Soil climate and frost heave along the Permafrost/Ecological North American Arctic Transect

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Abstract

The soil climate data has been collected during a recent biocomplexity study along a bioclimatic gradient in the North American Arctic Tundra. The measurements were made from South to North at: Happy Valley, Sagwon Hills, Franklin Bluffs, Deadhorse, West Dock, Howe Island, Green Cabin, Mould Bay and Isachsen research sites. Mean annual air temperature changes from around –10°C at the Happy Valley and Sagwon Hills sites to –16°C at Mould Bay and Isachsen. Mean annual ground surface temperature has even larger range, changing from –2°C to –15.5°C in the same direction. Mean annual ground temperature at the permafrost table changes from –3.5°C at Happy Valley to –15.5°C at Mould Bay and –14.7°C at Isachson. Snow depth is generally decreasing from the south to the north and snow density is generally increasing in the same direction. Measured maximal frost heave within the circles vary between 18-20 cm at the Deadhorse and Franklin Bluffs sites and less than 1 cm at West Dock.

Keywords: permafrost, temperature regime, active layer, snow cover, thermal offset, frost heave.

Introduction

Recent warming in permafrost temperatures was reported from many locations in the Circumpolar North (Harris and Haeberli, 2003; Isaksen et al., 2000; Pavlov and Moskalenko, 2002; Oberman and Mazhitova, 2001; Osterkamp, 2003a; Osterkamp and Romanovsky, 1999; Romanovsky et al., 2002 and 2007; Smith et al., 2005). At some of these locations that lay near to the southern boundary of permafrost, these warming already triggered long-term permafrost thawing. These changes in permafrost inevitably affect northern ecosystems and infrastructure make them evolve rapidly. Some of these changes could be advantageous, but most of them have negative consequences for the natural and human-made systems. Also, because of a wide variety in permafrost conditions and changes are present in the Arctic and sub-Arctic, different regions experience different rates or even different directions of these changes during the same time period. To document the temporal changes and spatial variability of permafrost in Alaska, a number of permafrost observatories were established in the late 1970s and early 1980s by the Geophysical Institute, UAF along the International Geosphere-Biosphere Program (IGBP) Alaskan transect, which spans the entire permafrost zone in Alaska (Osterkamp, 1986; Osterkamp and Romanovsky, 1999; Romanovsky and Osterkamp, 2001; McGuire et al., 2002; Osterkamp, 2003a, 2003b; Romanovsky et al., 2003).

Recent Biocomplexity Project of the University of Alaska Fairbanks, which investigated small pattern-ground features that occur along a transect in North America, has been funded by the National Science Foundation USA and is now in the final stage of its accomplishment (Walker et al., 200* and in review). This project made it possible to extend the IGBP Alaskan Transect into low- and high-Arctic regions in western Canada (Figure 1). It was a valuable addition to the Transect because it added the sites where permafrost temperatures are one of the coldest in the Northern Hemisphere. Also, a reduced vegetative cover and high ice content make permafrost in this region extremely vulnerable to recently observed and projected into the future changes in climate.

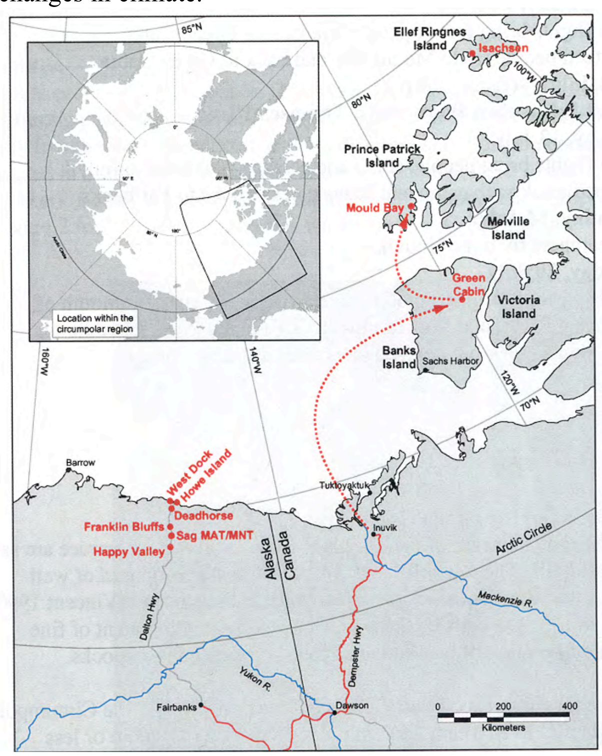

Figure 1, Location of research sites along the Permafrost/Ecological North American Arctic transect.

There are two types of natural gradients that will be discussed in this paper. One is the regional north to south gradient in air and soil temperatures, snow, and active layer thickness. Another is the local gradient in soil moisture and temperature, active layer thickness, and ground surface heave that is governed mostly by the surface vegetation distribution. The local gradients are the cause and, at the same time, the consequences of the non-sorted circles formation and evolution. The regional gradients in the atmospheric climate, soil climate, and vegetation also modulate the formation and development of pattern ground and are responsible for the specific morphological features of the pattern ground in the arctic landscapes. Soil and permafrost climate data together with air temperature, snow depth, and seasonal frost heave data collected at the sites along the Permafrost/Ecological North American Arctic Transect (NAAT) during the lifetime of the Biocomplexity project together with some previously collected temperature data will be discussed in this paper. First, we will provide a brief description of natural settings at the research sites and provide some information on measuring technique and used equipment. Further, using long-term data from several sites we will show how relatively short records from the biocomplexity project (2001-2006) fit a more general picture of temperature changes during the last 20 years. Then we will present data on soil climate and seasonal frost heave for the entire transect for the 2004-2006 time period. Finally, based on previous discussion we will formulate our conclusions.

A short sites description

Temperature, moisture and snow measurement stations were installed from South to North at: Happy Valley, Sagwon Hills, Franklin Bluffs, Deadhorse, West Dock, Howe Island, Green Cabin, Mould Bay and Isachsen (Figure 1). All these sites are located in continuous permafrost zone with relatively cold climate. Climatic conditions determine type of vegetation along this transect. All sites are within the tundra biome and represent all type of tundra from subzone A (or arctic desert) at Isachsen to subzone E (or southern tundra) at Happy Valley. The specific locations were chosen as representative of zonal conditions within each of five Arctic bioclimate subzones (A through E) (Walker et al., 2005). All the studies were located on fine-grained sediments conducive to the formation of non-sorted patterned-ground features and zonal vegetation. The Sagwon MAT and Happy Valley locations had acidic soils (pH<5.5), and all the others had nonacidic soils. Several sites (Howe Island, Green Cabin, Deadhorse, Franklin Bluffs) had soil pH values exceeding 8.0. The zonal vegetation varied from nearly barren surfaces with scattered mosses, lichens and very small forbs in the Subzone A to knee-high shrub-dominated tundra with thick moss carpets in Subzone E. A more comprehensive description of natural settings at the study sites can be found in (Walker et al., in review).

Methods of measurements

Small climate stations were established at each location. The air and ground-surface temperatures at each location were recorded using standard Campbell Scientific L107 thermistors. Two ground surface thermistors and two one-meter long arrays of thermistors (with approximately 10 cm distance between thermistors) were located about six meters apart, one in an unsorted circle and the other in between the circles. After pre-installment calibration, the precision of the sensors is better than 0.04°C. All measurements were made with one-hour time interval. The stations were operated and data were stored by Campbell Scientific CR10-X data loggers. A 20-watt regulated solar panel coupled with a 12 v battery was used for power supply. The installations are also part of the Permafrost Observatory Network (Osterkamp, 2003; Osterkamp and Romanovsky, 1999; Romanovsky and Osterkamp, 2001; Romanovsky et al., 2003). Snow depth was measured continuously with one-hour resolution at most of the sites using a Campbell Scientific SR50 Sonic Ranging Sensor that was connected to the Campbell data logger at the climate stations. Also, the maximum snow depth was measured every year manually at the Alaskan sites during spring (late April) field trips. At the Canadian sites maximum snow depth was measured manually once in early May 2006. The ground moisture (including the unfrozen water content in winter) was measured at two different depths within the unsorted circle and at two different depths in the inter-circle space. VITEL volumetric water content sensors (based on TDR technique) were used. Each of the VITEL sensors pared with additional L107 temperature probe. Moisture content was recorded hourly during the entire year.

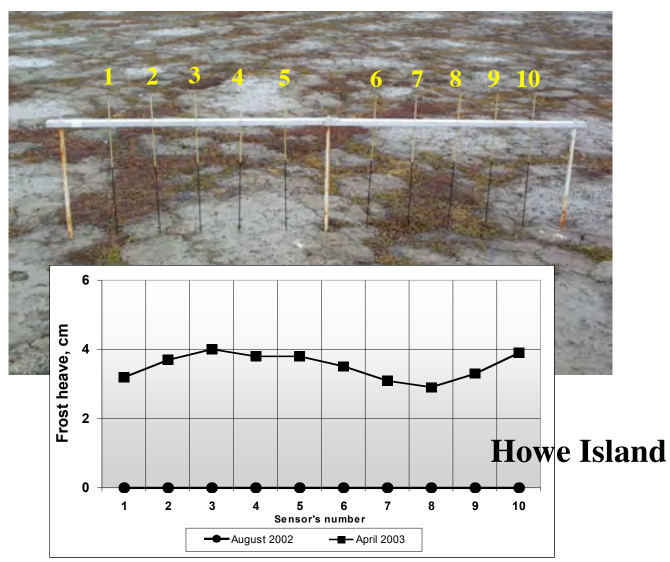

Figure 2, Frost heave measurements along the cross-section of a non-sorted circle at the Howe Island site.

Frost heave was monitored on and off the unsorted circles at all sites using two types of specially designed heave meters. Along the Dalton Highway portion of the

NAAT, a ten-pin heave instrument described in (Walker et al., 2004) was used (Figure 2). In the High Arctic, heave scribers were used. Each of these instruments consisted of a 2-m x 1.5-cm solid copper grounding rod that was driven 1.5 m into the ground, anchoring it in the permafrost. A steel plate and sleeve with an attached sharp steel scriber was placed on the rod, with the plate resting on the ground. The steel plate and scriber slid freely on the rod, rising with the frost heave in the winter and allowing the scriber to scratch a line on the copper rod. The length of the scratched line determined the amount of heave.

Long-term changes in the air, active layer and permafrost temperatures

When we describe atmosphere and soil climatic conditions for some period of time it is always important to have information on how this period looks in comparison with longer-time evolution of these parameters. It is especially important now when the climate experiences significant changes within short time intervals. Fortunately, we have a long-term (more than 20 years) continuous temperature records for three sites within the NAAT: West Dock, Deadhorse, and Franklin Bluffs. Data from the West Dock site are shown in Figure 3. This figure clearly shows a significant long-term warming trend in mean annual temperatures at all levels: air, ground surface, and permafrost at 20 meters depth. A linear trend in air and ground surface temperatures was 3°C for the last 20 years and increase in permafrost temperature at 20 m depth was 2°C. This figure also shows that during the period of the Biocomplexity project (2001-2006) soil climate was the warmest for the last 20 years. However, during this period the soil climate was relatively stable except for anomalously warm year 2003.

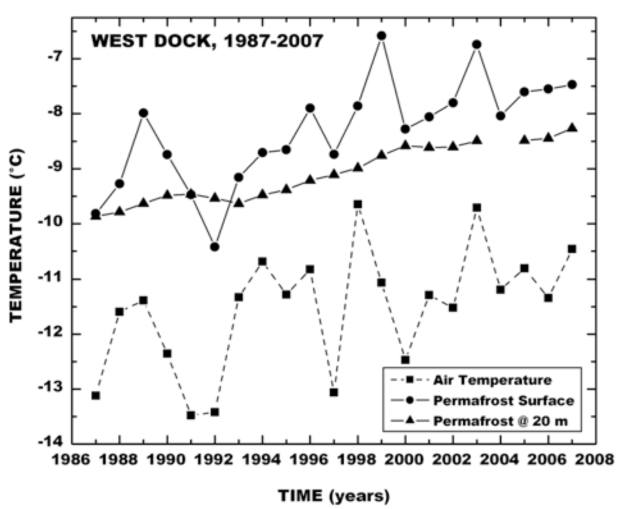

Figure 3, Time series of mean annual air (squares), ground surface (circles), and permafrost at 20 m depth (triangles) temperatures at the West Dock site.

Figure 3 also shows that the interannual variations in the surface temperature can differ significantly from the interannual changes in the air temperature. However, on a longer time scale (five years and longer), the match in these trends is very good. We came to similar conclusion analyzing long-term data from the East Siberian Transect (Romanovsky et al., 2007b). Similar results were obtained from the Deadhorse and Franklin Bluffs sites.

Snow, air and soil temperatures along the NAAT transect

All our sites are within the continuous permafrost area. However, there is a significant range of air and soil temperatures along this transect. Mean annual air temperature (MAAT) changes from around –10°C at the Happy Valley and Sagwon Hills sites to –16°C at Mould Bay and Isachsen (Figure 4) with mean July air temperatures vary in the range from 10°C at Happy Valley to 3°C at Isachsen (not shown). Elevated temperatures at Isachsen is an artifact, because only temperatures for 2005-2006 were available for this station (it was established in the Summer of 2005) and 2005-2006 year was substantially warmer in this region than 2004-2005. Data from the Mould Bay station show that MAT in 2005-2006 was by almost 2°C warmer than in 2004-2005. Mean annual ground surface temperature (MAGST) was by more than 1°C warmer as well.

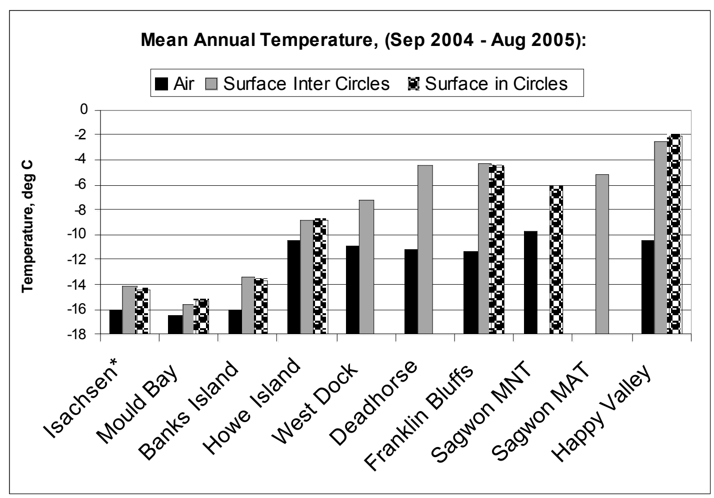

Figure 4, Mean annual temperatures (September 2004-August 2005, except for Isachsen where temperature were measured in 2005-2006) in the air (black) and at the ground surface within inter-circles (gray) and circles (polka-dot) along NAAT.

All Alaskan sites show very similar MAAT in the range between –9.7°C (Sagwon MNT) and –11.3°C (Franklin Bluffs). All Canadian sites are much colder with MAAT at or colder than -16°C. The spatial variability in MAGST is much more pronounced along NAAT. The warmest sites are all located in the inland part of the transect with temperatures as warm as -2°C (Happy Valley) and just below -4°C (Deadhorse and Franklin Bluffs). Relatively colder temperatures were observed at Sagwon Hills (-5°C and -6°C). All coastal sites in Alaska have lower MAGST with –7.2°C at West Dock and –8.8°C at Howe Island. The coldest MAGST were observed in the Canadian Arctic with MAGST typically at or below -14°C. It was shown in previous publications (Kade et al., 2006; Walker et al., in review) that summer temperatures at the ground surface within the unsorted circles are significantly warmer than in inter-circle areas. As it could be seen from Figure 4, it is not true for the mean annual surface temperatures, which are generally very similar for both circle and inter-circle areas. A possible explanation is that differential frost heave within the circles decreases snow depth here and decreases surface temperatures during the winter. Colder winter temperatures compensate summer warmer temperatures within the circles with a net effect close to zero.

Snow cover is the major factor that determines the difference between MAGST and MAAT. Our data show that this difference is much larger at the inland sites than at the site close to the Arctic coasts. Snow depth is generally decreasing from the south to the north and snow density is generally increasing in the same direction. The maximum snow thickness decreases from 60-70 cm at Happy Valley to 20 cm and less at the Banks Island and Mould Bay sites (Figure 5). Accordingly, the warming effect of snow on MAGST decreasing from 8°C at Happy Valley to only 1°C at the Mould Bay site. Mean annual soil temperature at the permafrost table changes from –3.5°C at Happy Valley to –15.3°C at Mould Bay (Figure 6). There is no noticeable difference in this parameter between circle and inter-circle areas.

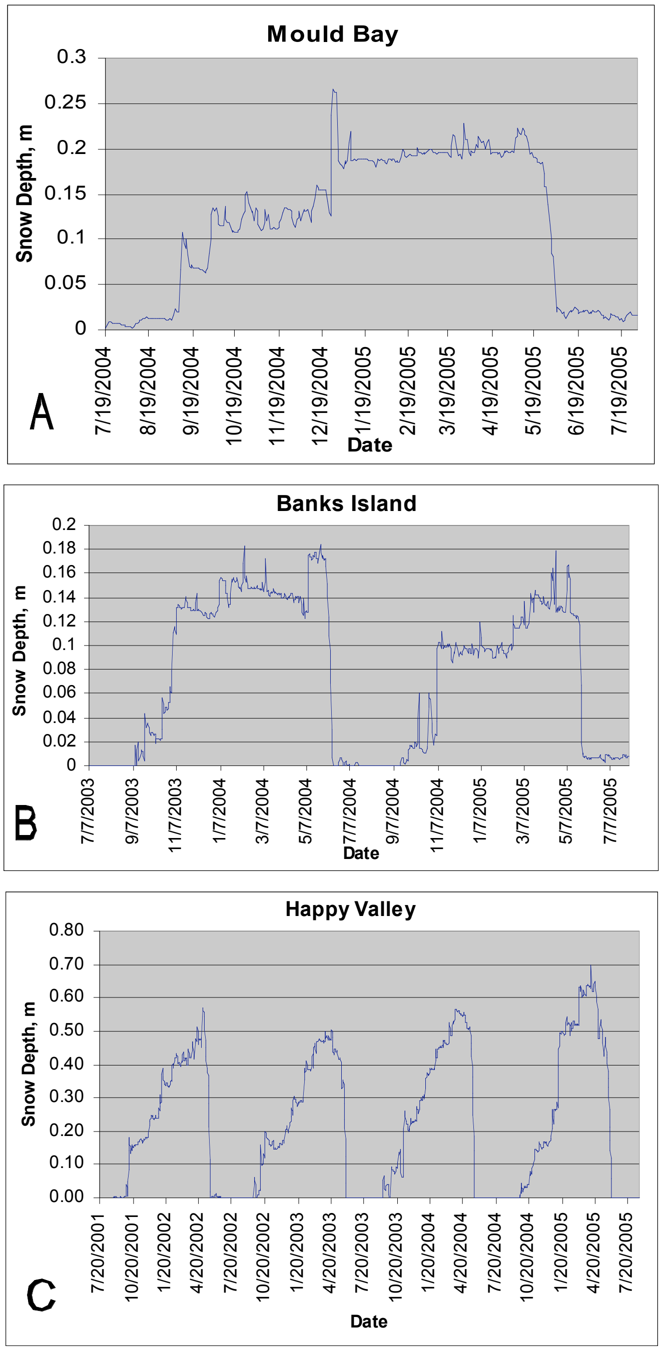

Figure 5, Hourly recorded snow cover depth at three sites: Mould Bay (A), Banks Island (B), and Happy Valley (C).

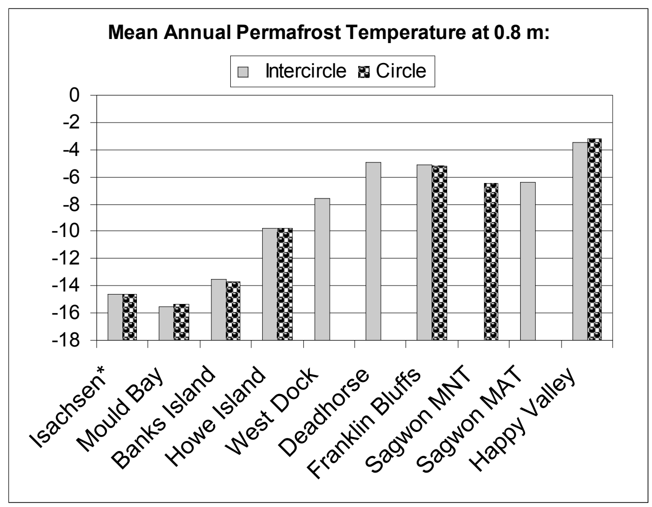

Figure 6, Mean annual soil temperatures at 0.8 m depth at different sites along NAAT.

Comparing Figures 4 and 6 we can see that the mean annual temperatures at the permafrost table are always colder than MAGST. This effect is very well known as a “thermal offset”. Thermal offset for most of the sites along NAAT in 2004-2005 was less than -1°C with the smallest number for Mold Bay (-0.1°C) and Banks Island (-0.15°C). For Isachsen, West Dock, Deadhorse, Franklin Bluffs, and Sagwon MNT, the thermal offset was in the range between –0.3 and –0.75°C. Significantly larger thermal offset was measured at the Howe Island site (-1°C), and for the acidic tundra sites Sagwon MAT (-1.3°C) and Happy Valley (-1.2°C). Increased thermal offset at the acidic tundra sites directly related to increased thickness of the organic soil layer that has significantly larger ratio of the thermal conductivities in the frozen and thawed states. This ratio is the most important parameter responsible for thermal offset (Romanovsky and Osterkamp, 1995).

Active layer depth

Active layer depth does not have a pronounced latitudinal trend and have a significant local variability depending on soil type and on the structure and density of the surface vegetation cover (Figure 7). At the localities with dense vegetation, the active layer depth could be from 20 to 40% smaller than within the non-sorted circles with much less or no vegetation. For example, the mean depth of thaw at the end of August 2005 in the vegetated tundra between non-sorted circles features was less at Happy Valley, the site with warmest soil-surface temperatures (active layer = 30 cm), than it was at Isachsen, the coldest site (almost 50 cm). Maximum active layer thickness was observed in the middle part of the transect at the sites Franklin Bluffs, Deadhorse, Howe Island, and Banks Island.

A large difference in the active layer thickness between non-sorted circles and inter-circle areas was observed in better vegetated sites Deadhorse, Franklin Bluffe, Sagwon Hills, and Happy Valley (Figure 7). Much less this difference was at the sites with less vegetation (Howe Island, Banks Island, Mould Bay, and Isachsen). Because of this local variability in the active layer thickness and because of the differences in the timing of freezing, the ground surface experiences a significant differential frost heave, which is mostly responsible for non-sorted circles development.

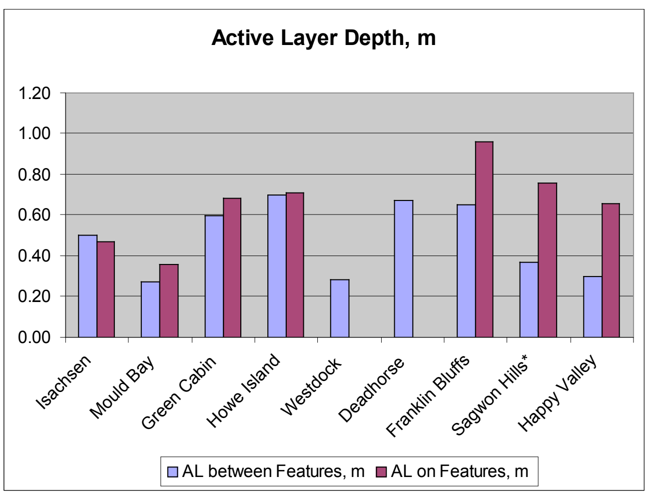

Figure 7, Maximum summer thaw (active layer depth) at the sites along NAAT.

Frost heave

Measured maximum frost heave within the circles vary between 18-20 cm at the Deadhorse and Franklin Bluffs sites and less than 3 cm at the Green Cabin site on Banks Island (Figure 8). Frost heave in inter-circle areas was typically less than 3 cm and very seldom reached 5 cm. Frost heave was greatest in the centers of non-sorted circles on silty loess soils at Deadhorse, Franklin Bluffs, and Sagwon MNT (20, 19 and 15 cm respectively) (Figure 8). Intermediate amounts of heave occurred on the clay soils at Isachsen, and the acidic tundra sites at Sagwon MAT (9 cm) and Happy Valley (9.5 cm). Heave was least at West Dock (0.4 cm), where there was a thick organic soil layer and no patterned ground. Differential heave (difference in the heave on the circles and between circles) was also greatest at Deadhorse and Franklin Bluffs (17 cm) where there was strong contrast in the vegetation on and between the patterned ground features. Differential heave was least (0 cm) at Isachsen, where the zones between pattern ground features are very narrow. Generally low amounts of heave occurred in the sandier soils at Mould Bay, Howe Island (Figure 2), and Green Cabin on Banks Island. Measured heave also vary significantly along the local topographical gradients illustrating the dependence of this process on local water availability. More information on governing physical processes responsible for frost heave and non-sorted circles formation and on numerical modeling of these processes could be found in (Nicolsky et al., 2008).

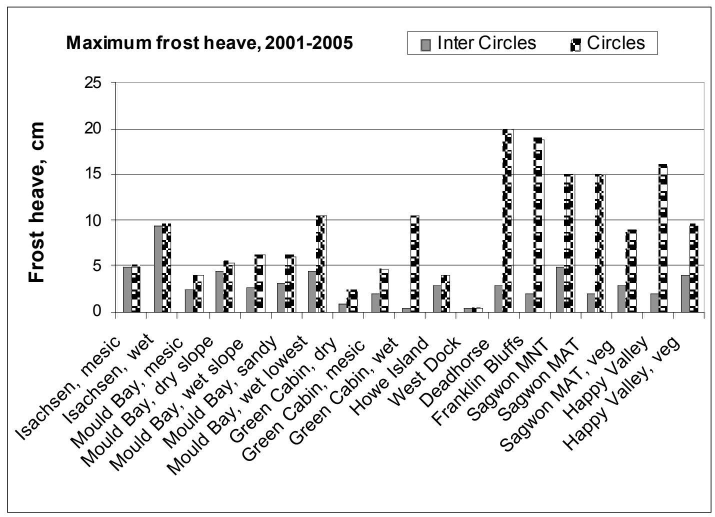

Figure 8, Maximum frost heave observed during period of measurents (2001-2005) at different sites along NAAT.

Conclusions

- A strong regional gradient exists in the air and soil temperatures along the North American Arctic transect. Mean annual air temperature ranges between –10°C and –16°C, while the mean annual soil temperatures are in the range between –2°C and –14°C.
- Snow cover differs significantly between the inland sites (Happy Valley, Franklin Bluffs) where the maximum snow depth is typically at 45-65 cm and the coastal sites (Howie and Banks Islands, Mould Bay, and Isachsen) with 15-25 cm.
- Local differences in surface conditions (vegetation and snow covers, soil physical properties etc.) are associated with the non-sorted circles, which produce significant local differences in the active layer depth, soil freezing rates, soil

ice formation and, as a result, a significant differential frost heave.

- The amount of heave is governed by the degree of these differences and by the water availability that changes along the local topographic gradients. The measured differential frost heave ranges between few cm at mesic and dry sites to almost 20 cm at wet sites on the Alaskan Arctic plain.

Acknowledgments

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