Active Layer Variability and Change in the Mackenzie Valley, Northwest Territories

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ABSTRACT
The Geological Survey of Canada has maintained an active layer monitoring network in the Mackenzie Valley, Northwest Territories since 1991. Active layer thickness exhibits a great deal of spatial and temporal variability particularly at tree dominated sites. Active layer thickness generally increased between 1991 and 1998 and then generally declined until about 2004. Since 2005 active layer thickness has generally increased reaching peak values in 2012, although still less than the 1998 peak. Although thicker active layers may result from higher summer air temperatures, warmer conditions during the preceding winter can also substantially contribute to active layer thickness.

RÉSUMÉ
Depuis 1991, la Commission géologique du Canada a tenu à jour un réseau de sites d'observation du mollisol dans la vallée du fleuve Mackenzie, Territoires du Nord-ouest. Des variations spatiales et temporelle importantes sont observées dans l'épaisseur du mollisol, spécialement pour les sites à couverture arborée. L'épaisseur du mollisol a généralement augmenté entre 1991 et 1998 pour par la suite décroître jusqu'à environ 2004. Depuis 2005 le mollisol s'est généralement épaissit avec des valeurs maximales obtenues en 2012 bien que celles-ci ne soit pas aussi élevées que celles obtenus en 1998. Quoique que l'augmentation de l'épaisseur du mollisol puisse être le résultat de températures estivales plus élevées, une augmentation des températures durant l'hiver qui précède peut aussi contribuer à son développement.

1 INTRODUCTION

The Mackenzie Valley landscape is characterized by widespread permafrost conditions ranging from continuous on the Beaufort coastal plain to sporadic in the south near the Northwest Territories (NWT) border (Figure 1). Changes in the ground thermal regime, including the thickness of the active layer (or seasonally thawed layer) above permafrost, may result in changes to ground stability and drainage and have environmental and infrastructure design and performance implications. The active layer responds to sub-climatic fluctuations compared to the deeper ground temperatures and can be an important indicator of interannual variability and annual trends.

The Geological Survey of Canada has maintained an active layer monitoring network in the Mackenzie Valley and Delta since 1991. The network originally comprised 66 sites, with 45 still operational, representative of vegetation and surficial materials in the region and instrumented to measure maximum thaw depth and ground surface subsidence or heave (Figure 1). This paper documents the variability in active layer conditions since the 1990s and updates an earlier assessment by Smith et al. (2009b).

2 STUDY AREA AND METHODS

The active layer monitoring transect extends from the Tuktoyaktuk Peninsula and Mackenzie Delta to southern NWT crossing both continuous and discontinuous permafrost zones (Figure 1). Vegetation conditions range

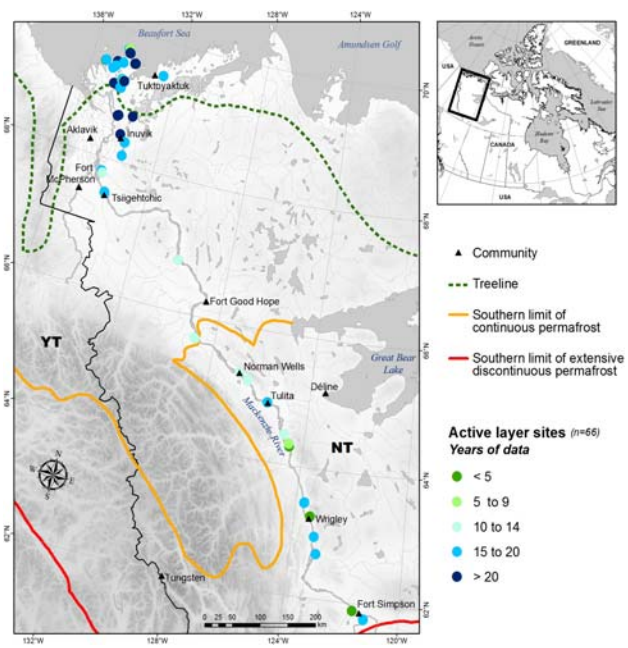

Figure 1. Location of active layer monitoring sites with number of years of data collection in the Mackenzie Valley, NWT. Permafrost limits after Heginbottom et al. 1995.

from tundra in the north to boreal forest in the south. The landscape of the region was largely shaped by continental glaciation and subsequent post-glacial drainage (Duk-Rodkin and Lemmen 2000). The terrain comprises moraine, lacustrine, fluvial and deltaic deposits of the northern Interior Plains. Ice-rich sediments, in particular lacustrine silts and clays, are common (Aylsworth et al. 2000). Impeded drainage, a feature of many areas, has resulted in the formation of wetlands, ponds and lakes and thick accumulations of peat. Extensive peatlands are found in the southern portion of the region, where organic cover may be several metres thick and highly influences the ground thermal regime (Aylsworth and Kettles 2000). In the north, the Mackenzie Delta region consists of a broad alluvial plain, with peatlands limited to surrounding tundra uplands (Burn and Kokelj 2009).

Long winters characterize the climate of the Mackenzie corridor with mean January temperatures ranging from -26.9 °C at Inuvik to -24.8 °C at Fort Simpson and mean July temperatures ranging from 14.1 °C to 17.4 °C for both location respectively (based on 1981-2010 climate normal, Environment Canada 2015). Total precipitation varies from 240 mm at Inuvik to 387 mm at Fort Simpson of which 40-50% falls as snow, which generally stays on the ground for seven to eight months of the year. Air temperatures have increased since 1990 by 0.26 ºC/decade and 0.53 ºC/decade in the north and south respectively (Figure 2).

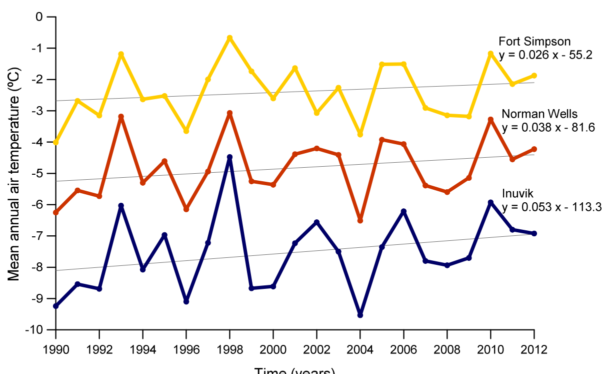

Figure 2. Mean annual air temperature with best-fit line for northern, central and southern Mackenzie Valley (from Environment Canada, 2015).

Sites were chosen to be representative of the vegetation and terrain conditions in the region (e.g. Nixon and Taylor 1994). Thaw tubes (Mackay 1973) were utilized to determine maximum annual thaw penetration relative to a reference datum, and maximum heave and subsidence of the ground surface. The active layer thickness (ALT) was determined from the maximum thaw penetration and the position of the ground surface at the time of maximum thaw.

Most sites were also equipped with instruments to measure air and near-surface ground temperature. Air temperature was recorded by a datalogger connected to a thermistor installed in a radiation shield at a height of 1.5 m. A similar datalogger with an internal sensor inserted 3 to 5 cm below the ground surface was utilized to measure near-surface ground temperature. Data loggers deployed were either OnSet HOBO® or Vemco® mini loggers with a resolution of ± 0.4 ºC, and an accuracy of ± 0.1 °C. Many sites are also instrumented for deeper ground temperature monitoring (Bonnaventure et al. this volume). Additional information on the monitoring network and data collection is available in Nixon and Taylor (1994), Smith et al. (2009a) and Duchesne et al. (2014).

3 RESULTS AND DISCUSSION

3.1 Spatial and temporal patterns

Mean ALT in the Mackenzie Valley for the period 1991-2013 ranged from less than 50 cm in the north to greater than 100 cm in the south (Figure 3). North of treeline,

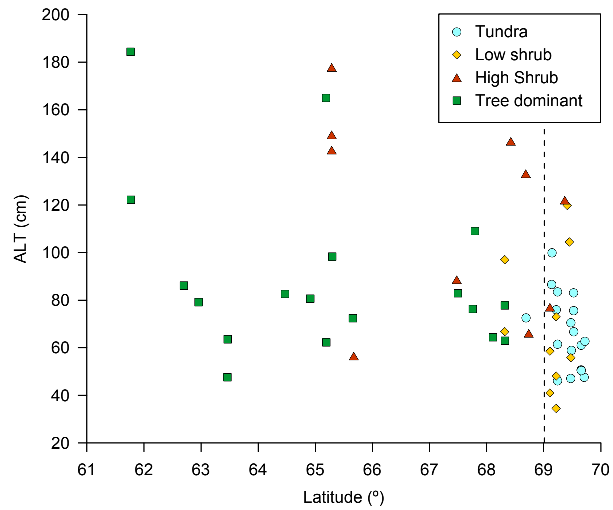

Figure 3. Mean active layer thickness (ALT) for all years for sites classified by dominant vegetation type. Dash line represents treeline.

active layers are generally thinner compared to those south of treeline. However, substantial spatial variability exists reflecting the influence of micro-topography, edaphic conditions and ice content. This large spatial variability is particularly apparent below treeline where the ALT can vary by more than 1 m (Figure 4). Average ALT

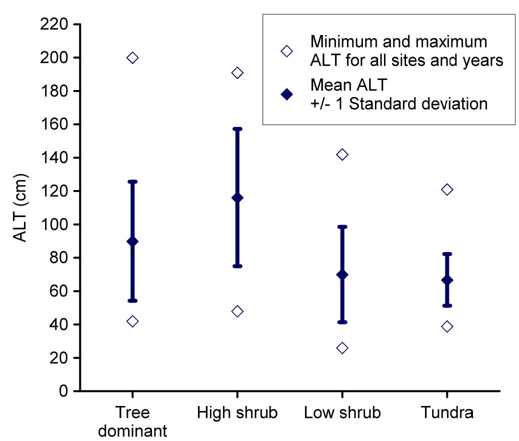

Figure 4. Mean and ranges in active layer thickness by dominant vegetation type. The overall mean ALT is for all years and all sites.

is generally greater for sites with high shrubs which can be partly explained by the implied thicker snow cover, due to the ability of vegetation to trap snow, which is highly insulating at these sites (Burn and Kokelj 2009; Morse et al. 2012; Palmer et al. 2012).

Temporal patterns in thaw penetration and ground surface elevation are shown for selected sites in Figure 5. Thaw penetration patterns show some similarity to those of air temperature, especially winter temperature, with both parameters exhibiting a great deal of interannual

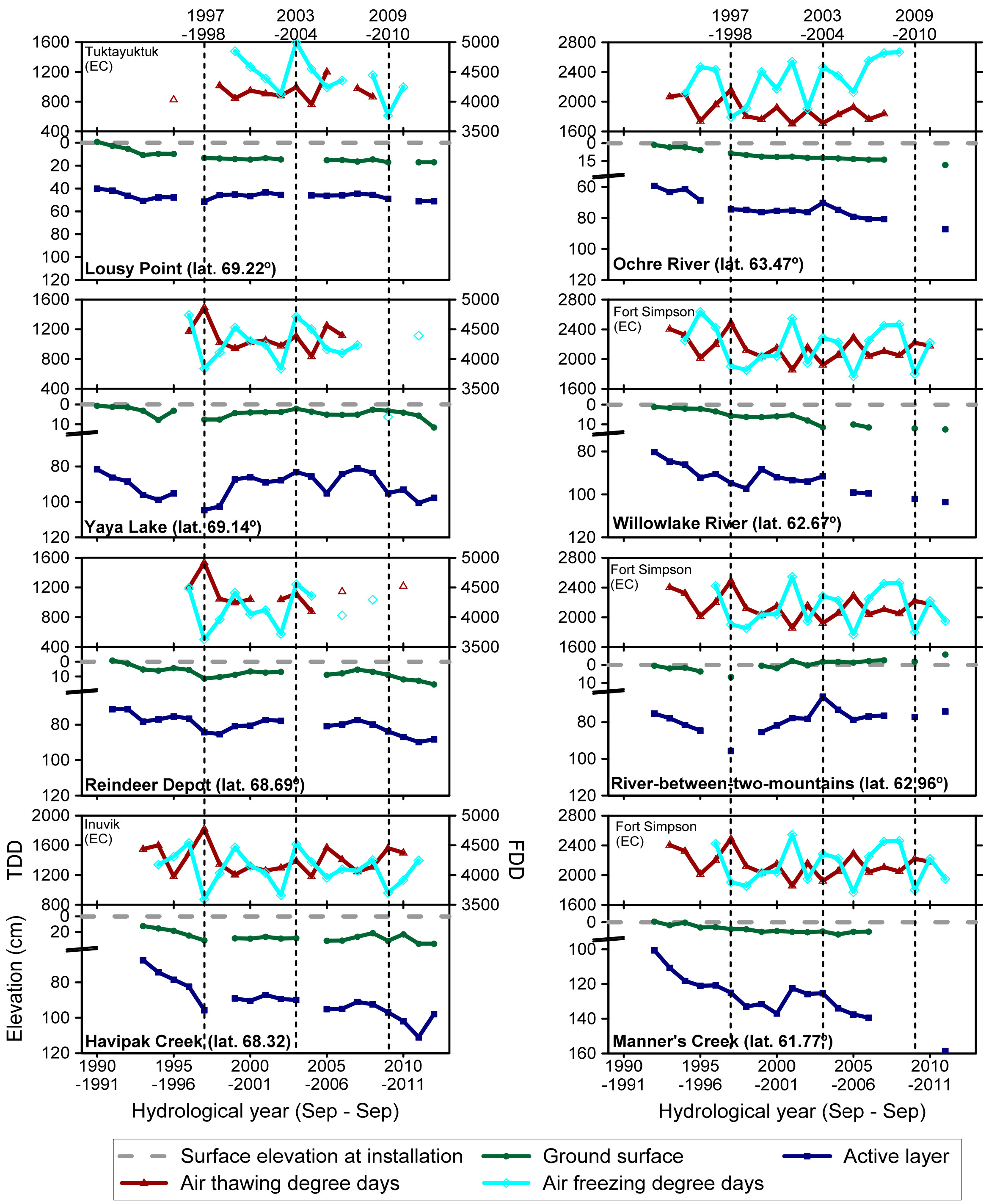

Figure 5. Air thawing (TDD) and freezing (FDD) degree days using site data or, where unavailable\sporadic, the closest Environment Canada (EC) weather station data. Ground surface elevation and maximum thaw penetration between 1990 and 2013. Northern sites are on the left while southern sites are on the right.

variability. The influence of air temperature on active layer development is evident with greater thaw penetration in many locations in warmer years such as 1998 and 2010. South of treeline, greater inter-site variability is observed and is a consequence of the insulating effect of the vegetation in summer and variable snow cover in winter. The moderating effect of ground insulation for these sites is apparent with a dampening of the active layer response to variations in air temperature, compared to sites above treeline, although some of the warmer (1998) and cooler (2004) years are noticeable (Figure 5).

Surface settlement that can accompany the thaw of ice-rich soils was also observed at some sites. Substantial subsidence was observed for example at the four northern sites shown in Figure 5 as well as Willowlake and Ochre River sites in the southern valley. Progressive thaw of ice-rich permafrost through time results in melting of ground ice and surface settlement, but very little actual change in maximum ALT relative to the ground surface (Smith et al., 2001). Consequently greater temporal variability in ALT will generally be associated with soils of low ice content and minimal thaw strain. Refreezing of the active layer in the fall can result in surface heave and a net increase in surface elevation if the thaw penetration the following year is less (such as in a colder year) and the surface does not settle back to the level it was the preceding summer.

Some general trends in ALT are apparent over the period of record when compared to a 10-year average (2002-2012) representing the longest continuous record at most sites (Figure 6). ALT generally increased between 1991 and 1998. The peak ALT value in 1998, which was about 8 cm greater than the 10-year average, occurred during the warmest year of the period of record (Figure 2). Throughout the Mackenzie Valley peak values for air thawing degree days (TDD_A) occurred during the summer of 1998 (Figure 5), as well as low values for air freezing degree days (FDD_A) in the 1997-98 winter. Following the 1998 peak, ALT generally declined until about 2004 with ALT over most of this period being less than 10-year average (Figure 6). This also coincided with a period of lower air temperatures. Since 2005 there has been a general increase in ALT with peak values being reached in 2012 (6 cm greater than 10-year average), although still less than the 1998 maximum value (Figure 6).

3.2 Influence of air temperature

Summer air temperatures are an important factor influencing active layer development and ALT. The air thawing index TDD_A (and often expressed as $\sqrt{TDD_A}$) is the climatic index commonly used for analysis (Brown et al. 2000; Hinkel and Nelson 2003)

Although thicker active layers generally occur where TDD_A is higher (Figure 7a) there is a large amount of scatter in the relation, and sites with similar TDD_A can have a large range in ALT. Summer air temperature has a greater influence on active layer development at tundra sites where there is less insulation and a more direct

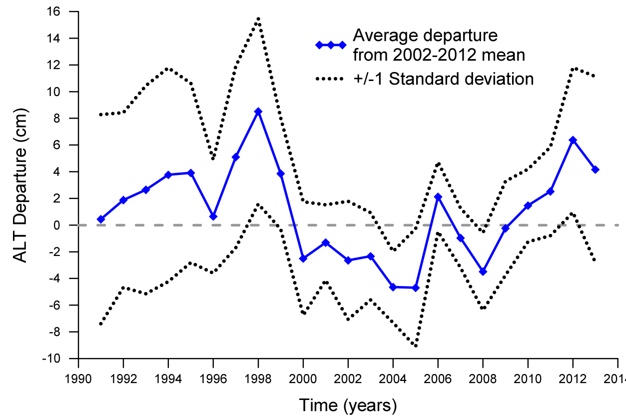

Figure 6. Mean ALT departures from 2002-2012 average for all sites.

relation between climate and ground thermal conditions (Smith et al. 2009b) as indicated by the higher slope of the regression line compared to that for forested sites (Figure 7a). There is a stronger relation between the near-surface thawing index (TDD_S) and ALT especially for forested sites (Figure 7b) as TDD_S provides a better indication of the energy that is available for thawing of the ground where there is substantial shading and insulation (Smith et al. 2009b).

The air freezing index (FDD_A) is more variable on a site basis than TDD_A, as shown by the error bars on figure 7c, suggesting that the conditions during the winter may also explain some of the interannual variability observed in ALT. The relation between FDD_A and ALT exhibits a great deal of scatter but for some forested sites greater ALT is associated with lower values of FDD_A. The surface freezing index (FDD_S) exhibits less variability on a site basis than FDD_A and the relation between FDD_S and ALT displays less scatter (Figure 7d). Interannual variability in FDD_S will be due to variability in both winter air temperature and snow cover conditions.

For some sites there has been a general decrease in FDD_S over the record period. This is the case for forested sites (Francis Creek, Ochre River and Fort Simpson) as shown in Figure 8. This reduction in the freezing index is not necessarily associated with an earlier start to the thaw season. There is no obvious trend in the date on which surface temperatures first rise above 0°C (Figure 9). Warmer winter conditions lead to less cooling of the ground in winter and therefore a lower energy requirement to raise ground temperatures to 0°C in the spring and summer (Frauenfeld et al. 2004; Burn and Zhang 2010; Bonnaventure and Lamoureux 2013; Morse et al. 2012). Increases in ALT may therefore be a result of decreases in FDD_S associated with warmer winter air temperatures (and lower FDD_A) and possibly an increase snow cover. The potential for winter warming under future climates may have an important influence on active layer development.

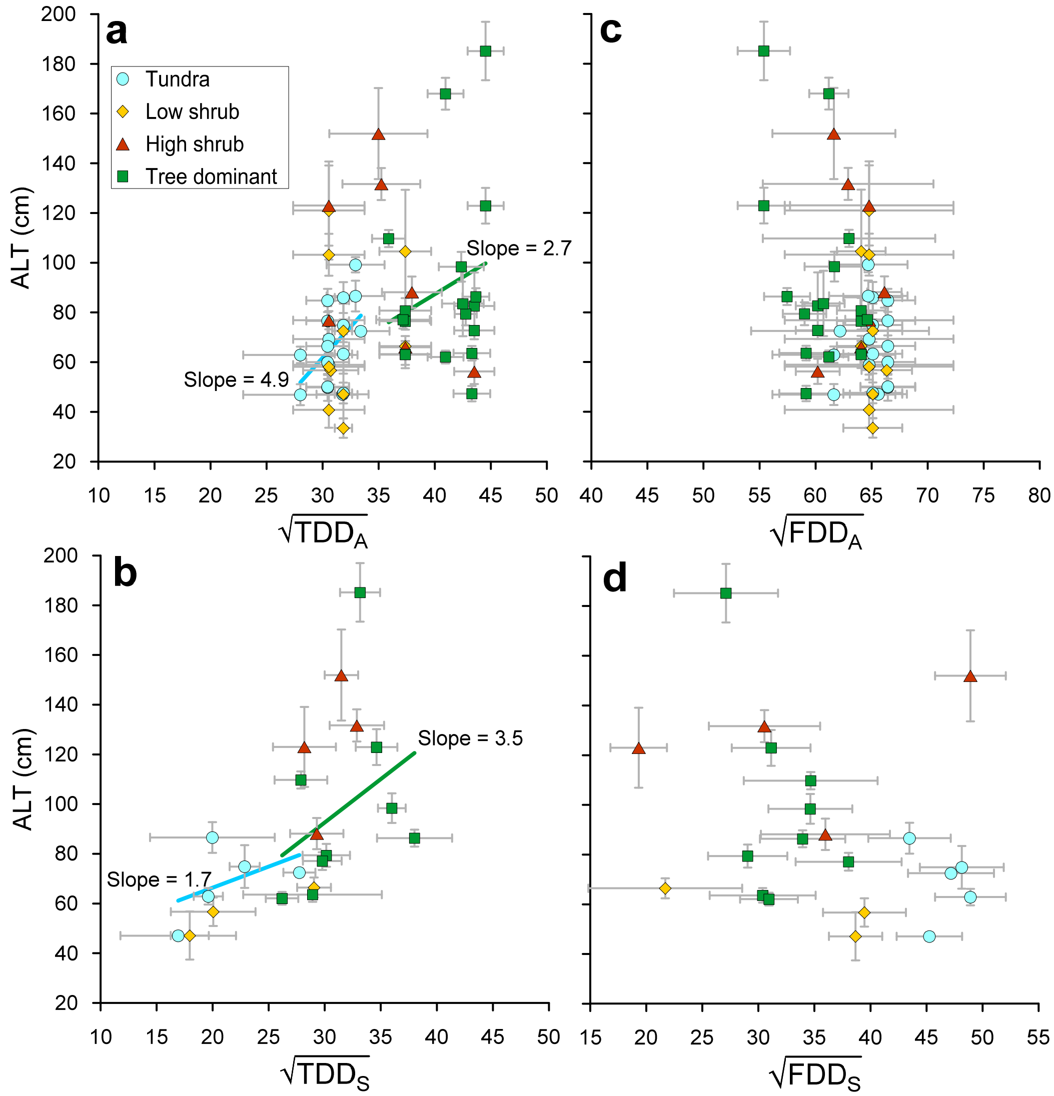

Figure 7. Mean ALT versus air thawing (a) and freezing (b) indices, and, when available, near-surface thawing (c) and freezing (d) indices. The error bars represent +/- 1 standard deviation from the mean. Linear fit is shown for both tundra and tree dominant sites in (a) and (c).

4 SUMMARY

Data collected from the active layer monitoring network in the Mackenzie Valley has facilitated assessments of the range in ALT for representative vegetation and terrain types. ALT exhibits a great deal of spatial and temporal variability particularly for tree dominant sites. Thicker active layers generally occur below treeline, but the thickest active layers are observed at sites with high shrubs.

Greater thaw penetration occurred in many locations during warm years such as 1998 and 2010. In ice-rich soils this increase in summer thaw penetration is associated with significant surface settlement though there may be little change in ALT.

ALT increased between 1991 and 1998. The maximum ALT in 1998 was followed by a thinning of active layers to 2005, with increasing ALT to 2012. Although higher summer air temperatures may be associated with thicker active layers, warm conditions during the preceding winter may also be a contributing factor to active layer development.

The active layer monitoring network has provided relevant baseline information in an important transportation/transmission corridor in the NWT. Essential information has been provided to better understand the impacts of a changing climate on the permafrost environment and to inform the development of adaptation strategies to deal with these impacts.

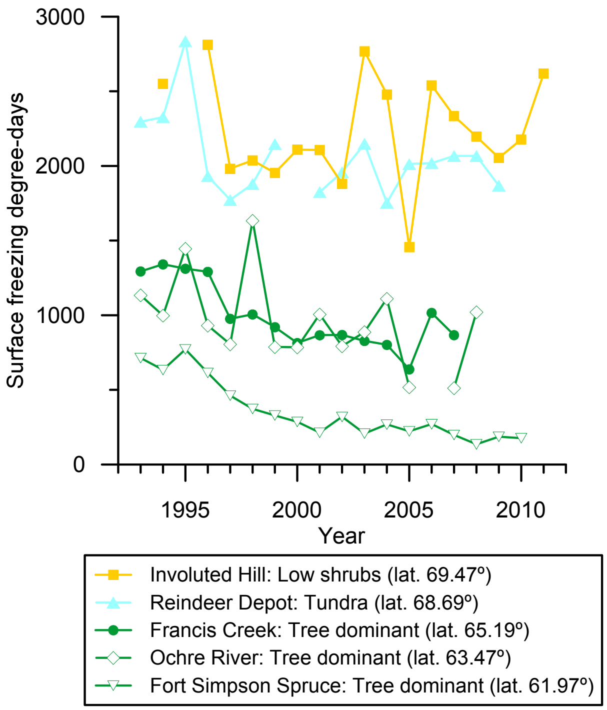

Figure 8. Surface freezing degree-days over time for selected sites.

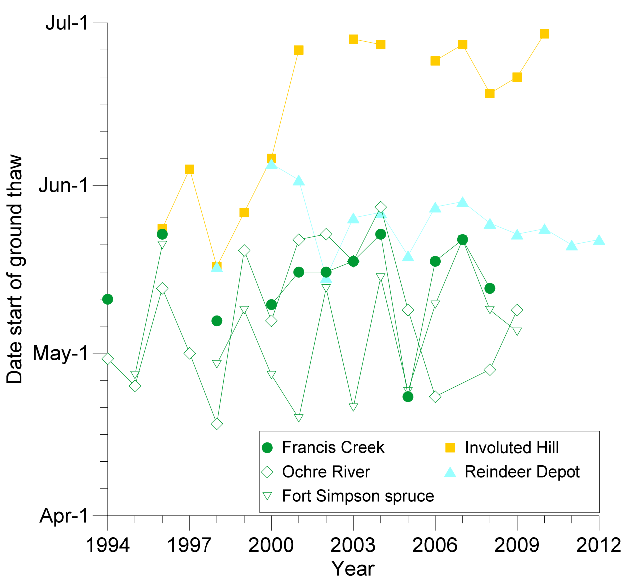

Figure 9. Date of start of thaw season (when ground temperature rises above 0 ºC) over time for selected sites.

ACKNOWLEDGEMENTS

Support for this project is provided by Natural Resources Canada. The maintenance of the monitoring network has benefitted from various funding sources over the years including the Government of Canada's International Polar Year Program and the Program for Energy Research and Development. Logistical support was supplied by the Inuvik Research Centre and the Polar Continental Shelf Project. We are thankful for the support and assistance provided by communities in the Northwest Territories. Mark Nixon was instrumental in the establishment and maintenance of the monitoring network. Jason Chartrand provides support for data management and processing. We thank Peter Morse for many helpful comments. ESS contribution number 20150110.

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