temperatures across the arctic (Osterkamp 2008; Romanovsky et al. 2008; Serreze et al. 2000; Smith et al. 2005), though the timing and magnitude of this warming varies regionally.

Increasing or decreasing permafrost temperatures are not always an indication of similar trends in air temperatures. Snow is a very effective insulator due to its low thermal conductivity, and therefore has a strong influence on the thermal regime of the ground (Williams and Smith 1989). Long-term changes in the accumulation of snow can affect the temperature of the ground without changes occurring in air temperature (Goodrich 1982), and can actually counteract the effects of changes in air temperature on ground surface temperatures (Gruber et al. 2004; Taylor et al. 2006).

This paper analyzes trends in climate and permafrost temperature records from four widely separated sites across northern Canada (Figure 1). The response of permafrost at these sites is assessed against both annual and seasonal air temperature trends.

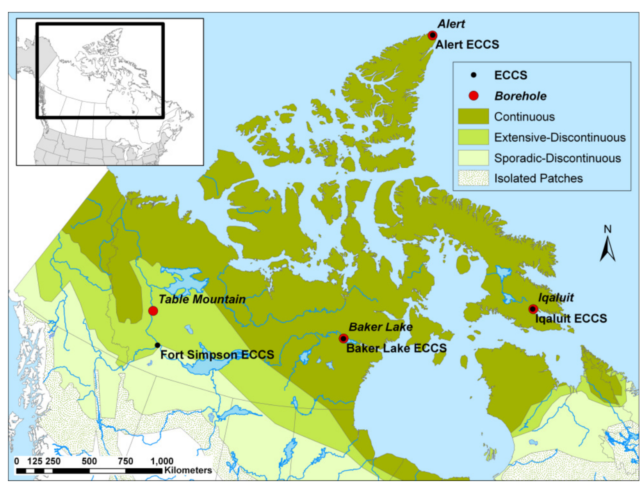

Figure 1. Location of study sites and the closest Environment Canada Climate Stations (ECCS) in relation to the permafrost zones (Heginbottom et al. 1995).

2 STUDY SITES

The locations of the four sites considered in this study are shown in Figure 1. Three of the sites (Alert, Baker Lake, and Iqaluit) are located in the tundra environments of the continuous permafrost zone in Nunavut, and the fourth (Table Mountain) is in a boreal forest in the extensive discontinuous permafrost zone of the Mackenzie Valley Northwest Territories.

The permafrost thermal monitoring sites at Alert are the most northerly monitoring sites in the world (Smith et al. 2005) located at the northernmost point of Ellesmere Island (82°30'N and 62°25'W; Figure 1). The five boreholes are located in a cold and dry polar desert environment with little to no vegetation (Smith et al. 2003; 2005). All of the boreholes are located within 2.8 km of an Environment Canada Climate Station (ECCS) located at 82°31'N and 62°16'W (Figure 1). Previous analyses conducted on data from this site, up to 2004 are presented by Smith et al. (2003; 2005) and Taylor et al. (1982; 2006).

Similar substrate is found at all of the boreholes. The overburden ranges from 2.4 to 4 m and is composed of mainly till and shattered rock that is in-filled with ice (Taylor et al. 1982). The exception is the overburden at BH1 which is composed of silt, sand, and shattered rock. The underlying bedrock is commonly argillite, and in some places greywacke.

The Alert boreholes are located along an elevational transect from BH1 near the coast at 5 m a.s.l. to BH3 located on a plateau at 170 m a.s.l. (Taylor et al. 2006). BH4 and BH5 are on opposite sides of an east-west valley aligned with the prevailing winter winds (Taylor et al. 1982). Ground temperatures have been measured since 1978 to depths of 15 to 60 m. In 2000 automatic data loggers were connected to cables at BH3, BH4 and BH5 to provide higher frequency data collection. Air and ground surface temperature sensors were also installed. In 2002 weather stations were installed at BH3, BH4 and BH5 to measure air temperature, wind speed and snow depth.

The permafrost thermal monitoring site at Iqaluit (63°44'N and 68°28'W; Figure 1) is at an estimated elevation of 109 m and lies in the southern part of Baffin Island just over 1 km north of the coast of Frobisher Bay. The site is maintained by Environment Canada. The exposed tundra site is on massive bedrock, overlain by a thin till veneer with fairly well developed soil and sparse vegetation (GTN-P 2009). Two boreholes, 5 m deep, were drilled and instrumented in 1988 and 1989. A weather station was installed between the two boreholes in 1997. The closest ECCS is in Iqaluit at 63°45'N and 68°33'W, approximately 4.1 km from the borehole site (Figure 1). A brief analysis of ground temperatures at this site up to 2002 can be found in Smith et al. (2005).

The Baker Lake monitoring site is located at 64°19'N and 96°2' W (Figure 1). A 3 m borehole was instrumented in 1997. Manual ground temperature measurements were made on a monthly to bi-monthly basis. In 2002 a ground surface temperature sensor and a weather station were installed, and a logger was attached to the temperature cable. Surficial materials consist of till composed of coarse gravels and sands with low ice contents, and a peat layer at the surface that is less than 15 cm thick (GTN-P 2009). The arctic tundra site with moderate vegetation is expected to have permafrost thicknesses of up to 200 m (Smith et al. 2005).

The Baker Lake ECCS, is located at 64°18'N and 96°4'W at an elevation of 18 m (Environment Canada 2009) and is approximately 3 km from the borehole (Figure 1). Previous analyses of site data to 2003 can be found in Smith et al. (2005), and to 2007 in Throop et al. (2008).

The permafrost thermal monitoring site at Table Mountain is located in the Mackenzie Valley at 63°36'N and 123°37'W (Figure 1). The site is in a coniferous forest at the approach to a south-facing slope at 265 m elevation off the Norman Wells pipeline right-of-way. Ice-rich lacustrine silty clay underlies the site (Smith et al. 2008). A 20 m borehole was instrumented with a thermistor cable in 1985 and manual measurements were made on a monthly or bimonthly basis from 1985 to 1995. An automatic data logger was attached to the temperature cable in 1995 to record temperatures to a depth of 17 m. A weather station was installed in 2003 to record air temperature, snow depth and wind speed. The closest ECCS is in Fort Simpson at 61°45'N and 121°14'W, which is approximately 230 km from the borehole site (Figure 1).

3 METHODS

3.1 Instrumentation

Boreholes are instrumented with YSI thermistor cables which have an accuracy of ±0.1°C. Eight channel data loggers manufactured by RBR Ltd. are connected to cables and collect data at eight hour intervals. The measurement system allows for a resolution of ±0.01°C. The weather stations, manufactured by Campbell Scientific, are equipped with a YSI thermistor to measure air temperature (accuracy and resolution better than ±0.1°C) and all except Iqaluit are equipped with an SR50M acoustic snow sensor (accuracy ±1.0 cm, resolution 0.01 mm). The sites at Alert, Baker Lake and Table Mountain are equipped with single channel Vemco miniloggers to record air and near surface ground temperatures, and have an accuracy of ±0.5°C and a resolution of ±0.3°C.

3.2 Hind-casting air temperature record

The sites in this study had ground temperature monitoring instrumentation in place before on-site air temperature and snow depth sensors were installed. Each of the four sites is close to an ECCS, which collects high frequency, quality controlled meteorological data. Continuous records of hind-cast air temperatures were produced for each site, beginning earlier than the period of ground temperature monitoring, through correlation of overlapping monthly on-site and ECCS data.

Air temperature records were hind-cast using the following method. Monthly average air temperatures were acquired from the nearest ECCS overlapping the period of on-site measurements at each site's weather station. The ECCS and on-site data were correlated to observe the strength of the relationship and to determine the line-of-best-fit equation. Historical monthly air temperatures from the ECCS were input to the best-fit equation to hind-cast on-site monthly air temperatures over the entire period of ECCS monitoring. Four seasonal relationships were plotted for Table Mountain because monthly average air temperatures varied considerably from the Fort Simpson ECCS monthly air temperatures. Each best-fit equation was used to hind-cast monthly values and to calculate mean annual air temperatures (MAAT) and seasonal average air temperatures. Seasonal averages were based on the following: autumn – September to November; winter – December to February; spring – March to May; and summer – June to August.

The hind-cast MAAT and seasonal average air temperatures were visually assessed for warming or cooling trends. Regression analyses were then conducted on the trends to test for statistical significance.

3.3 Standardization of ground temperature record

Ground temperature data were collected manually in the earlier years of monitoring and automatically in more recent years at Alert, Baker Lake, and Table Mountain. The manual data produced a discontinuous record of ground temperatures with one or two measurements per month, and sometimes missing months entirely. A method was developed (Throop 2010, and described below) to determine the mean annual ground temperature (MAGT) at each depth for the years with episodic manual data, and was applied to Alert BH3, BH4, and BH5, and Baker Lake. At Table Mountain a simple average was taken from the manual measurements because most of the temperature measurements considered were acquired below the depth of zero annual amplitude (ZAA).

MAGTs were first calculated at each depth above ZAA from all years of continuous data. Next, three sets of averages were calculated per month consisting of approximately 10-day intervals for these same years (this is dependent upon how many days in each month, e.g. September 1-10, 11-20, 21-30, and August 1-10, 11-20, 21-31). For every year of continuous data the 10-day average was subtracted from its corresponding MAGT to obtain the deviation of each 10-day period from the mean. An average deviation for each 10-day period was calculated from all years to produce a standard value for those dates. The calculated 10-day deviation for the corresponding date and depth were subtracted from each manually collected temperature value. These values, representing an indication of the MAGT from each manual reading, were averaged to obtain a calculated MAGT for the entire year. In this way, all the data were used, but the MAGT was not weighted by changes in the frequency of sampling. In order to calculate the MAGT at depths below ZAA, a simple average was taken from the manual measurements over the course of one year between September 1 and August 31.

MAGTs were calculated differently at Alert BH1 and BH2 because only manual measurements exist for these sites. Temperatures below ZAA were averaged to obtain MAGTs for each year, and MAGTs above ZAA were calculated using weighted averages. To calculate MAGTs using weighted averages, each manual reading was used to represent half of the number of days between it and the previous reading, and half of the number of days until the next reading. The temperature values from each manual reading over a September to August year were multiplied by the appropriate number of days, then added together, and lastly divided by 365 to obtain an approximate MAGT.

3.4 Snow

Snow was assessed using snow depth-days (SDD) at Alert, Baker Lake, and Table Mountain. SDD are calculated by adding together each daily snow depth value throughout the season. This value takes into account both the depth and duration of snow accumulation, and therefore encapsulates inter-annual variability (Karunaratne and Burn 2003). Manual snow surveys were conducted at Iqaluit and are used as an indication of typical snow conditions for the area (Eley 2005).

4 RESULTS

4.1 Alert

The hind-cast air temperature records at Alert BH3, BH4, and BH5 have slight climatic differences due to the local topography of the area: BH5 is the warmest, BH3 is slightly colder, and BH4 experiences the lowest MAAT of the three (Figure 2). A significant climatic cooling trend of 0.3°C per decade was observed between 1950 and 1975 ($p=\leq 0.05$). This was followed by a significant warming trend of 0.4 to 0.5°C per decade ($p=\leq 0.01$).

There are significant trends in autumn and winter average air temperatures (Figure 3). Autumn air temperature increased significantly since the late 1970's by 0.9°C per decade ($p=\leq 0.05$), and winter air temperature increased by 0.4°C per decade since the early 1970's ($p=\leq 0.05$).

More snow generally accumulates at BH1 (maximums between 10 and 80 cm) than at BH2, (maximums between 5 and 50 cm; Smith et al. 2003). BH3 accumulates significantly more snow than BH4 or BH5, and it persists for most of the winter season from the end of August or September until the end of June or July, with SDD values ranging between 5210 and 15130, averages between 21 and 50 cm, and maximum depths between 37 and 76 cm. Snow accumulations at BH4 are variable inter- and intra-annually, with SDD values that range from 2080 to 5680, averages between 8 and 22 cm, and maximum depths between 19 and 48 cm. BH5 is typically blown clear of snow, with only short and sporadic periods of accumulation with maximum depths less than 20 cm. BH5 is most exposed to the extreme arctic air temperatures during winter and SDD values ranged between 10 and 370 from 2002-2005.

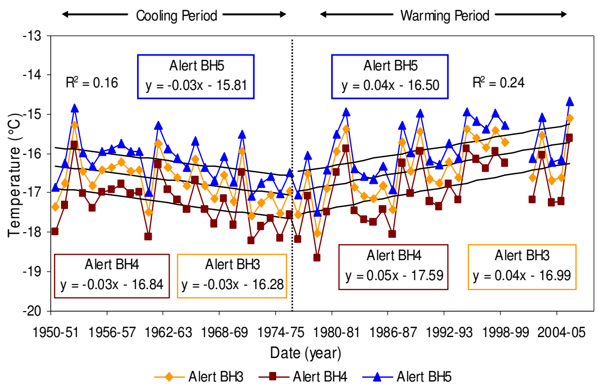

Figure 2. Hind-cast MAATs at Alert BH3, BH4 and BH5 from correlated Alert, Nunavut, ECCS data (Environment Canada 2009) between 1950 and 2006. Significant trends are indicated by the solid lines.

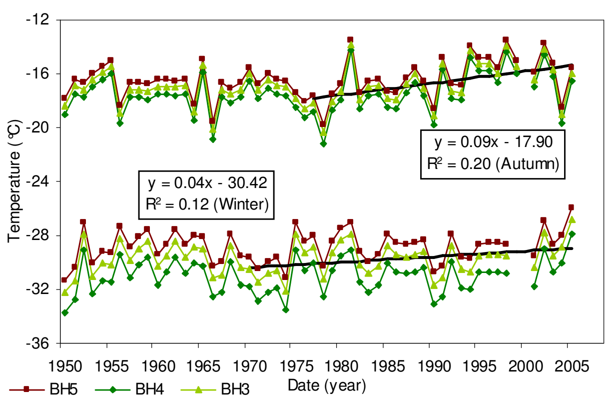

Figure 3. Winter and autumn average air temperatures at Alert BH3, BH4, and BH5 (labelled by season and number of borehole) from hind-cast monthly Alert ECCS data (Environment Canada 2009). Statistically significant warming trends are shown by the solid line.

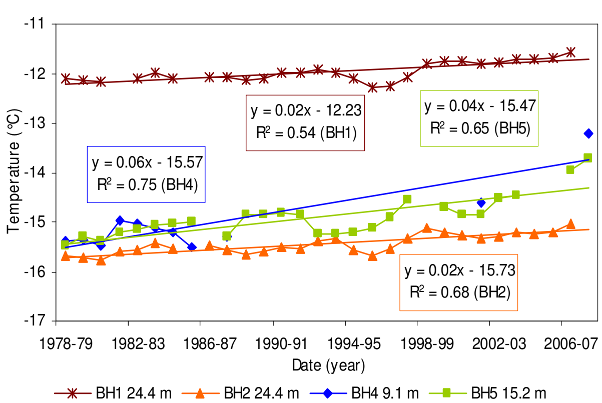

Figure 4. MAGTs from BH1, BH2, BH4, and BH5 at Alert, Nunavut, between 1978 and 2008. Significant warming occurred at these four sites over the monitoring period (p=<0.001).

Ground temperatures warmed significantly over the monitoring period at BH1, BH2, BH4, and BH5 (p=<0.001; Figure 4). MAGTs at BH1 and BH2 warmed by about 0.2°C per decade at 24.4 m depth. The ground at BH4 warmed the most at 9.1 m depth by about 0.6°C per decade, although there is a sizeable gap in the data between 1988 and 2000, followed by BH5 at 15.2 m depth which warmed by about 0.4°C per decade. Care should be taken in comparing the magnitude of the trends between the Alert sites as they are occurring at different depths. The trend at BH4 for 9.1 m is the greatest, but also the shallowest; and shallower ground temperatures respond more to climatic changes than deeper ones.

4.2 Iqaluit

Two distinct and significant trends exist in the hind-cast Iqaluit MAAT record (Figure 5). A cooling trend of 0.4°C per decade occurred between 1948 and 1992 (p=<0.01), and a warming trend of 1.4°C per decade occurred between 1993 and 2006 (p=<0.05).

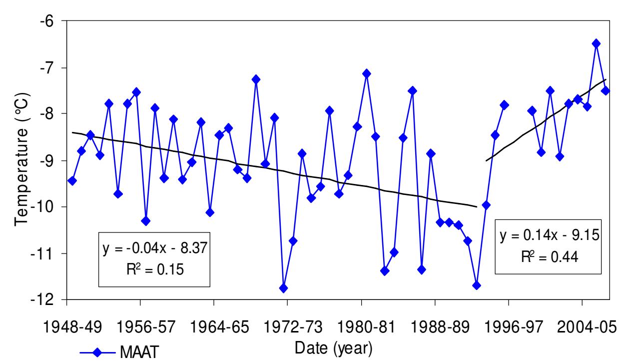

Figure 5. Hind-cast MAAT at the Iqaluit borehole sites between 1948 and 2007, obtained from correlated Iqaluit ECCS data (Environment Canada 2009). Significant trends are indicated by the solid lines.

A significant decrease in spring average air temperatures of 0.7°C per decade occurred between 1948 and 1992 (p=<0.01; Figure 6). Significant warming trends of 2.3°C per decade occurred in both winter and autumn between 1993 and 2006 (p=<0.05; Figure 6).

The Iqaluit borehole site is subject to wind scouring and snow redistribution. The snow accumulation is minimal overall, varies spatially and is discontinuous through time (Eley 2005).

Significant warming trends in MAGTs were observed at both of the Iqaluit boreholes beginning at the same time as air temperature warming, in 1993 (p=<0.01). The MAGT at 5 m at both BH1 (Figure 7) and BH2 increased by 2.0°C per decade. The air and ground temperatures at this site are closely linked and follow similar patterns, and both show a cooling trend between 1988 and 1993 followed by warming (Figure 7). The dip in air and ground temperatures in 1992-93, was likely a result of the Mount Pinatubo eruption that occurred in June 1991 and ejected large quantities of aerosols into the atmosphere, causing a temporary cooling around the globe (Hansen et al. 1996; Bassett and Lin 1993).

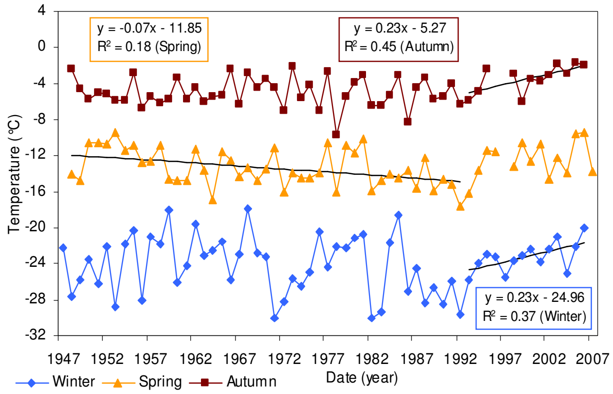

Figure 6. Significant cooling trend in hind-cast spring average air temperatures between 1948 and 1992 ($p \leq 0.01$), and significant warming trends in hind-cast winter and autumn average air temperatures between 1993 and 2006 ($p \leq 0.05$) at Iqaluit, Nunavut (Environment Canada 2009).

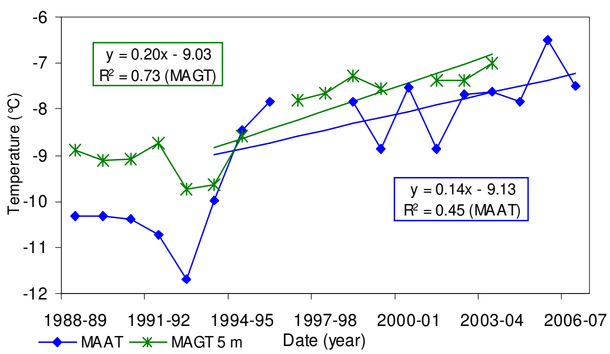

Figure 7. MAGTs from Iqaluit BH2 at 5 m depth and MAATs from correlated ECCS data (Environment Canada 2009) between 1988 and 2004, showing significant warming trends in both since 1993 ($p \leq 0.001$).

4.3 Baker Lake

MAAT at Baker Lake increased significantly between 1975 and 2007 by 0.6°C per decade ($p \leq 0.01$; Figure 8). Seasonal average air temperatures increased significantly during the winter and autumn (Figure 8). Winter air temperatures increased by 0.4°C per decade throughout the entire record of hind-cast data from 1951 until 2007 ($p \leq 0.01$), and autumn air temperatures increased by 1.3°C per decade from about 1984 until 2007 ($p \leq 0.05$).

The site at Baker Lake has low tundra vegetation and is prone to drifting snow, creating variable snow conditions inter- and intra-annually. Between 2002 and 2006 SDD ranged between 3000 and 7280. Average annual snow depths ranged between 13 and 28 cm, and maximum depths ranged between 25 and 56 cm.

The ground temperature record available between 1997 and 2007 at Baker Lake is too short to observe a trend, although MAGTs do follow the pattern of MAAT over the same period (Figure 9). The MAGTs have likely warmed along with MAATs between 1975 and 2007.

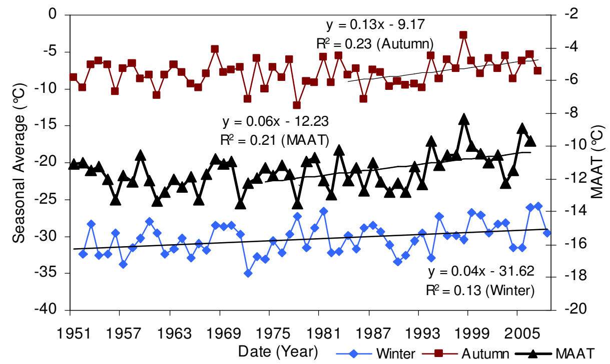

Figure 8. Hind-cast MAAT, and autumn and winter average air temperature trends at Baker Lake, Nunavut, from 1951 to 2007 (Environment Canada 2009). Statistically significant increasing trends are observed in MAAT between 1975 and 2007 ($p \leq 0.01$), winter over the entire record ($p \leq 0.01$), and autumn between 1984 and 2007 ($p \leq 0.05$). Note: MAAT is plotted on a secondary axis.

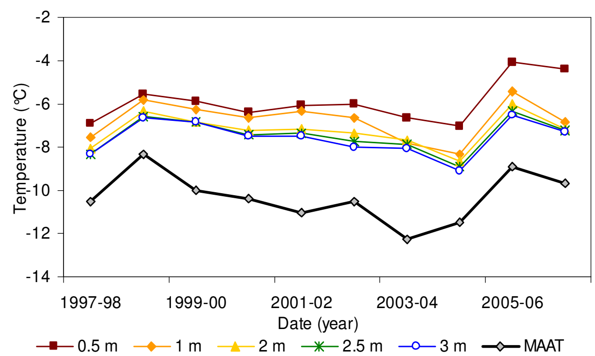

Figure 9. MAGTs and MAAT at Baker Lake between 1997 and 2007 showing the similarities between the two.

4.4 Table Mountain

MAAT increased significantly at Table Mountain over the entire record between 1964 and 2008 by 0.6°C per decade, or about 2.5°C overall ($p \leq 0.001$; Figure 10). Winter and summer air temperatures also increased significantly over the entire monitoring period by 1.2°C ($p \leq 0.001$) and 0.3°C ($p \leq 0.01$) per decade, respectively (Figure 10).

There are two full years of on-site snow depth data at Table Mountain between 2003 and 2005. Both years were similar in terms of accumulation, depth, and duration.

Values of SDD were 8559 and 8959, averages were 42 and 44 cm, and maximum depths were 85 and 74 cm, respectively. During both years the snow arrived in mid-to-late October and melted in early-to-mid May. Manual snow surveys conducted between 1986 and 1991 indicate that maximum depths ranged between 45 and 70 cm (Burgess 1993).

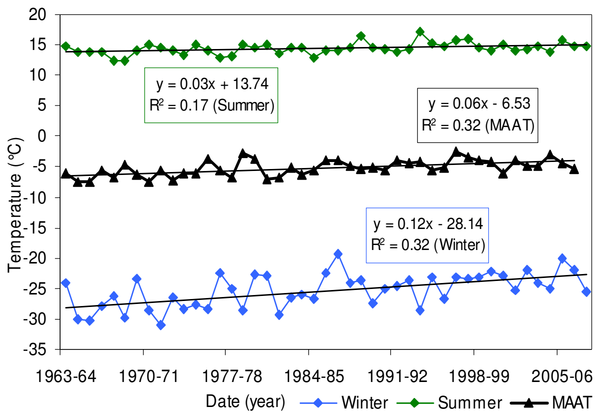

Figure 10. Hind-cast MAATs, and winter and summer average air temperatures for Table Mountain, Northwest Territories. Significant warming trends are shown with a solid line.

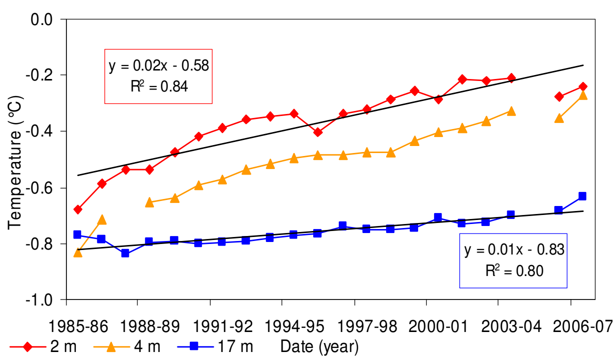

Figure 11. MAGTs at 2, 4, and 17 m at Table Mountain, Northwest Territories, between 1985 and 2008. Increasing trends are significant at all depths, and only the lines for the shallowest and deepest (2 and 17 m) are shown.

Permafrost temperatures at Table Mountain are within one degree of 0°C, and the depth of ZAA is shallow, just below 2 m. MAGT increased with significance at all depths over the monitoring period between 1985 and 2007 ($p=\leq 0.001$; Figure 11). The trends at 2 and 17 m increased by 0.2 and 0.1°C per decade, respectively.

5 DISCUSSION

Ground temperatures at four of the five boreholes at Alert (excluding BH3) have increased significantly since 1978 following increasing MAATs in recent decades. The magnitude of warming at each of these boreholes varied due to variations in the characteristics of the snow-pack. Permafrost temperatures at Iqaluit also increased, though the trend began more than a decade later in the early 1990's, following the regional climatic warming trend. During the period of thermal monitoring at Baker Lake there was no significant warming trend evident in the shallow permafrost temperatures. However, given how closely the ground temperatures track the air temperature (Figure 9) it is likely that there has been longer term ground warming associated with increasing air temperatures since the 1970s. It is important to note that the determination of a long-term trend is difficult at this site due to the short record and the shallow ground temperatures recorded which are affected by shorter-term climatic variations than deeper temperatures would be. Permafrost temperatures increased the least at the Table Mountain thermal monitoring site, but this warming is important due to the proximity to 0°C and the high moisture/ice content in the underlying sediments.

The magnitude of the response in the ground varies among the sites that have warmed, due primarily to the magnitude and direction of the air temperature trend, as well as varying site-specific factors. The Alert BH4 and BH5 sites accumulate the least amount of snow in winter and lack a surface buffer layer, and therefore the permafrost has warmed the most at these sites compared to that at BH3, where snow depths are greater. The increase in ground temperatures at Alert can therefore be attributed to the significant autumn and winter warming trends observed in the region beginning in the 1970's (Figure 3).

At Iqaluit, air and shallow permafrost temperatures are closely linked (Figure 7). The MAGT at 5 m has increased by about the same amount as the MAAT since the early 1990's, which occurred later than the warming trends observed at the other study sites. The magnitude of this delayed warming in MAATs and MAGTs has been strongest compared to the other sites, with autumn and winter driving the warming.

The timing of the climatic trends at Iqaluit correspond to observations made in northern Quebec by Allard et al. (1995; 2002), where decreasing trends in air and permafrost temperatures occurred into the early 1990's, followed by increasing trends. Intense climatic cooling was also observed by Hansen et al. (1996) from 1965 to 1995 in the region between Hudson Bay and Greenland, occurring mostly in the winter and spring. Allard et al. (1995) concluded that the decreasing trend was due mainly to significant winter cooling, as opposed to year-round cooling. Winter average air temperatures at Iqaluit decreased by about 0.6°C per decade between the late 1940's and the early 1990's, but the inter-annual variability in winter temperatures was too high for the trend to be considered significant, whereas the spring average temperatures did decrease significantly by 0.7°C per decade over the same period (Figure 6). When combined, average air temperatures over the winter and spring (December to May) decreased significantly between 1948 and 1993 by 1.3°C per decade ($p=\leq 0.05$).

The MAAT record at Baker Lake does not show a distinct trend prior to the 1970's (Figure 8), although warming did begin about the same time as at Alert, in the mid-1970's. South of Baker Lake in northern Manitoba, Camill (2005) observed a significant winter warming trend of approximately 0.4°C per decade during the latter half of the 20th century at 4 of the 5 sites for which climate records were analyzed. These trends are similar to that observed for Baker Lake.

The increasing trend in MAGTs at Table Mountain is less than that observed at the other study sites. Although this warming has been slight, it has been continuous over the monitoring period, on the order of 0.1 to 0.2°C per decade (Figure 11). The significant warming trend in MAAT of 0.6°C per decade since the mid 1960's (Figure 10) is reduced by the latent heat effects acting at this site where permafrost temperatures are very close to 0°C (Smith et al. 2005), as well as the surface buffering from vegetation, the organic mat, and continuous snow during winter. Seasonal trends in air temperature in this region differ from that at other study sites as warming has occurred mainly in the summer and winter.

Increases in winter average air temperature have occurred at all of the study sites and this is likely the primary contributor to the overall warming of climate and permafrost at the sites. The sites with the least amount of snow accumulation are at Iqaluit and Alert BH4 and BH5. The low snow cover in combination with increasing winter air temperature has resulted in the greatest degree of permafrost warming at these sites.

6 CONCLUSIONS

MAATs increased at all of the sites in recent decades. The earliest observed warming began in the mid 1960's in western Canada, (e.g. Table Mountain, NWT, +0.6°C/decade), followed by warming in the mid 1970's at Alert and Baker Lake, Nunavut (+0.4 and +0.6°C/decade, respectively), and since the early 1990's, with the most rapid warming of all the sites, at Iqaluit, Nunavut (+1.4°C/decade). Cooling occurred at Alert, Nunavut, between the early 1950's and the mid 1970's (-0.3°C/decade), and at Iqaluit, Nunavut, between the late 1940's and the early 1990's (-0.4°C/decade).

Air temperature at all sites increased significantly during the winter months (December, January, and February) in recent decades. The greatest magnitudes of winter warming occurred at Iqaluit since 1993 (+2.3°C/decade), followed by Table Mountain since 1964 (+1.2°C/decade), Baker Lake and Alert since 1951 and 1970, respectively (+0.4°C/decade). Significant warming also took place during autumn (September, October, and November) at Baker Lake (+1.3°C/decade), Iqaluit (+2.3°C/decade), and Alert (+0.9°C/decade), and during the summer (June, July, and August) at Table Mountain (+0.3°C/decade). The only site where significant seasonal cooling occurred was at Iqaluit during spring (March, April, and May) between 1948 and 1992 (-0.7°C/decade).

Warming trends in mean annual ground temperatures were observed at Alert, Iqaluit, and Table Mountain in recent decades. Ground temperatures at all of the Alert boreholes, except BH3, increased between 1978 and 2008 at depths close to or greater than ZAA (+0.2 to +0.6°C/decade). Permafrost temperatures at both of the Iqaluit boreholes are closely related to air temperatures, more so than all of the other thermal monitoring sites considered, and increased significantly at 5 m depth between 1988 and 2004 (+1.6 to +1.9°C/decade). MAGTs at Table Mountain increased between 1985 and 2007 but at a lower rate (+0.1 to +0.2°C/decade,) than that observed in other regions. This slight increase in ground temperature at Table Mountain is important because it represents a progressive change in unfrozen moisture in the fine-grained, ice rich permafrost at the site.

The results presented indicate that warming of permafrost that was observed at the end of the 20th century is continuing throughout northern Canada into the 21st century. Increasing winter air temperatures appear to be largely responsible for the increases in ground temperature. Where snow cover was minimal, increasing winter air temperatures were found to have a greater effect on ground temperatures than at sites with deeper snow cover. However, changes in snow depth may also occur as the climate changes. Investigations need to be made into changes in snow and seasonal air temperature trends to determine the sensitivity of the permafrost thermal regime to changing climate.

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