

# 13 Years of Observations at Alaskan CALM Sites: Long-term Active Layer and Ground Surface Temperature Trends

Dmitry A. Streletskiy, Nikolay I. Shiklomanov, and Frederick E. Nelson  
*Department of Geography, University of Delaware, Newark, USA*

Anna E. Klene  
*Department of Geography, University of Montana, Missoula, USA*

## Abstract

Active layer monitoring is an important component of efforts to assess the affects of global change in permafrost environments. In this study we used data from 13 (1995-2007) years of spatially oriented field observations at a series of 16 representative Circumpolar Active Layer Monitoring (CALM) sites in northern Alaska to examine temporal and spatial trends in active-layer thickness and its relation to climatic, surface, and subsurface conditions. The observation strategy consisted of measuring active-layer thickness on regular 1 ha and 1 km<sup>2</sup> grids representative of environmental conditions on Alaska's North Slope. The measurement program also involves continuous air and soil temperature monitoring, periodic frost heave and thaw subsidence using Differential Global Position System (DGPS) as well as landscape, vegetation, and soil characterization. This paper showcases CALM observation procedures and analysis designed to monitor processes and detect changes not anticipated in the original CALM protocol of the early 1990s.

**Keywords:** *active layer; Alaska; CALM; Circumpolar Active Layer Monitoring; surface temperature; thaw subsidence*

## Introduction

The active layer is the most dynamic part of the permafrost system, and undergoes many changes in its properties during each annual cycle. These fluctuations involve variations of ice/water content, thermal conductivity, density, mechanical properties, and solute redistribution (Ershov 2002), all of which are of critical importance for many natural phenomena and processes in permafrost and periglacial environments (French 2007). Most biological and hydrological activities in Arctic soils are confined to the layer of seasonal thaw (Hinzman 1991). Active-layer monitoring is an important component of efforts to assess the effects of global climate change in Arctic environments. The Circumpolar Active Layer Monitoring (CALM) program is a network of sites at which data about active-layer thickness (ALT) and related climatic, vegetation, and soil parameters are collected. The CALM network involves more than 160 sites underlain by permafrost in polar regions and selected mountainous environments (Brown et al. 2000, Nelson et al. 2004).

In this study we used data from 13 years (1995-2007) of extensive, spatially oriented field observations at a series of 16 CALM sites on the North Slope of Alaska to examine landscape-specific temporal trends in active-layer thickness and air and soil temperature. CALM strategies are evolving constantly, and this paper showcases CALM observation procedures and analysis designed to monitor processes and detect changes not anticipated in the original CALM protocol of the early 1990s. Details of the analyses and results will be presented in series of manuscripts currently in preparation.

## Study Area

Of the 41 CALM-designated sites in Alaska, 29 are located on the North Slope (Shiklomanov et al. 2008). In this paper we report observed long-term trends of air and ground surface temperature and active-layer thickness from 16 sites with continuous records for 13 years (1995-2007).

The sites selected for analysis are distributed along the primary climatic gradient in northern Alaska (Figure 1). The sites span the regional spectrum of vegetation and terrain conditions in two dominant physiographic provinces: the Arctic Coastal Plain in the north and Arctic Foothills in the south (Wahrhaftig 1965).

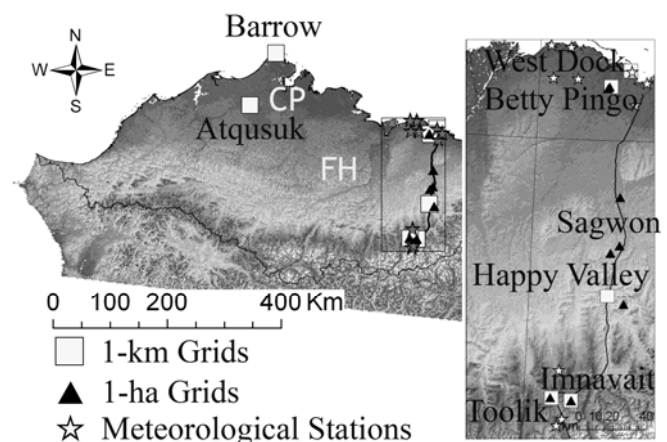


Figure 1. Geographic distribution of Alaskan CALM observational sites used in the present study. Gray tones represent elevation, with brighter shades indicating higher elevations. Physiographic provinces are indicated by white lettering: CP – Coastal Plain, FH – Foothills. Black font is used name specific sites, mentioned in the text.

The elevation of the Arctic Coastal Plain increases gradually from north to south, reaching about 100 m at its southern edge. Pure drainage and low relief create conditions for development of thaw lakes. Thaw lakes and thaw-lake basins occupy from 20 to 50% of the area. The coastal plain is dominated by wet sedge polygonal tundra on soils associated with windblown loess deposits (Walker et al. 2003).

The Arctic Foothills province extends between the Arctic Coastal Plain and the Brooks Range, and is characterized by hills and plateaus divided by river valleys. The area was glaciated during the Pleistocene and surface deposits are mostly glacial till with discontinuous loess cover (Bockheim et al. 1998). Differences in underlying deposits create distinct geochemical contrast in soils, leading to differences in vegetation species and organic layer thickness (Walker et al. 1998). Based on soil pH, areas of tundra can be subdivided into acidic (pH < 5.5) and nonacidic (pH > 5.5) classes. Soils in nonacidic tundra have thinner organic horizons, a significantly thicker active layer, and greater cryoturbation than soils of acidic tundra (Bockheim et al. 1998).

The entire study area lies in the zone of continuous permafrost. The only areas possibly without permafrost are occupied by deep bodies of water that fail to freeze to the bottom in winter (Pew 1975).

## Methodology

Of the 16 CALM sites used in the analysis described in the next section, nine consist of 1 ha plots established to represent relatively homogeneous examples of the landscape categories found in particular physiographic provinces. The selection of landscapes was guided by regional Landcover map derived from Landsat imagery (Auerbach et al. 1996). The resulting map depicts five primarily landscape units dominated by: wet tundra (WET), moist acidic tundra (MAT), moist nonacidic tundra (MNT), shrublands (SHR) and barrens. The detailed characteristics of the 1 ha sites were presented in Shiklomanov & Nelson (2003), and Klene et al. (2001b); their geographic distribution is shown in Figure 1. Beginning in 1995, the active layer has been probed at least annually at the 1 ha sites. The procedure involves pushing a metal rod, calibrated in cm, to the point of refusal, interpreted in most cases to be the frost table. Thaw depth measurements at each site were obtained by probing at 5 m intervals along the plot's two perpendicular and one diagonal transect, resulting in 71 points per plot per probing date. Air and soil surface temperature were measured continuously at two-hour intervals over the 1995-2007 period (data are available for the 1996-2006 period) with an array of Onset<sup>TM</sup> portable data loggers. At each site one logger is mounted on a mast, with thermistors placed approximately 2 m above the ground in a radiation shield. Seven to ten loggers are distributed over each of the 1-ha plots, with thermistors placed at the vegetation/soil interface at locations representative of microtopographic conditions (Klene et al. 2001b, Klene et al. 2008).

Periodic thaw depth measurements were also conducted at seven surveyed and georeferenced 1 km<sup>2</sup> grids over the period 1995-2007. These sites were established in northern Alaska during the 1980s and 1990s to monitor long-term ecosystem change (Brown et al. 2000). Four grids (Barrow, Atkasuk, Betty Pingo and West Dock) are situated on the Arctic Coastal Plain and the remaining three (Happy Valley, Innvait Creek and Toolik Lake) are in the Arctic Foothills (Figure 1). The 1 km<sup>2</sup> grids were selected to represent more generalized conditions found in each physiographic province. Detailed descriptions of 1 km<sup>2</sup> sites are provided by Hinkel & Nelson (2003). Each grid consists of a square array of surveyed permanent stakes separated by 100 m, yielding an array of 11 x 11 nodes across each grid. Replicated active layer sampling was conducted by manual probing at each stake, yielding a maximum of 121 data points per grid per probing date. The active layer was not measured at locations where grid points intersect rocks or deep water. A significant portion of the Toolik and Innvait sites are underlain by coarse glacial material that is impenetrable for metal probes. These sections of the Toolik and Innvait grids were excluded from the analysis.

Each grid is instrumented for air and ground surface temperature measurements using equipment similar to that at the 1 ha sites. In addition, at each 1 km<sup>2</sup> site ground temperature is monitored at hourly intervals at the standard depths of 0, 5, 10, 15, 20, 25, 30, 35, 45, 70, 95 and 120 cm using Campbell Scientific<sup>TM</sup> and Measurement Research Corporation instrumentation. The periodic, spatially oriented frost heave and thaw subsidence measurements using Differential Global Position System (DGPS) were initialized in 2001 at two Coastal Plain 1 km<sup>2</sup> sites and one Foothills 1 ha site (Little et al. 2003, Streletskiy et al. 2005). Measurements are performed twice each year at the beginning (June) and the end (August) of the thawing season, using a hierarchical nested sampling design (Nelson et al. 1999). A series of additional sites were instrumented with meteorological towers to measure air and soil surface temperature at locations unrepresented by the 1-ha and 1-km<sup>2</sup> plots.

## Analytical Results

### *Air temperatures Trends*

Air temperature trends from individual sites were analyzed using procedures outlined in Shiklomanov & Nelson (2002). In this paper we present monthly air temperatures, integrated over physiographic provinces.

Regionally, air temperature increases from north to south. Mean annual air temperature over the study period varied between -9.2 and -12.0°C on the Coastal Plain and between -7.3 and -10.3°C in the Foothills. Mean summer air temperature (June-August) on Coastal Plain varies between 5.5 and 8.7°C, while at Foothills ranges from 6.8 to 11.7°C. This climatic pattern demonstrates the pronounced influence of the Arctic Ocean during the summer, throughout the Coastal Plain. Province-specific 12-year (1995-2006) records of mean, minimum, and maximum annual air temperature, as observed at CALM sites, are shown in

Figure 2. There is a slight decline in mean and maximum annual air temperature for Coastal Plain and in maximum annual air temperature for Foothills.

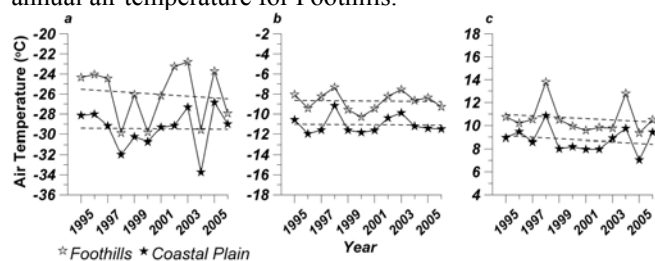


Figure 2. Twelve-year (1995-2006) records of annual minimum (a), mean (b), and maximum (c) monthly air temperature, as observed at CALM Coastal Plain and Foothills sites.

*Duration of Thawing period*

The duration of the thawing period was estimated based on analysis of mean daily air temperature at individual sites by counting consecutive days with temperatures above 0.5°C. Results were averaged over physiographic provinces.

On average, the thawing period on the coastal plain is almost 10 days shorter than in foothills. However this difference ranges from 2 to 16 days, depending on year. Province-specific 12-year records of thaw-period duration, as observed at CALM sites, are shown in Figure 3. Both provinces experienced an increase in the duration of thawing, attributable to both the earlier initiation of the thawing and later freezing.

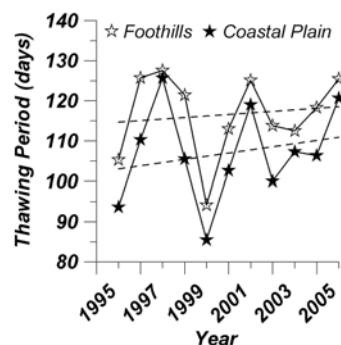


Figure 3. Province-specific 12-year (1995-2006) records of the duration of thawing period, as observed at CALM sites.

*Effect of vegetation of ground surface temperature*

Analysis of ground surface temperature was aimed primarily at evaluating the effects of vegetation and the characteristics of different landscape units on the ground thermal regime. The daily air and soil-surface temperature data, obtained at the homogeneous 1 ha sites, were used to calculate average difference between surface and air temperature ( $\Delta T$ ) for the warm period (June-August). To evaluate the effect of vegetation on the ground thermal regime further, the landscape-specific values of empirical summer n-factors were calculated. The n-factor, defined operationally as the ratio of the Degree-Day sum at the soil surface to that in the air (Carlson 1952), has been used in cold regions engineering since the 1950s to estimate soil surface temperature from air temperature records. Estimation of n-factors has been found to be a useful, simple approach for deriving attenuation of climatic signals by vegetation covers (Klene et al. 2001a, b, Kade et al.

2006). An analysis of winter n-factors for the study sites is presented elsewhere in this volume Klene et al. (2008).

Values of  $\Delta T$  and n-factors obtained at individual sites were averaged to represent individual landscapes and physiographic provinces. To account for interannual climatic variability, the annual landscape- and province-specific values of  $\Delta T$  and n-factor were averaged over a 12-year (1995-2006) period and are presented in Table 1

The vegetated surfaces in both physiographic provinces show negative values of  $\Delta T$  and n-factors values of less than unity, indicating the cooling influence of vegetation on ground temperature during the warm period. The distinct values of  $\Delta T$  and n-factor indicate the distinct thermal influence of landcover types characteristic of the Coastal Plain and Foothills physiographic province. The moist acidic tundra (MAT) of the foothills province has the largest negative value of  $\Delta T$  (-3.8°C) and the smallest value of n-factor (0.52). The smallest negative  $\Delta T$  value (-1.2°C) and highest n-factor value (0.78) were found in moist nonacidic tundra (MNT) of the coastal plain. Regionally, values of  $\Delta T$  and n-factor for similar landscape units vary from north to south in response to the increase in density of the vegetation cover. This effect is evident from differences in  $\Delta T$  and n-factor for moist nonacidic tundra in two physiographic provinces. The thermal influence of MNT is greater in the Foothills than on the Coastal Plain.

Unvegetated surfaces, which consist of sand, gravel, and bedrock along streams and atop hills and mountains, show positive values of  $\Delta T$  and values of n-factors of more than unity, indicating a warming influence of barren surfaces on ground thermal regime.

**Table 1.** Landscape-specific 12-year (1995-2006) average values of  $\Delta T$  and n-factors, as estimated from air and ground surface temperature measurements at representative 1 ha CALM sites.

Landscape Unit	Coastal Plain		Foothills	
	$\Delta T$ , °C	N-factor	$\Delta T$ , °C	N-factor
Barrens	1.0	1.20	1.6	1.22
MNT	-1.2	0.78	-2.6	0.71
MAT			-3.8	0.52
Shrublands			-3.1	0.57
WET	-2.2	0.66	-2.3	0.74

*Annual thawing propagation*

The annual dynamics of thawing were evaluated by analyzing thawing intensity curves for four 1 km<sup>2</sup> sites. The Barrow and Atkasuk sites were selected to represent the coastal plain, while Happy Valley and Toolik are representative of foothills. The thawing intensity curves were constructed by calculating a daily increase in thaw depth as a portion of the maximum annual active-layer value. The daily values of thaw depth for each site were estimated using ground temperatures observations from an array of 12 thermistors, distributed vertically from the surface to 1.2 m depth. The daily depth of thaw penetration was assumed to coincide with interpolated position of the 0°C isotherm. For the silty soils characteristic of northern Alaska, the correspondence between thaw depth, as

determined by mechanical probing, and the position of 0°C isotherm is generally quite good (Brown et al. 2000).

The analysis of annual thawing intensity curves indicates that, depending on site and year, 95% to 99% of maximum thaw propagation is reached by mid August, when annual CALM ALT observations by mechanical probing are starting at North Alaskan sites.

To evaluate the physiographic province-specific intensity of annual thaw penetration, independent of interannual variability in climatic conditions, relative increases in thaw depth were plotted as function of relative time:  $Z/Z_{max}=f(T/T_{th})$ , where  $Z$  is the thaw depth at time  $T$  and  $Z_{max}$  is the annual maximum thaw depth, achieved over thawing period  $T_{th}$ . Site-specific 12-year averages of thawing intensity for two coastal plain (Barrow (BRW) and Atqasuk (ATQ)) and two foothills (Happy Valley (HV) and Toolik (Tool)) locations are shown in Figure 4. The thawing intensity curves for all four locations are similar, indicating that relationship between annual thaw depth propagation and dimensionless time is uniform for different surface, subsurface, and climatic conditions. Figure 4 demonstrates that regardless of location, 44% of annual thaw occurring during the first quarter of the thawing period; during the half of thawing period thaw depth reaches 70% of its maximum; after 3/4 of the thawing period, thaw depth is at 88% of its maximum; and 96% of active layer is developed during the 90% of thawing season. These numbers closely correspond to values obtained at three drastically different locations in Russia (Yakutsk, Vorkuta and Igarka) by Pavlov (1984). The best-fit quadratic equation, presented in Figure 4, can be applied to estimate the active-layer thickness using thaw depth measurements performed at different time during the summer.

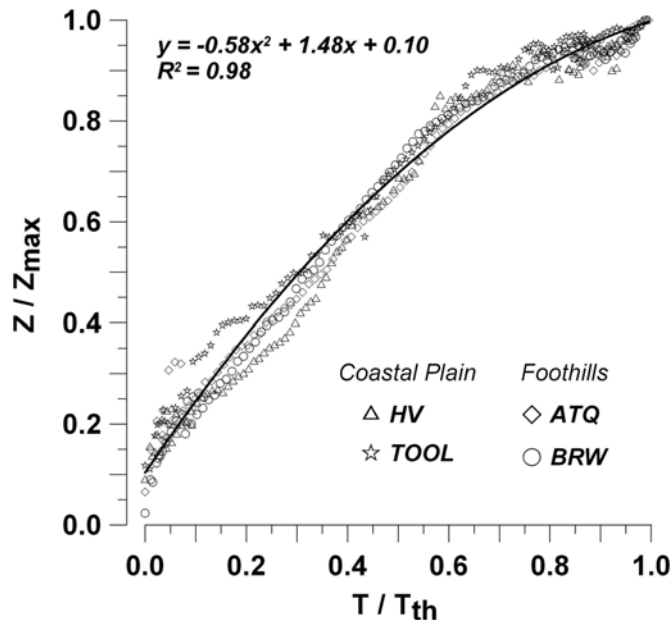


Figure 4. Site-specific 12-year averages of thawing intensity for two coastal plain (Barrow BRW and Atqasuk ATQ) and two foothills (Happy Valley HV and Toolik TOOL) locations.  $Z$  is thaw depth at time  $T$  and  $Z_{max}$  is annual maximum thaw depth achieved over the thaw period  $T_{th}$ .

*Interannual variability of active-layer thickness*

The interannual dynamics of active-layer thickness were evaluated by analyzing annual, site-specific averages of thaw depth values obtained at the end of thawing period.

Site-specific 13-year (1995-2007) records of annual active-layer thickness for different landscape categories and physiographic provinces are shown in Figure 5. The records indicate a declining active-layer trend over the 1995-2007 period for all coastal plain and foothills sites, which generally corresponds to a decline in summer temperature over the same period (Figure 2 c). The maximum values of ALT were recorded in 1998, 2004, and 2006, the years that experienced the warmest summers (Figure 5). The general agreement between ALT and summer air temperature records stipulates strong degree of climatic forcing on ALT.

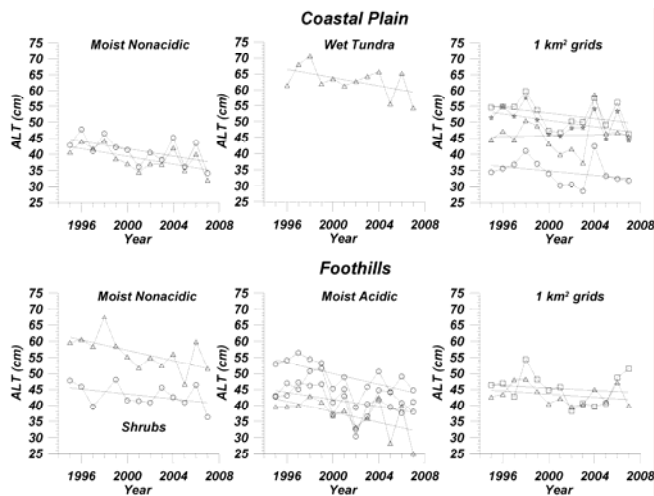


Figure 5. Site-specific 13-year (1995-2007) records of annual active-layer thickness. Nine 1 ha sites are grouped by landscape category characteristic of two physiographic provinces. Six 1 km<sup>2</sup> sites are grouped by physiographic provinces. The Imnavait 1 km<sup>2</sup> site is not shown due to data quality issues.

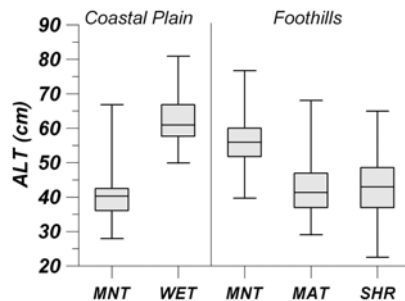


Figure 6. Statistical distribution (box plot) of ALT values for different landscapes characteristic of the two physiographic provinces.

*Landscape-specific active-layer characteristics*

Previous studies, conducted at Alaska CALM sites (Nelson et al. 1998, 1999, Nelson & Hinkel 2003), demonstrated the existence of landscape-specific thermal differences manifested through similar magnitudes of thaw propagation. Although thaw depth can experience significant interannual variability in response to climatic forcing (Figure 5), the presence of landform elements shows

spatial regularity at the landscape scale and results in landscape-specific thaw depth patterns that repeat on an interannual basis (Nelson et al. 1998, Hinkel & Nelson 2003). Figure 6 shows statistical distributions of ALT, averaged over the 1995-2007 period for different landscapes, characteristic of two physiographic provinces. The landscape- and province-specific mean values of ALT are presented in Table 2.

Table 2. Landscapes- and province-specific values of active-layer thickness.

Landcover categories	Coastal Plain	Foothills
Moist nonacidic tundra	40.0	56.4
Moist acidic tundra		40.5
Moist low shrub tundra		43.0
Wet graminoid tundra	62.9	49.1

To evaluate the landscape-specific thermal response to climatic forcing, annual ALT values from representative 1 ha sites were correlated with the square root of Degree-Days of Thawing (DDT), estimated from site-specific air temperature records and accumulated by the date of thaw depth measurements (Shiklomanov & Nelson 2003). A plot of square root of DDT against thaw depth (Figure 7) yields distinct linear landscape-specific relations indicating differences in thermal landscape sensitivity to climatic forcing.

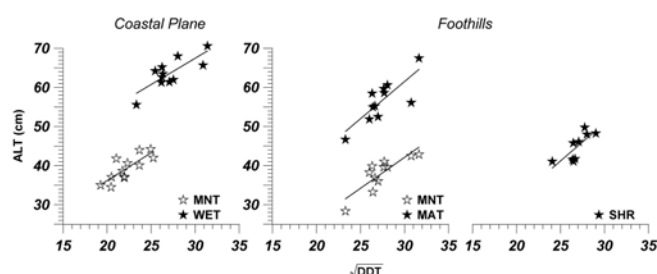


Figure 7. Plot of square root of air DDT against thaw depth for several 1-ha sites characteristic of dominant landscapes in the coastal plain and foothills provinces. Each data point represents annual end-of-thawing season measurements for the 1995-2006 period.

#### Ground subsidence

Because thaw penetration into an ice-rich layer at the base of the active layer is accompanied by loss of volume (thaw consolidation), straightforward measurement of active-layer thickness by such methods as mechanical probing may not always yield accurate estimates of changes in the permafrost system. Periodic thaw subsidence measurements using DGPS technology allowed us to address this problem effectively. Figure 8 shows the results of active layer and ground subsidence measurements over 2001-2006 period at two locations, representative of the coastal plain and foothills physiographic provinces. The total subsidence over five year period was 12 cm at the coastal plain site and 13 cm at the foothills site.

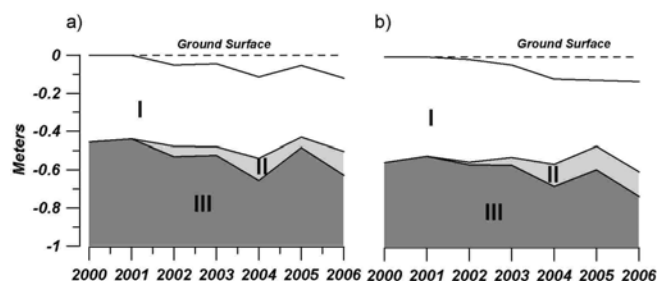


Figure 8. Annual changes in position of ground surface and ALT as measured by mechanical probing for representative coastal plain (a) and foothills (b) CALM sites. I- ALT as measured by probing; II- ALT, corrected for ground subsidence; III-permafrost.

To account for ground subsidence in the active layer record, the annual changes in position of the ground surface, relative to the level in the year 2000, were added to the active layer measurements, produced by mechanical probing (Figure 8). Results from the two sampling locations indicate a monotonic increase in thaw penetration between 2001 and 2006.

## Conclusions

The results of 13-year active layer, air, and ground temperature observations at CALM sites in north-central Alaska indicate that: 1) there is a slight decline in mean and maximum annual air temperature on the Coastal Plain and in maximum annual air temperature in the Foothills. The period of observations was characterized by an increase in the length of the thawing period in both physiographic provinces; 2) The spatially oriented ground surface temperature observations within representative landscapes facilitates evaluation of the effect of ground cover on the ground thermal regime. The distinct values of  $\Delta T$  and  $n$ -factor indicate the unique thermal influence of landcover types characteristic of the Arctic Coastal Plain and Arctic Foothills physiographic provinces; 3) The results of active layer observations obtained by mechanical probing over 1995-2007 period indicate a pronounced decreasing trend in ALT for all landscape types, characteristic of dominant physiographic provinces; 4) Although thaw depth can experience significant interannual variability in response to climatic forcing, the presence of landform elements shows spatial regularity at the landscape scale and results in landscape-specific values of active-layer thickness. However, the annual rate of thaw propagation is similar for sites characterized by different surface, subsurface, and climatic conditions; 5) The results of DGPS survey indicate that soil consolidation accompanying penetration of thaw into an ice-rich stratum at the base of the active layer has resulted in subsidence of the surface, accounting for the lack of apparent thickening of the active layer (as traditionally defined).

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