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Source: Arctic, Antarctic, and Alpine Research, 49(1) : 173-185

Published By: Institute of Arctic and Alpine Research (INSTAAR), University of Colorado

URL: https://doi.org/10.1657/AAAR0016-039

Arctic, Antarctic, and Alpine Research, Vol. 49, No. 1, 2017, pp. 173–185
DOI: http://dx.doi.org/10.1657/AAAR0016-039

Quantifying surface temperature inversions and their impact on the ground thermal regime at a High Arctic site

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ABSTRACT

Air and ground temperature data collected at Canadian Forces Station Alert, Nunavut, Canada, have been analyzed to investigate the potential role that air temperature inversions play in influencing the spatial variation of permafrost thermal conditions in coastal areas of the High Arctic. Frequent, persistent air temperature inversions have been documented using a series of weather stations deployed along an elevation gradient inland from the coast. During inversion periods, which may last several days, air temperatures in valley bottoms can be up to 10 °C lower than adjacent stations located at elevations 47 to 130 m higher. The occurrence of air temperature inversions during the winter combined with thin snow cover suggest a mechanism explaining the observation of lower winter ground-surface temperatures and colder permafrost conditions in valley bottoms compared to higher elevations.

Introduction

Typically, the temperature in the lower atmosphere decreases with altitude as the influence of the surface boundary layer is diminished (Oke, 1987). This concept is well understood and explains why surface sites at higher elevations are typically colder than adjacent lower locations at similar latitudes. The atmosphere is, however, a complex and dynamic system that is influenced by many factors on a variety of spatial and temporal scales. One example of this dynamic behavior is the development of atmospheric temperature inversions that can affect free-air conditions in the atmosphere as well as surface sites at lower elevations. Atmospheric temperature inversions are characterized by an increase in air temperature with altitude and represent an atypical situation in the lower atmosphere (Oke, 1987). Inversions are also present at the surface, as the elevation increases and boundary level conditions change or have less effect in steeper terrains (Lewkowicz and Bonnaventure, 2011). Temperature inversions are frequent in the High Arctic and in high-elevation mountain locations due to a variety of causes and are often influenced by the characteristics of the terrain and vegetation distribution (Bonnaventure et al., 2012). One mechanism leading to the development of surface inversions in cold regions is the highly negative radiation balance that occurs over snow and ice for a large portion of the year, but particularly during the winter (Munn et al., 1970; Bradley et al., 1993; Taylor et al., 1998). Inversions can also develop in the shoulder seasons in cold coastal regions by this mechanism as a result of stark contrasting conditions in the landscape between still-present melting sea ice and the surrounding snow-free terrain (Atkinson and Gajewski, 2002). This effect is locally magnified if winds blow toward the land bringing cold air inland. Additionally, in areas of considerable relief, cold-air drainage into valleys also contributes to the development of inversions at the surface (Blackadar 1957; Lewkowicz and Ednie, 2004). This occurs under stable conditions in high-elevation terrain as cold dense air (due to long-wave radiation loss) sinks and is funneled toward valley bottoms.

Air temperature heterogeneity in cold regions, including the coastal High Arctic, is a climatic pattern that has an impact on the spatial variation of the vegetation as well as the ground thermal regime. Studies in northwestern Canada have shown that ground surface temperatures and even the distribution of permafrost are controlled by the inversion pattern over variable topography (Taylor et al., 1998; Lewkowicz et al., 2012; Bonnaventure and Lewkowicz, 2013; O'Neill et al., 2015). As a result, this allows permafrost to be present in the valley bottoms where stable cold air can collect, whereas permafrost is then absent at higher elevations above the typical depth of the inversion (Taylor et al., 1998; Bonnaventure et al., 2012). Although this has been examined in areas of high elevation in moderately high latitudes (e.g. 60–65°N), the effects on the ground thermal conditions at higher latitudes where relief is subtler but overall climate is colder have yet to be extensively quantified. Furthermore, understanding the coupling between the air temperature field and the variability of subsurface temperatures in the High Arctic is critical in determining how climatic change affects different parts of the continuous permafrost landscape.

Bradley et al. (1993) have documented significant reductions in surface-based inversion depths between 1966 and 1990 across the North American Arctic, which have been accompanied by an increase in surface temperatures. A number of factors may be responsible for these changes including shifts in atmospheric circulation and higher levels of greenhouse gases (Pavelsky et al., 2011). Because inversions at the surface are more frequent during cold air conditions, the recently observed asymmetric climatic change, with the majority of warming occurring in autumn and winter, likely impacts inversion characteristics (Serreze et al., 2000; AMAP, 2011; Serreze and Barry, 2011; Kane et al., 2013). The landscape evolution of a permafrost environment is thus inherently coupled with the overall climate, which influences inversion frequency and strength. This includes the ground thermal regime with consequent impacts on landscape stability embracing mass movement, hydrology, vegetation, geochemistry, and ecosystem health in general. Linkages between changes in air temperature and ground temperature tend to be more direct in the High Arctic due to the low surface buffering effect associated with sparse vegetation and thin snow cover (Smith and Burgess, 2004; Smith et al., 2012; Throop et al., 2012; Bonnaventure et al., 2016). In the Canadian High Arctic, surface inversions may occur more than 70% of the time in winter (Bradley et al., 1993) and therefore may be an important factor influencing the spatial variability of the ground thermal regime.

In 1978 a permafrost observatory was established at Canadian Forces Station (CFS) Alert, Nunavut, at which ground temperatures have been measured in five boreholes located in a transect that extends from the coast with a total elevation range of about 165 m (Taylor et al., 1982). Taylor et al. (2006) suggested that the prevalence of intense atmospheric temperature inversions may counteract and supersede the normal atmospheric lapse rate, thus influencing the spatial variation in the ground temperatures. Data generated from this observatory were used to document the frequency, duration, and strength of air temperature inversions over an elevation gradient, to examine the influence these inversions may have on the ground surface temperature and the deeper ground thermal regime, and to determine the role temperature inversions may play in influencing the response of permafrost to climate warming. Currently both climate and permafrost models that examine climate change show this region of the High Arctic as uniform and homogeneous, when in fact an understanding of this area's heterogeneity is essential to utilize these models to their full potential. The goal of this paper is to document the strength of these inversions over the observation period while examining the influence these phenomena have on the spatial variability of the permafrost temperatures so that future studies examining the impact of climatic change can draw from a more representative view of the existing thermal heterogeneity for model applications.

Study Area and Instrumentation

The permafrost observatory is located on northern Ellesmere Island (Fig. 1) at CFS Alert (82.5°N, 62.4°W). It was established in 1978 for engineering and scientific purposes through collaboration among the Department of Energy Mines and Resources (now Natural Resources Canada), National Research Council, and the Department of the National Defence. Collaboration with Environment Canada in more recent years has facilitated installation of additional instrumentation and continuing data collection. The permafrost observatory consists of five instrumented boreholes up to 60 m in depth, located along a transect (Fig. 1, Table 1) that extends from the coast at BH1 (5 m a.s.l.) to above the marine sediment level at BH3 (170 m a.s.l.). Three of the boreholes are located on flat terrain (BH1, BH2, and BH3) while BH4 and BH5 are located on the opposite sides of an east–west valley. BH4 is located part way down a gentle (4°) south-facing slope, whereas BH5 is on a more rugged slope (9°–17°) that faces north.

The bedrock geology is dominated by a fine-grained varved argillite consisting of quartz and calcite and a coarser calcareous greywacke. The thin overburden of glacial, fluvioglacial, and marine sediments overlies a layer of shattered rock up to 3.8 m thick that is infilled with ice (Taylor et al., 1982). The overburden consists of

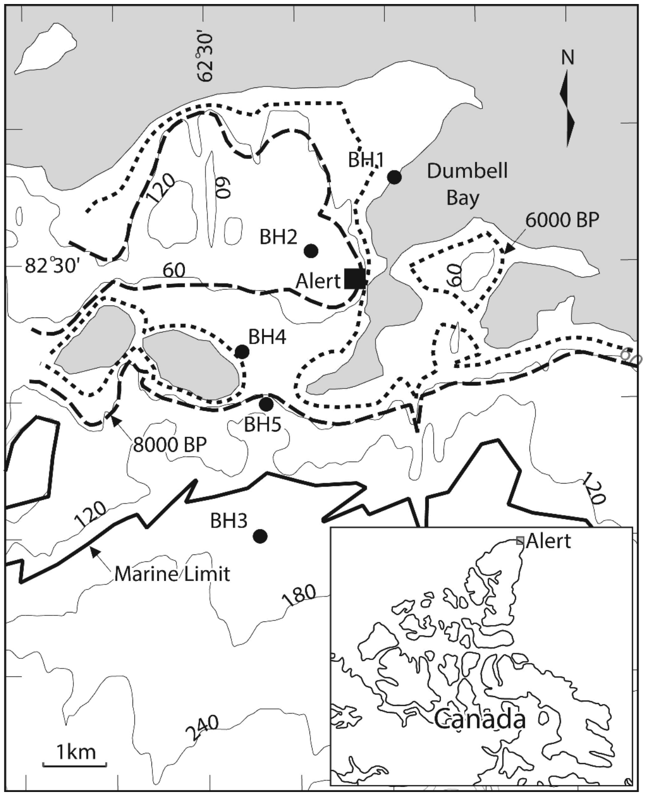

FIGURE 1. Location of boreholes at Canadian Forces Station Alert. Thin lines are elevation contours (interval 60 m). Dashed lines indicate the approximate position of the shoreline 6000 and 8000 years ago (based on England, 1976), with the maximum marine sediment limit at 135 m shown by the solid line.

marine silt at BH1 and till at the other sites. Permafrost is estimated to be more than 600 m thick with a typical active layer thickness of less than 0.8 m in late summer (Smith et al., 2003), although greater thaw depths have been observed in recent years. The area was subjected to postglacial uplift, and the marine sediment limit is estimated to be 135 m a.s.l. (England, 1976) with all borehole sites except BH3 emerging during 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 (ca. 3000 years ago, based on the emergence curve of England, 1976). Taylor et al. (1982) has provided further details on the geology and permafrost conditions of the area.

The climate is cold and dry with a mean annual air temperature of −17.7 °C, based on 1981–2010 normal for the Environment Canada weather station at Alert (Environment Canada, 2016). Maximum daily air temperature is above 0 °C 80 days per year on average, and the normal freezing and thawing degree-day indices are 6625 and 199, respectively. Temperature inversions at Alert are frequent during the winter and occurred 80% of the time between 1967 and 1986, according to Bradley et al. (1993). Total annual precipitation is 158 mm of which about 90% falls as snow (Environment Canada, 2016). The maximum month-end snow cover (measured at the Environment Canada station Alert) of 39 cm occurs in April, but snow depth is highly variable throughout the area due to wind exposure and variable topography (Smith et al., 2003). Dominant wind direction is from the west in the winter months (Environment Canada, 2016).

Multi-thermistor temperature cables were installed to depths up to 60 m in five boreholes (Fig. 1, Table 1), and manual temperature measurements were made at monthly to quarterly intervals from the date of borehole installation to the summer of 2000. In July 2000, the cables at BH3, BH4, and BH5 were connected to eight-channel data loggers manufactured by RBR Ltd. (Ottawa, Ontario, Canada) to record temperatures at 8 h intervals. The thermistors were calibrated to an absolute value of ±0.1 °C with a resolution of 0.01 °C. Instrumentation was also installed at these three boreholes to measure air temperature and temperature just below the ground surface at a depth of 3 to 5 cm. Instrumentation to measure ground surface temperature was installed at BH1 and BH2 in August 2001. Air and ground surface

TABLE 1

Site description information and instrumentation for the five boreholes shown in Figure 1.

Site	Elevation (m a.s.l.)	Surficial material	Temperature cable	Weather station (air temperature, snow depth wind speed)	Single channel logger air, surface temperature
BH1	4.6	Marine silt, sand	60 m	No	Surface
BH2	77.2	Till (moraine)	60 m	No	Surface
BH3	170	Till (moraine)	15 m with logger	Yes	Air and surface
BH4	37.3	Till (moraine)	15 m with logger	Yes	Air and surface
BH5	85.1	Till (moraine)	60 m with logger	Yes	Air and surface

temperatures were recorded at 4 h intervals by single channel loggers (manufactured by Vemco [Bedford, Nova Scotia, Canada]) with an accuracy of ±0.5 °C and a resolution of 0.3 °C. In summer 2002, weather stations manufactured by Campbell Scientific (Edmonton, Alberta, Canada) consisting of an air temperature sensor, acoustic snow sensor, and anemometer were installed at BH3, BH4, and BH5. This enabled collection of additional data on site microclimatic conditions and also facilitated hourly recording of air temperatures to a higher accuracy (generally better than ±0.2 °C over the range of temperatures measured) and precision (0.01 °C) than that possible with the instrumentation installed in 2000. Further details on the original instrumentation are provided in Taylor et al. (1982) and Smith et al. (2003).

Although air and ground temperature data have been collected at the site for several years, the analysis presented in this paper focuses mostly on the 2002–2006 period. This was the longest period for which an almost continuous record of air and ground surface temperatures were acquired at the three borehole sites to facilitate a comparison between sites and to investigate the frequency and impact of air temperature inversions.

Results

Ground Temperature

Ground temperatures for the five boreholes were compared using ground temperature envelopes for the period of August 2001 to August 2002 (Fig. 2). Although additional data exists, this period was selected for illustration because it represents a period where all boreholes recorded ground data continuously without failure and thus could be compared directly. As permafrost temperatures, especially at depth, are a result of long-term climate and do not respond sharply to short-term fluctuations in temperature from year-to-year, this period provides a typical snapshot of thermal conditions around the CFS Alert permafrost observatory (e.g. Smith et al., 2012; Throop et al., 2012). The annual temperature profile indicates that the seasonal thermal wave propagates to depths of about 25 m due to the moderate substrate thermal conductivity and lack of a surface vegetation buffer layer. Ground temperatures were highest at BH1, with mean annual ground temperature (MAGT) of −11.5 °C at the measurement depth closest to the zero annual amplitude depth (Fig. 2). BH1 has the lowest elevation and is closest to the coast, but also receives the greatest amount of snow (based on periodic manual measurements) of the five sites. BH3, at the highest elevation, has ground temperatures (MAGT= −14 °C) higher than that of all sites except BH1. BH2 has the lowest ground temperatures (MAGT = −15.2 °C) of those on the transect and, although BH2 is located on a plateau area (Fig. 1), it is at a lower elevation than both BH3 and BH5. Mean annual ground surface temperature (MAGST) can be determined by extrapolation of the mean ground temperature below the level of zero annual amplitude to the ground surface, as shown by Taylor et al. (1982). Using this method, the mean annual ground surface temperature at BH1 is −12.9 °C, BH3 is −14.2 °C, and BH2 is −15.8 °C. It was not possible to determine the mean annual surface temperature for BH4 or BH5 as temperatures are not measured below the level of zero annual amplitude at those sites; however, they appear to be similar to BH2 as Taylor et al. (1982) found through extrapolation of

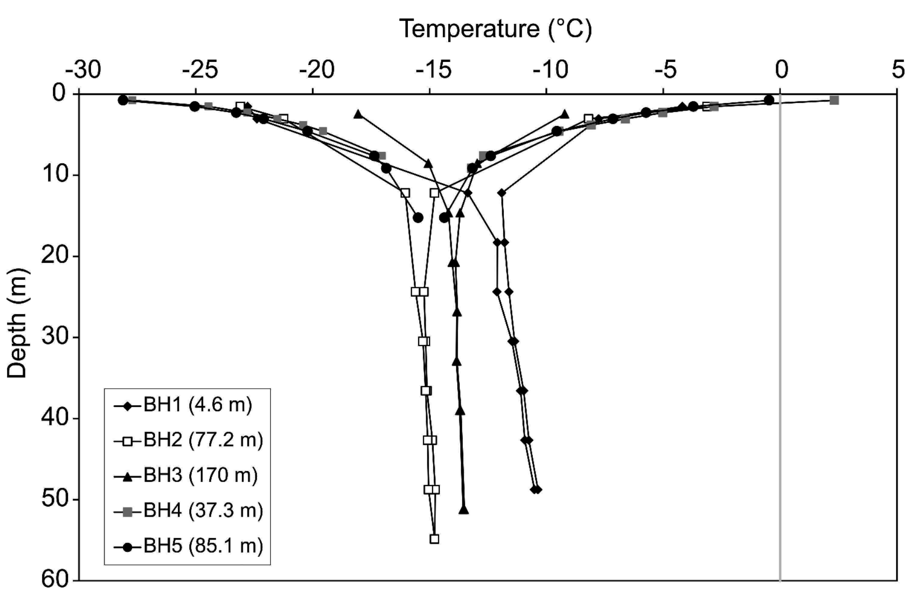

FIGURE 2. Ground temperature envelopes for the period August 2001 to August 2002 for the five boreholes. The elevation of each borehole is provided in the legend.

the shallow temperatures, with BH4 having the lowest value. MAGT at the deepest measurement depth was –15 °C (9 m) and –14.9 °C (15 m) for BH4 and BH5, respectively. The annual range in shallow ground temperatures can be quite large and was observed to be the largest for BH4 and BH5, where it was greater than 20 °C (Fig. 2).

Records of ground surface temperatures for 2002–2005 (Fig. 3) acquired from the single channel loggers at BH3, BH4, and BH5 indicate that winter temperatures were generally lower at BH4 and BH5 compared to BH3. Mean annual ground surface temperatures calculated for the period of record (Fig. 3) indicate that colder conditions were found in the valley bottom at BH4 (–14.2 °C) compared to that at higher elevation at BH3 (–12.4 °C).

Snow Cover Effects

When low levels of precipitation are typical, local snow accumulation patterns are relatively consistent in the High Arctic from year-to-year, accumulating in topographically controlled locations (Yang and Woo, 1999; Bonnaventure et al., 2016). Snow depth records obtained from the weather stations at BH3, BH4, and BH5 for the period 2002–2006 are shown in Figure 4. Snow depths were thinnest, and generally less than 30 cm, at BH4 and BH5 compared to that at BH3 or BH1 (based on monthly manual observations), where snow depths were often greater than 50 cm. BH4 and BH5 are located in a valley aligned with the prevailing westerly wind, which results in redistribution of snow (Taylor et al., 1982) and can result in periods during the winter where a snow cover is absent or only a few centimeters thick. The presence of a thin snow cover resulted in much lower winter ground surface temperatures at BH4 and BH5 compared to that at BH3, as shown in Figure 3.

Air Temperature along an Elevation Gradient

Monthly air temperatures determined from the weather station records at the three boreholes are shown in Figure 5 for the August 2002 to August 2006 period. Although summer air temperatures were similar, winter temperatures were generally lower at BH4 compared to the higher elevation sites, with the mean temperature for September to April ranging from 0.5 to 4 °C below that at BH5, for example (Table 2, Fig. 6). The average air temperature for the entire 2002–2006 period was lowest at BH4 (–16.1 °C) compared to BH3 (–15.7 °C) and BH5 (–15.4 °C).

The hourly air temperature data acquired from the three weather stations at BH3, BH4, and BH5 were analyzed to identify periods when air temperature inversions occurred, and to determine their frequency, duration, and strength. Comparisons were made between pairs of sites (i.e. BH3 and BH4, BH3 and BH5, BH4 and BH5) to determine the proportion of each month where the air temperature at the lower elevation site was below that at the higher elevation, indicating the occurrence of a temperature inversion. Temperature inversions occurred throughout the year (Fig. 7) but were more frequent during the colder period between October and April (as Munn et al., 1970, also observed at High Arctic sites), when they may occur more than 50% of the time (especially between BH4 and the other two sites). Although inversions were documented between the three pairs of sites, they occurred less fre-

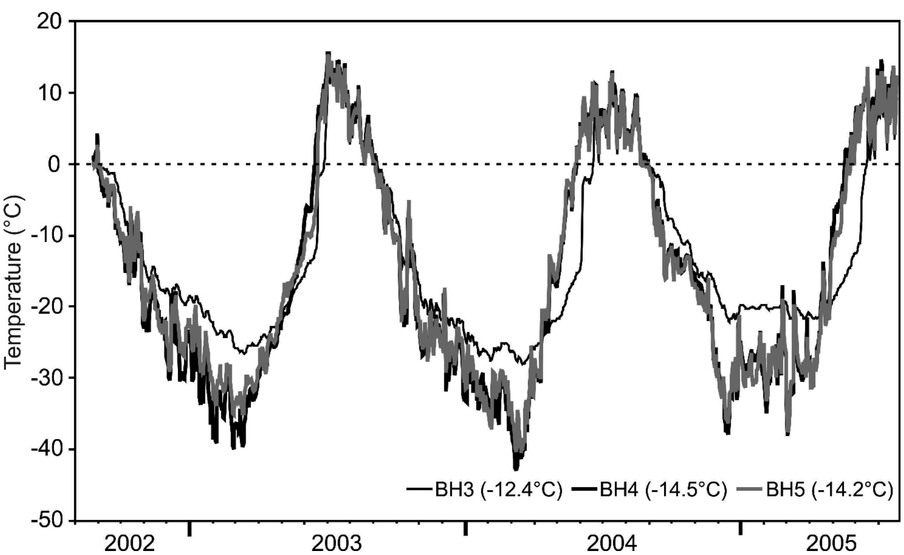

FIGURE 3. Average daily ground surface temperatures recorded between August 2002 and July 2005 at BH3, BH4, and BH5. The mean ground surface temperature recorded over the observation period for each site is shown in the legend. The average ground surface temperature over the same period for BH1 and BH2 (not shown on graph) is –12.9 and –13.8 °C, respectively.

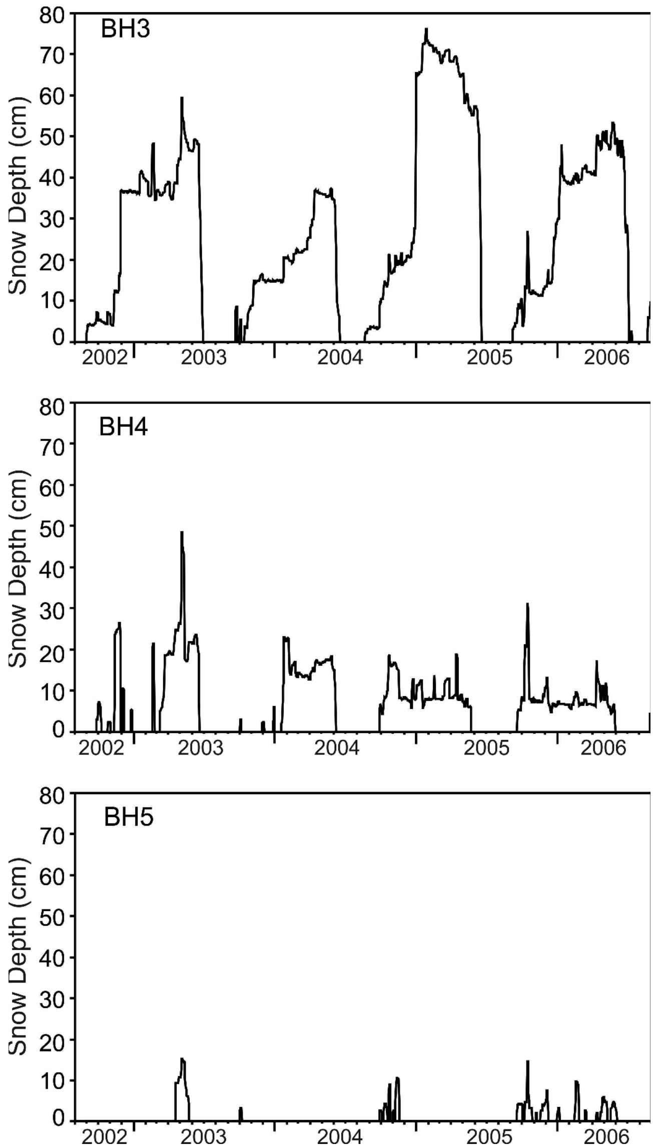

FIGURE 4. Snow depth recorded at the Campbell weather stations at BH3, BH4, and BH5, August 2002 to August 2006.

quently between BH3 and BH5 and most frequently between BH5 and BH4 (more than 80% of the time during cold months). Also, inversions between BH3 and BH5 were more evenly distributed throughout the year with a slightly higher frequency occurring in the summer. Inversions did occur between BH3 and BH4 where the difference in elevation is the largest but were less frequent than that occurring between the two sites at lower elevation (BH4 and BH5).

To determine the duration of the temperature inversion, we calculated the length of runs (or continuous periods) during which the air temperature at the lower elevation was lower than that at the higher elevation. For each period of inversion identified, the difference in the average air temperature recorded at each station over the inversion period was determined to provide an indication of the strength of the inversion. The strength of the inversion (difference in temperature in °C) between pairs of stations for inversions longer than 12 h in duration is shown for the 2002–2006 period in Figure 8. Table 3 provides a statistical summary of the strength and duration of inversions between each pair of stations.

The strength of the inversions varied from <1 °C to >10 °C. Throughout the observation period, the average difference in air temperature during an inversion was more than 2 °C (Fig. 8, Table 3). Adjusting for the difference in elevation between pairs of stations (47 to 132 m), the average strength of inversions was greatest between BH4 and BH5 where it was 5 °C per 100 m; the maximum was as high as 14 °C per 100 m (Table 3). The strength of inversions also tended to be greater during the colder period of the year, October to April (Fig. 8). The average duration of inversions (Table 3) was about one day, but there were several occurrences of inversions of up to a week. Temperature inversions lasting longer than 12 h were more frequent and persistent between BH4 and the other two higher elevation sites and less frequent between BH3 and BH5 (Fig. 8, Table 3).

Discussion

Impact and Mechanism

The results (Fig. 7, Table 3) indicate that air temperature inversions occur frequently at the CFS Alert permafrost observatory with more frequent and persistent winter inversions occurring between the valley bottom (BH4) and the site on the valley side (BH5), which is 47 m higher. As shown in Figure 8, air temperatures in the valley bottom may be several degrees below those at higher elevation during an inversion (which may last a few days) and result in lower winter air temperatures in the valley bottom (Figs. 5 and 6) and lower overall mean air temperatures at BH4 compared to the other two higher elevation sites. The largest difference in mean air temperature during the observation period (0.71 °C) was between BH4 and BH5. The annual air freezing degree-day index (Table 4) over the period of record was also 200 to 400 degree-days higher for BH4 compared to BH5. The similarity in mean air temperatures observed at BH3 and BH5 and the lower frequency of temperature inversions between these sites may indicate that the temperature inversions were generally confined to lower elevations and may be associated with cold air settling in the valley bottom. The results of this analysis support the idea of cold-air drainage rather than cold air being blown in from the adjacent ice-covered ocean. During the period of the year with the most frequent

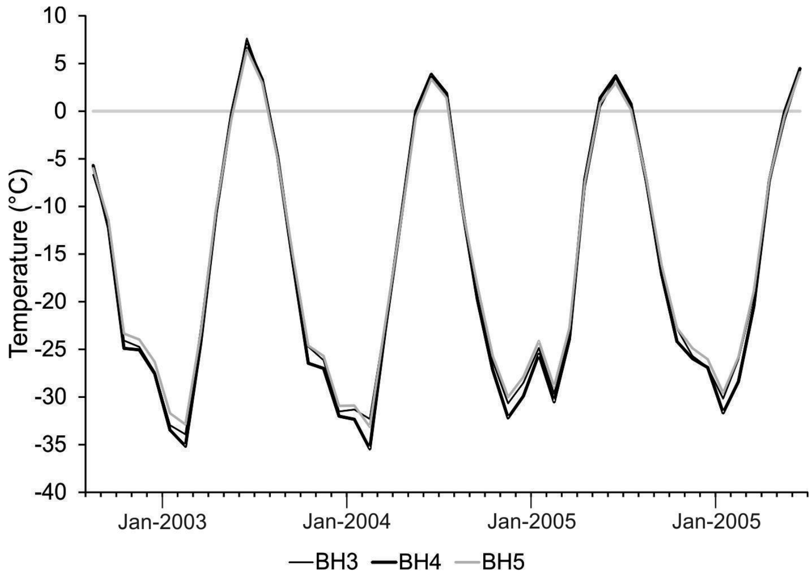

FIGURE 5. Monthly mean air temperature for August 2002 to August 2006, determined from air temperature records obtained from the Campbell weather stations at BH3, BH4, and BH5.

inversions (October–April) winds were light (a majority of the time less than 2 m s^{-1}) during times of inversion and came from the west (Fig. 9). Additionally, the lack of diurnal thermal heating during the winter due to the extremely high latitude of the CFS Alert permafrost observatory also supports the idea of stable cold-air drainage, which can collect in the valley bottom.

It appears that the presence of inversions, which form from year-to-year in similar locations, has an effect on the variability of permafrost temperature. Although BH3 is located at a higher elevation than the other monitoring sites, the mean annual ground temperature is higher than all other sites (Fig. 2) except BH1, which is adjacent to the coast and has a thicker winter snow cover. For example, MAGST (determined through extrapolation of deeper temperatures) at BH3 is 1.5 °C higher than at BH2, located at an elevation approximately 100 m lower. The mean ground surface temperature measured between 2002 and 2005 at BH2 is also about 1.5 °C below that at BH3. In addition, mean ground surface temperature recorded at BH4 is about 2 °C below that at an elevation 132 m higher at BH3; however, this can be attributed partly to the deeper snow cover at the higher elevation site (BH3) in addition to air temperature inversion.

Taylor et al. (2006) suggested that the higher ground temperatures at higher elevation could possibly be attributed to persistent winter atmospheric inversions that counteract the normal atmospheric lapse rate. The results presented here appear to support this suggestion. For example, although the thinner snow cover at BH4 (Fig. 4) compared to BH3 is partly the reason for lower ground surface temperatures at BH4, especially in the winter, this does not account for the lower winter ground surface temperatures observed at BH4 compared to BH5, located at 47 m higher elevation (Fig. 3). In winter 2002–2003 and 2003–2004, in particular, the ground surface-freezing index was 212 and 390 degree-days greater at BH4 compared to BH5 (Table 4). Although thin snow covers occurred during the observation period at BH4 and BH5, snow depth was generally greater at BH4, which has a slightly lower winter n-factor (ratio of surface to air freezing indices) on average, although still greater than 0.9 (Throop et al., 2012). The combination of a thin snow cover at BH4 and the occurrence of frequent and persistent winter air temperature inversions have likely resulted in greater winter cooling at BH4, and a lower mean surface temperature

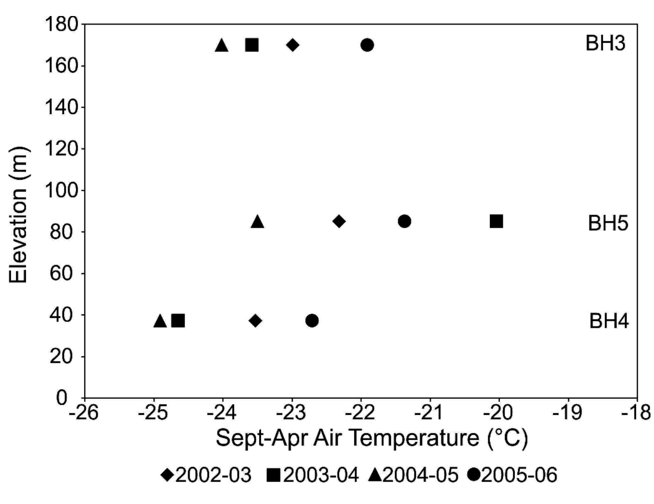

FIGURE 6. Variation in freezing season (September–April) average air temperatures with elevation based on data collected at the weather stations at the borehole sites BH3, BH4, and BH5.

TABLE 2

Mean, minimum, and maximum air temperatures (°C) for the low sun period (September to April), determined from records from the three weather stations.

Period \ Station		BH3 (170 m)	BH5 (85 m)	BH4 (37 m)
	mean	–23.0	–22.3	–23.5
Sep 2002–Apr 2003	min	–39.1	–38.2	–41.2
	max	–0.8	1.3	1.8
	mean	–23.6	–20.0	–24.7
Sep 2003–Apr 2004	min	–38.3	–39.2	–41.2
	max	1.7	4.2	0.8
	mean	–24.0	–23.5	–24.9
Sep 2004–Apr 2005	min	–40.3	–40.0	–41.2
	max	–1.9	–1.1	–0.3
	mean	–21.9	–21.4	–22.7
Sep 2005–Apr 2006	min	–40.6	–39.2	–40.5
	max	2.8	3.7	4.3

compared to the other two sites located at a higher elevation. Although a higher surface freezing index was also observed for BH4 compared to BH5 in winters 2000–2001 and 2001–2002 (see Throop, 2010), this is not the case for the winter of 2004–2005 (Table 4), although there are periods where winter ground surface temperatures at BH4 were lower than that at BH5 (Fig. 3). Snow covered the ground for a longer continuous period during winter 2004–2005 compared to the previous two years (Fig. 4) and this may have been a factor in reducing of the effect of air temperature inversions at BH4.

Mean annual ground temperature at BH2 was observed to be lower than at BH3, which is almost 100 m higher in elevation (Fig. 2). There are no air temperature measurements at BH2, but it is likely that BH2 was affected by lower winter air temperatures in response to persistent inversions. Although periodic manual snow depth measurements indicated that snow depth was generally greater at BH2 compared to BH4 and BH5, it was less than that at BH3. The surface freezing index based on records from the ground surface temperature sensor at BH2 indicate that this was greater than that at BH3 over the 2002–2006 period. The surface freezing index at BH2 for the same period was only greater than that at BH5 for winter 2003–2004 when it was about 250 degree days higher. Air temperature inversions may therefore be a factor influencing ground surface temperatures and partially be responsible for the lower ground temperatures at BH2.

Permafrost Thermal Heterogeneity

In order to examine the potential permafrost thermal heterogeneity created by surface inversions, an analysis was conducted using the TTOP (temperature at the top of permafrost) model (Smith and Riseborough, 2002):

$$T_{TOP} = \frac{(r_k n_t TDD_a) - (n_f FDD_a)}{P} \quad (1)$$

$$n_t = \frac{TDD_s(\textit{thawing season})}{TDD_a(\textit{thawing season})};\; n_f = \frac{FDD_s(\textit{freezing season})}{FDD_a(\textit{freezing season})}, \quad (2)$$

where r_k is the thermal conductivity ratio of the ground (thawed/frozen); n_t and n_f are the thawing and freezing n-factors that represent scaling factors between summer (plant vegetation effect) and winter (snow cover effect) air and ground surface temperatures; TDD_s, TDD_a, FDD_s *and* FDD_a are the surface and air thawing and freezing indices (Celsius degree-days); and P is the annual period (365 days).

This simple empirical model utilizes seasonal n-factors (freezing and thawing) that relate ground surface tem-

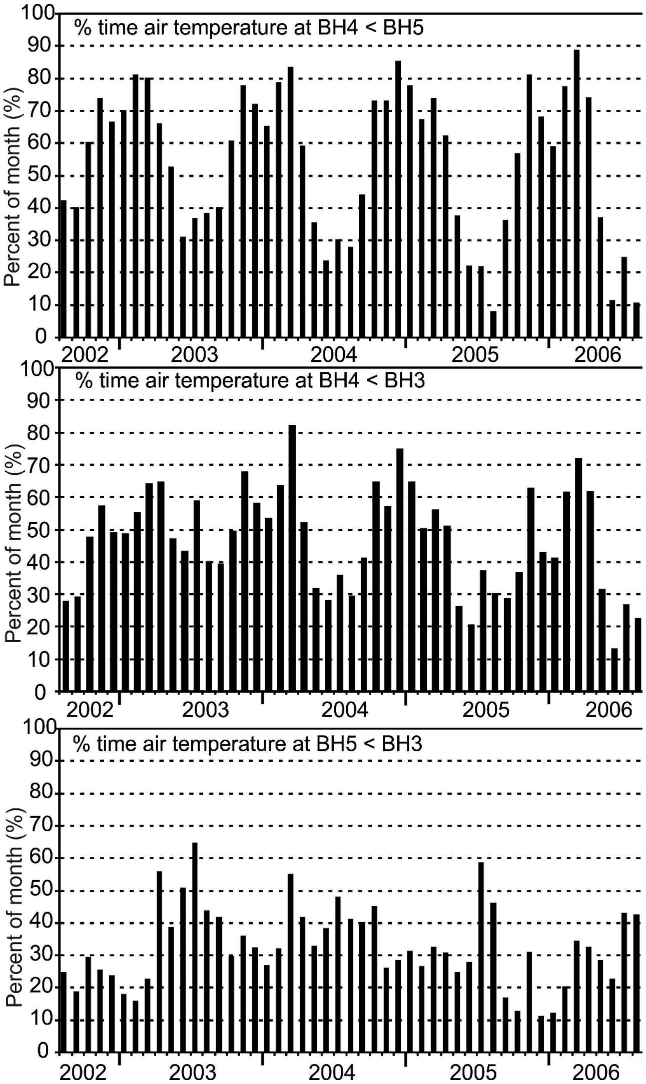

FIGURE 7. Proportion of each month between August 2002 and August 2006 during which air temperature inversions were observed between pairs of stations.

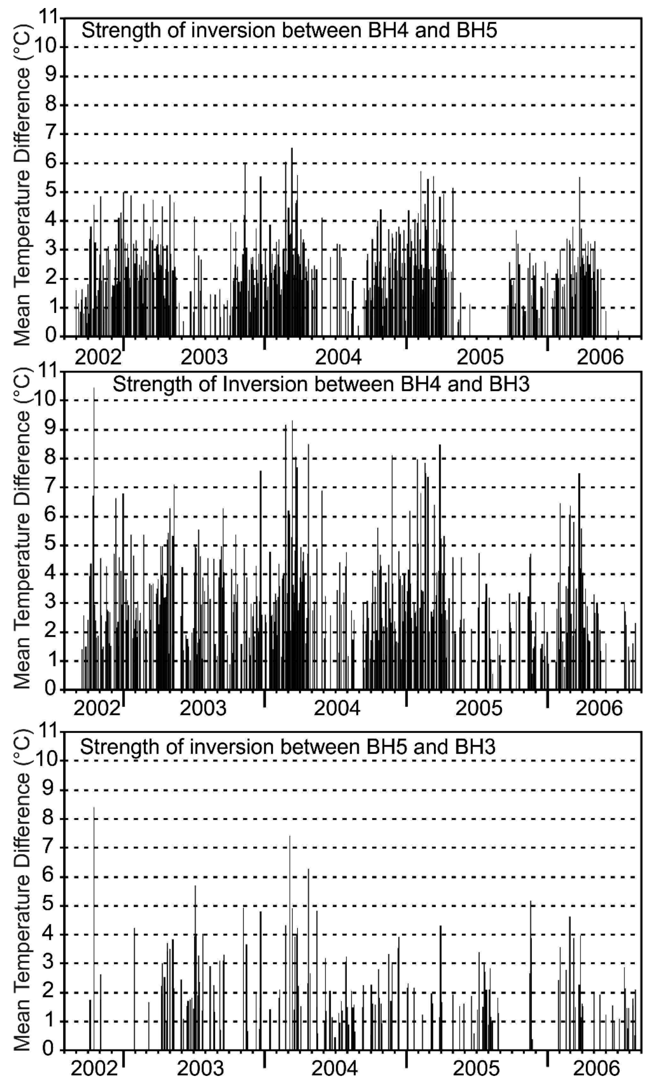

FIGURE 8. Strength of air temperature inversions longer than 12 h in duration occurring between pairs of boreholes between August 2002 and August 2006. The mean difference in air temperature during the inversion period represents the strength of the inversion.

TABLE 3

Duration of air temperature inversions and strength of inversions lasting longer than 12 h. Strength is given both as an absolute difference in air temperature and as the change in temperature with elevation. The standard deviation (s.d.) is given with the average values.

	Approx. elevation difference (m)	Avg. strength (and s.d.)	Range in strength	Max duration (h)	Avg duration (h, s.d.)
Between BH4 and BH5	47	2.35 °C (1.14) 5 °C per 100 m	0.19–6.49 °C 0.4–14 °C per 100 m	187	29.1 (25.4)
Between BH4 and BH3	132	3.12 °C (1.63) 2.4 °C per 100 m	0.3–10.45 °C 0.2–8 °C per 100 m	182	22.9 (15.6)
Between BH5 and BH3	85	2.28 °C (1.32) 2.7 °C per 100 m	0.4–8.40 °C 0.5–10 °C per 100 m	92	22.1 (13.8)

TABLE 4

Air and ground surface freezing index (degree-days) for BH3, BH4, and BH5. FDD_a and FDD_s are the air and surface indices, respectively.

Station Period		BH3 (170 m)	BH5 (85 m)	BH4 (37 m)
2002–2003	FDD_a	5953	5790	6080
	FDD_s	5016	5951	6341
2003–2004	FDD_a	6151	6121	6381
	FDD_s	5516	5966	6177
2004–2005	FDD_a	6101	5947	6264
	FDD_s	4641	5741	5589

peratures to air temperatures as an empirical alternative to evaluating the energy balance. This approach allows combinations of scenarios to be examined, including inversion intensity and variable snow cover for boreholes BH4, BH5, and BH3 (Table 5). For simplicity, summer conditions (TDD_a and n_t) are assumed to be the same for all three boreholes with an n_t value of one to be representative of sparse vegetation conditions. Surficial geology is also assumed to be similar across the boreholes and consists predominantly of till. The lack of a prolonged period of ground temperature near 0 °C during active layer freeze-back (zero curtain) and relatively small to non-existent thermal offset (i.e., difference between surface temperature and TTOP) are also indicative of fairly dry conditions (Taylor et al., 1982; Throop, 2010). With little moisture existing in the near surface a thermal conductivity ratio (r_k) value of one was utilized, which is similar to that used in other dry High Arctic environments (e.g., Bonnaventure et al., 2016). To consider just the inversion effects, an n_f value of one was used to represent the lack of snow cover, with variable values of n_f (based on observed air and ground surface temperatures) used to examine the effects of variable snow cover.

Considering only the effects of the inversion, the difference in TTOP between the two lower elevation sites (BH4 and BH5) is 0.8 °C (Table 5). This is greater than the 0.5 °C difference in surface temperature found by Taylor et al. (1982) and the 0.3 °C difference in mean annual surface temperature for the 2002–2005 period (Fig. 3). If differences in snow cover between the sites are considered using the n_f determined from the site data, TTOP at BH3 is much higher than at the other two

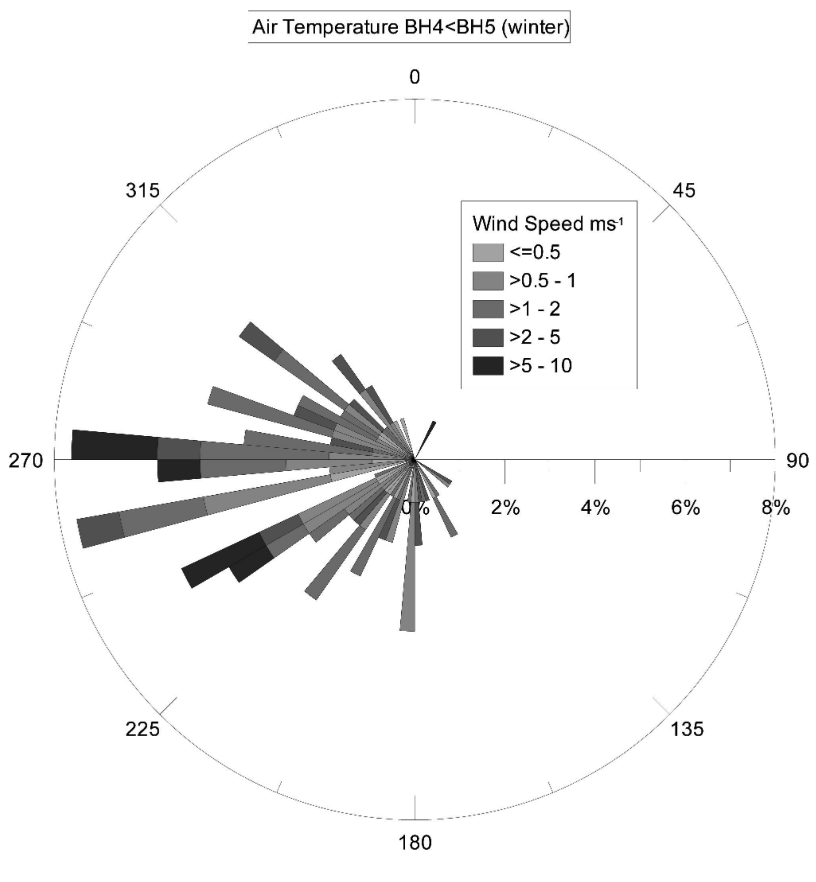

FIGURE 9. Analysis of prevailing wind direction during periods of inversion (air temperature at BH4 < BH5) longer than 12 h in duration for the winter months (October–April) during 2002–2006. Average wind speed (m s^{-1}) during inversions is also shown and is based on records from the weather station at BH4.

sites because of the greater amount of snow resulting in a lower n_f value of 0.89 (Table 5). Average n_f values for the other two sites are similar with a slightly lower value for BH4 compared to BH5 (although there can be individual years where they are almost the same as snow cover is similar) resulting in TTOP at BH4 being about 0.5 °C warmer than at BH5. Considering the combined effect of air temperature inversion and variable snow cover, the resulting TTOP at BH4 is about 0.3 °C lower than that at BH5, which is in good agreement with the observed difference in mean annual surface temperature (Fig. 3). The addition of the inversion effect also results in a greater difference in TTOP between BH3 and BH4, with TTOP at the lower elevation site being about 1.5 °C lower (Table 5), which is similar to the observed difference in surface temperature. This simple modeling exercise demonstrates that the effect of persistent inversions may be considerable (up to 0.8 °C reduction in TTOP) at sites with limited snow cover, such as BH4 and BH5.

Inversion Comparison

There have been relatively few studies that quantify and examine the mechanism and distribution of inverted surface lapse rates. Recent examples in the literature include the work done by Pagès and Miró (2009) in the Pyrenees, as well as work in western Canada by Taylor et al. (1998), Lewkowicz and Bonnaventure (2011), Chaput and Gajewski (2014), and O'Neill et al. (2015). The conclusions thus far indicate that inversions are more persistent in winter under stable air conditions. Another major conclusion is that although inversions appear to occur commonly in areas where relief is present, their intensity and the impact on the ground thermal regime can be substantially different in areas of differing climate. Lewkowicz and Bonnaventure (2011) showed that both latitude and continentality affect the inversion itself, ultimately aiding to control permafrost distribution. These conclusions have been significant, as often climate models and projections utilize standard surface lapse rates (e.g. –6.5 °C km^{-1}), which are highly inappropriate on both seasonal and annual scales. An example of this includes the WorldClim climate product (Hijmans et al., 2005), which is an impressive data set but has been shown to produce inaccurate results in areas of high relief in western Canada where observed local surface lapse rates differ greatly (Lewkowicz et al., 2012).

This study builds on the work by Taylor et al. (2006) to show that areas in the High Arctic are not only

TABLE 5

The temperature at the top of permafrost (TTOP), scenario modeling to examine the impact of inversions and snow on thermal permafrost heterogeneity across BH4, BH5, and BH3. The air thawing index (TDD_a) and thawing n-factor (n_t) are based on summer 2003 observed air and ground surface temperatures. The freezing n-factor (n_f) values for scenarios considering snow cover effects are based on average values for the 2002–2005 period using observed air and ground surface temperatures. The air freezing index (FDD_a) values are based on 2002–2003 observed values (Table 4).

Scenario	Site and elevation	TDD_a	n_t	FDD_a	n_f	$TTOP$ (°C)
Inversion only	BH4 (37 m)	365	1	6080	1	–14.90
	BH5 (85 m)	365	1	5790	1	–14.10
	BH3 (170 m)	365	1	5953	1	–14.55
No inversion; variable snow, cold winter air temperature	BH4 (37 m)	365	1	6080	0.96	–14.23
	BH5 (85 m)	365	1	6080	0.99	–14.73
	BH3 (170 m)	365	1	6080	0.89	–13.07
No inversion; variable snow, warm winter air temperature	BH4 (37 m)	365	1	5790	0.96	–13.47
	BH5 (85 m)	365	1	5790	0.99	–13.94
	BH3 (170 m)	365	1	5790	0.89	–12.36
Both effects	BH4 (37 m)	365	1	6080	0.96	–14.23
	BH5 (85 m)	365	1	5790	0.99	–13.94
	BH3 (170 m)	365	1	5953	0.89	–12.76

prone to the development of surface inversions but experience some of the strongest inversions seen to this point. Although the levels of absolute relief are less in the High Arctic compared to areas of complex topography in western Canada, the inversion strength when compared directly is substantially greater. During the winter months the surface lapse rate around Dawson City in the continental Yukon has been shown to be greater than +5 °C km^{-1} for an annual surface lapse rate of about +1 °C km^{-1} (Lewkowicz and Bonnaventure, 2011), which is similar to that found by Taylor et al. (1998) at Norman Wells, Northwest Territories (NWT), and O'Neill et al. (2015) across an alpine treeline on Peel Plateau, NWT. At the Alert site this value appears to be about an order of magnitude greater, averaging +50 °C km^{-1} (+5 °C/100 m) between BH4 and BH5 and +24 °C km^{-1} (+2.4 °C/100 m) between BH4 and BH3 (Table 3), which agrees with earlier observations in the High Arctic by Bradley et al. (1992). Although the impact of inversions does not control permafrost distribution in the same way in the High Arctic as in western Canada, understanding the thermal variability as climate changes is critical to understand how these impacts will be manifested at the regional, local, and micro scale.

Summary and Conclusions

Frequent persistent air temperature inversions have been documented at the CFS Alert permafrost observatory. During winter air temperature inversions, the air temperature in the valley bottom may be several degrees below that recorded at sites at 47 to 132 m higher elevation. These colder conditions, which can last for several days, along with the relatively thin snow cover, have resulted in colder ground surface conditions and greater winter heat loss from the ground in the valley bottom compared to sites at higher elevation. This likely explains the lower permafrost temperatures that are observed in the valley bottom as this pattern persists from year to year. The simple modeling exercise further demonstrated that the effect of inversions can be considerable where snow cover is thin, reducing temperature at the top of permafrost by up to 0.8 °C.

The results of the analysis suggest that the occurrence of air temperature inversions may be an important factor determining the spatial variation in permafrost thermal state in High Arctic environments. The temperature inversions are a particularly important factor where snow cover is thin and does not provide insulation from the low winter air temperatures, such as the case for the valley sites examined at CFS Alert. Changes in the depth, frequency, or strength of air temperature inversions that may accompany changes in climate may therefore be an important factor determining the response of permafrost environments in the High Arctic to climate warming.

Acknowledgments

Support for this research has been provided by Natural Resources Canada and various other sources over the years including the Government of Canada's Climate Change Action fund, Action Plan 2000, and the International Polar Year Program. The continuing support of Department of National Defence and Environment Canada and their staff at CFS Alert is greatly appreciated. Upgrading of instrumentation would not have been possible without the efforts of M. Burgess, A. Taylor, V. Allen, and the late D. Riseborough. Assistance with data processing and analysis was provided by J. Chartrand. Comments by three anonymous reviewers were also helpful in improving the manuscript. ESS Contribution No. 20100445.

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MS submitted 29 June 2016
MS accepted 15 December 2016