Changes in Permafrost and Active-layer Temperatures along an Alaskan Permafrost-Ecological Transect

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ABSTRACT
In this paper we report changes in permafrost temperatures during the last 30 years in Alaska. Most of the research sites in our network are located along an Alaskan Permafrost-Ecological Transect. This transect spans all permafrost zones in Alaska. Most of the sites in Alaska show substantial warming of permafrost since the 1980s. The magnitude of warming has varied with location, but is typically from 0.5 to 3°C. However, this warming is not linear in time and is not spatially uniform. While permafrost warming has been more or less continuous on the North Slope of Alaska with a rate between 0.2 to 0.5°C per decade, permafrost temperatures in the Alaskan Interior started to experience a slight cooling in the 2000s that has continued during the first half of the 2010s. The observed climate warming has triggered permafrost degradation in Alaska, especially in the north and at the locations which are affected by human activities.

RÉSUMÉ
Dans cet article, nous présentons les changements de température du pergélisol durant les 30 dernières années en Alaska. La plupart des sites de recherche du réseau sont situés en Alaska, le long d'un transect «pergélisol-écologique». Ce transect traverse toutes les zones de pergélisol en Alaska. La plupart de ces sites montre un réchauffement important du pergélisol depuis les années 80. L'ampleur du réchauffement, qui varie selon les endroits, oscille entre 0.5 et 3 °C. Toutefois, ce réchauffement n'est ni linéaire dans le temps, ni spatialement uniforme. Dans la région de North Slope, le réchauffement du pergélisol a été plus ou moins régulier avec une augmentation des températures d'environ 0.2 à 0.5 °C par décennie, tandis qu'à l'intérieur de l'Alaska, les températures du pergélisol ont refroidi légèrement depuis les années 2000 et le début des années 2010. Ces variations climatiques ont déclenché la dégradation du pergélisol en Alaska, particulièrement dans le nord et dans les endroits affectés par les activités humaines.

1 INTRODUCTION

The impact of climate warming on permafrost and the potential of climate feedbacks resulting from permafrost thawing have recently received a great deal of attention (Schaefer et al. 2012; Schuur et al. 2015). Permafrost is defined as soil, rock and any other sub-surface earth material that exists at or below 0°C for two or more consecutive years. On top of the permafrost is the active layer, which thaws during the summer and freezes again the following winter. The mean annual temperature of permafrost and the thickness of the active layer are good indicators of changing climate and therefore designated as Essential Climate Variables (ECVs) (Smith and Brown 2009) by the Global Climate Observing System (GCOS) Program of the World Meteorological Organization. Increasing permafrost temperatures and active layer thickness caused by climate warming affect the stability of northern ecosystems and infrastructure, and are predicted to cause the release of carbon into the atmosphere in the form of carbon dioxide and methane (Schaefer et al. 2014; Schuur et al. 2015).

The monitoring network of the Thermal State of Permafrost (TSP) program was established during the Fourth International Polar Year and in Alaska, is represented by two major permafrost temperature measurement networks. One network is operated since 1970s by the U. S. Geological Survey, predominantly within the North Slope of Alaska (Clow and Urban, 2003; Clow, 2014). The second network was established in the late-1970s and early-1980 by Professor Emeritus T. E. Osterkamp and has been supported since then by the Permafrost group at the Geophysical Institute University of Alaska Fairbanks (Osterkamp, 2003b and 2008; Romanovsky et al. 2002, 2003 and 2014). Most of the research sites in this network are located along an Alaskan Permafrost-Ecological Transect (McGuire et al. 2002; Walker et al. 2008) (Fig. 1a). This transect spans all permafrost zones in Alaska from the southern limits of permafrost near Glennallen to the Arctic coast in the Prudhoe Bay region. In this paper, the results of more than 30 years of permafrost and active layer temperature observations along this transect are presented in this paper.

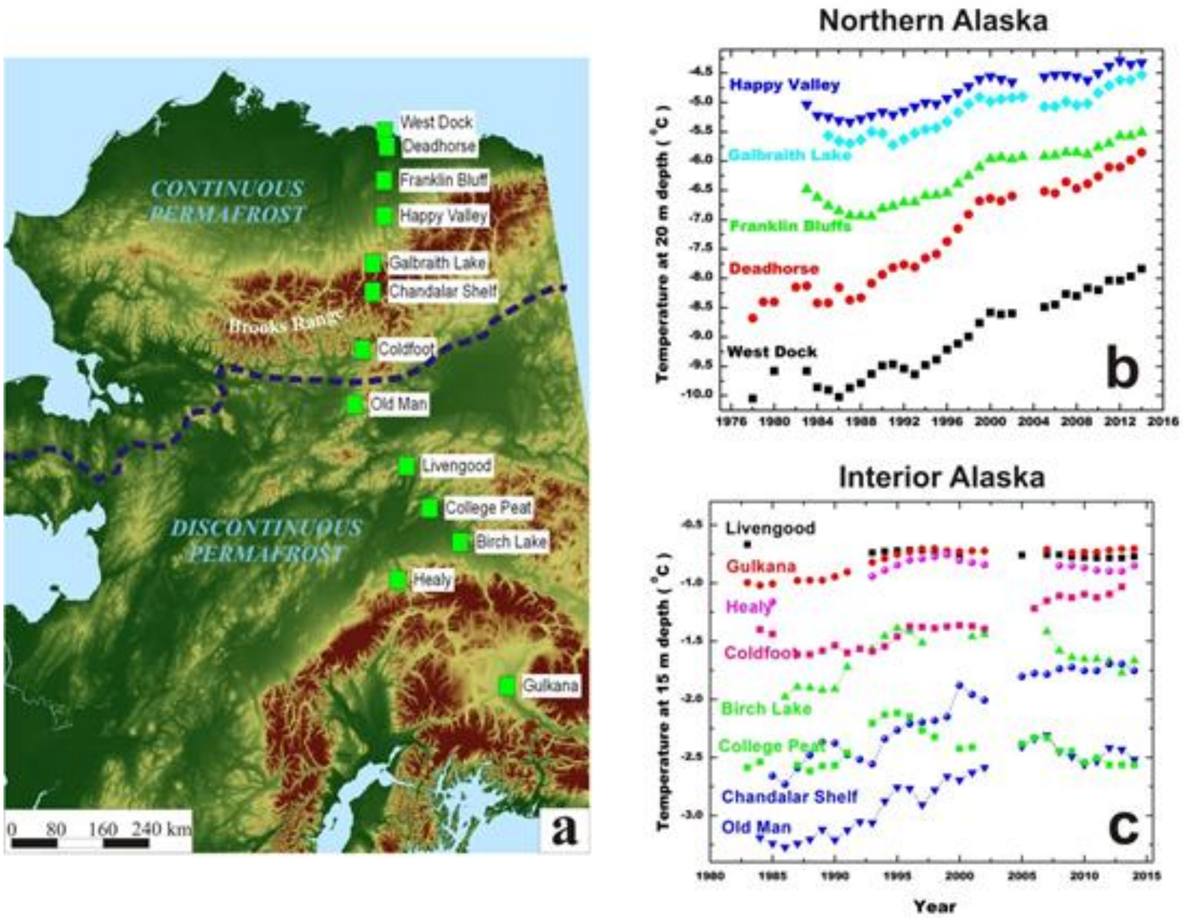

Figure 1. (a) Continuous and discontinuous permafrost zones in Alaska (separated by the broken blue line) and location of a north-south transect of permafrost temperature measurement sites; (b) and (c) time series of mean annual temperature at depths of 20 m and 15 m below the surface, respectively, at the measurement sites (updated from Romanovsky et al. 2014).

2 METHODS

Permafrost temperatures define the thermal state of permafrost and were obtained by lowering a calibrated thermistor into a borehole, or recording temperature from multi-sensor cables permanently or temporarily installed in the borehole (GTN-P, 2012). Some measurements were performed manually with a portable temperature logging system and others by data loggers. The accuracy and resolution of the thermistors and measurements in these studies is ±0.02°C or better. The depth of boreholes varies from less than 10 m to greater than 100 m. At many sites data loggers were utilized for daily measurement of air and shallow ground temperatures to reduce the number of site visits and to provide a continuous record of ground temperatures.

Current results are based in part on data collected in boreholes that were drilled from the late 1970s to the late 1980s throughout the permafrost regions of Alaska (Osterkamp, 2003a, 2003b). New permafrost observatories were established in the 2000s at Imnaviat Creek, Toolik Lake, Bonanza Creek, Barrow, Gakona and other locations in Alaska.

3 RESULTS

At most Alaskan permafrost observatories there was substantial warming during the 1980s and especially in the 1990s (Fig. 1). The magnitude and nature of the warming varies spatially, but was typically from 0.5°C to 2°C at the depth of zero seasonal temperature amplitude over this 20 year period (Osterkamp 2008). However, during the 2000s, permafrost temperature was relatively stable on the North Slope of Alaska (Romanovsky et al.

2011; Smith et al. 2010; Shiklomanov et al. 2010) (Fig. 1b), with even a slight decrease (ranging from 0.1°C to 0.3°C) in Interior Alaska during the last seven years (Fig. 1c).

The latest data may indicate that the coastal warming trend has propagated southward towards the northern foothills of the Brooks Range, where a noticeable warming in the upper 20 m of permafrost has become evident since 2008. In 2014, new record high temperatures at 20 m depth were measured at all permafrost observatories on the North Slope of Alaska (hereafter North Slope) except for Happy Valley (Figs. 1a, 1b). Changes in permafrost temperatures at 20 m depth typically lag about one year behind the changes in surface temperatures. The summer of 2013 was particularly warm on the North Slope and thus contributed to the 20 m temperature increase. The increase in 2014 was substantial; 20 m temperatures in 2014 were 0.07°C higher than in 2013 at West Dock and Deadhorse, and 0.06°C higher at Franklin Bluffs (Fig. 1b) on the North Slope. A 0.09°C increase was observed at Galbraith Lake (Fig. 1b) in the northern foothills of the Brooks Range. Permafrost temperature in 2014 at Happy Valley was 0.03°C higher than in 2013, but still 0.03°C lower than its maximum in 2012. Temperature at 20 m depth has increased between 0.18 and 0.56°C per decade since 2000 on the North Slope (Fig. 1b).

Figures 2-4 allow better understanding of what causes this permafrost temperature increase. Permafrost temperature obviously follows the changes in the mean annual ground surface temperature that, in turn, follow the changes in mean annual air temperature. The decadal time scale trend in permafrost temperature is almost identical to the decadal trend in the air temperature. This may be an indication that there was no significant trend in snow cover depth in the Alaskan Arctic during the last 30 years. Only recently (during the last 5 years), it seems that the rate of change in near-surface permafrost temperatures begin to exceed the rate of increase in the air and deep permafrost temperature (Figures 2, 3 and 4). This may indicate an increase in snow cover depth during this period. Figures 3 and 4 also show that the latest climate warming have brought near-surface ground temperatures on the North Slope to an unprecedentedly high level. While the mean annual temperatures at the ground and permafrost surfaces in Deadhorse during the mid-1980s were near -8°C (Fig. 3), in 2014 the mean annual temperature at the ground surface was only -1.3°C and -2.2°C at the surface of permafrost. These temperatures are just slightly lower (-1.8 and -2.6°C respectively) at the Franklin Bluffs site (Fig. 4). This level of ground surface and permafrost surface temperature is more typical for Interior Alaska and indicates that permafrost in some areas of the North Slope is losing its thermal stability.

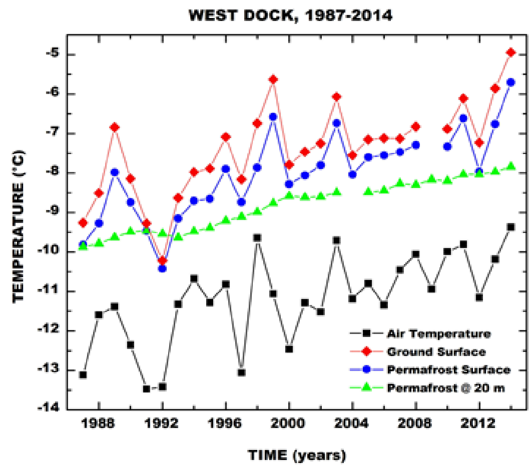

Figure 2. Mean annual temperatures of air, ground surface, permafrost surface, and permafrost at 20 m depth recorded at the West Dock permafrost observatory from 1987 to 2014 on the North Slope of Alaska.

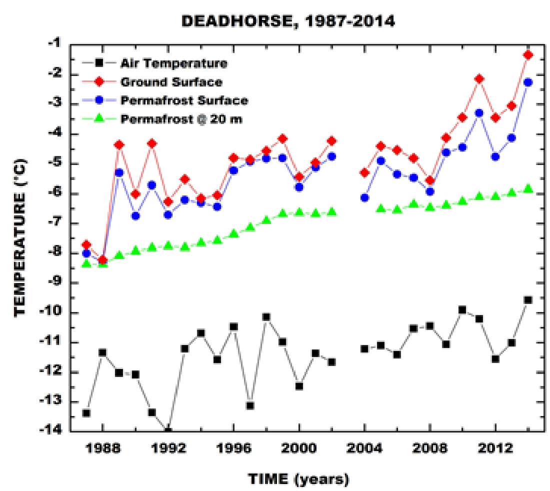

Figure 3. Mean annual temperatures of air, ground surface, permafrost surface, and permafrost at 20 m depth recorded at the Deadhorse permafrost observatory from 1987 to 2014 on the North Slope of Alaska.

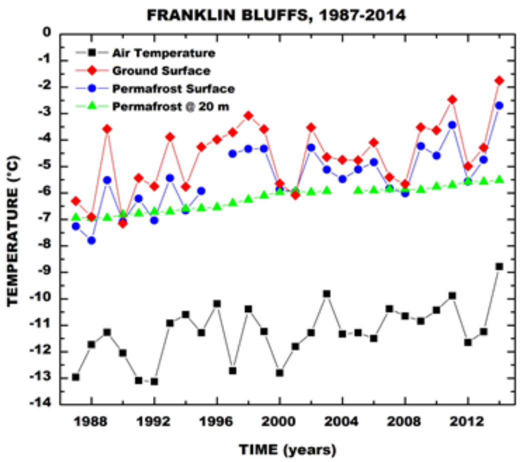

Figure 4. Mean annual temperatures of air, ground surface, permafrost surface, and permafrost at 20 m depth recorded at the Franklin Bluffs permafrost observatory from 1987 to 2014 on the North Slope of Alaska.

Analysis of the seasonality of changes in ground temperature shows that the warming is occurring in both summer and winter, but the major part of the increase occurs during the cold season. As a result, the re-freezing of the active layer takes more and more time (Fig. 5). While the complete freeze-up of the active layer on the North Slope in the mid-1980s typically occurred in the first half of October (Romanovsky et al. 2003), the typical freeze-up dates in the first half of the 2010s shifted to mid-December. In the winter of 2013-2014, an unprecedented date of freeze-up (January 15) was observed at the Deadhorse site (Fig. 5).

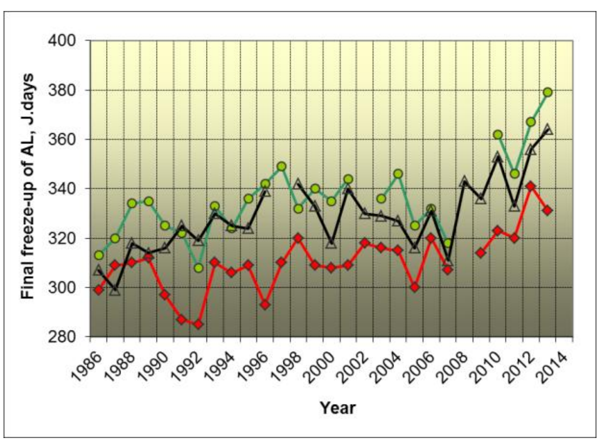

Figure 5. The dates of complete freeze-up of the active layer (Julian days) at West Dock (red diamonds), Deadhorse (green circles), and Franklin Bluffs (black triangles).

This date of freeze-up is more typical for the Fairbanks area. During the last 30 years, the average date of freeze-up increased by almost two months. Higher permafrost surface temperatures supply a significant amount of heat to the deeper permafrost. This leads to substantial increase in permafrost temperatures not only at the surface but also at depth. Thus, the temperature of permafrost at 50 m depth at West Dock and Deadhorse increased by almost 1°C during the last 30 years (Fig. 6). These data also indicate that the average long-term heat flux into the permafrost at these two sites was on the order of 0.5 W/m^2 during the last 30 years.

Since the early 2000s, we also record changes in permafrost temperature in two 50-m deep boreholes near Barrow (Fig. 7). The data show that changes in permafrost temperature near Barrow are similar to that observed in the Prudhoe Bay area. These data also allow us to reconstruct the past changes in ground temperature using our GIPL permafrost model (Romanovsky et al. 2002; Nicolsky et al. 2007). This model was calibrated specifically to the Barrow environmental conditions using observational data (Hinkel et al. 2001). The calibrated model was then forced by climate data collected at the Barrow meteorological station. The results of this reconstruction are shown in Fig. 8. The results indicate that the warming over the last 30 years was partially the result of recovering from the colder 1960s and 1970s. However, by the late 2000s, the ground temperatures have already significantly exceeded the level that existed at any time during the last nearly 100 years (Fig. 8). Fig. 9 shows that this increase in ground temperature was the result of increasing air temperature and was also accelerated by an increase in snow depth during the last 30 years.

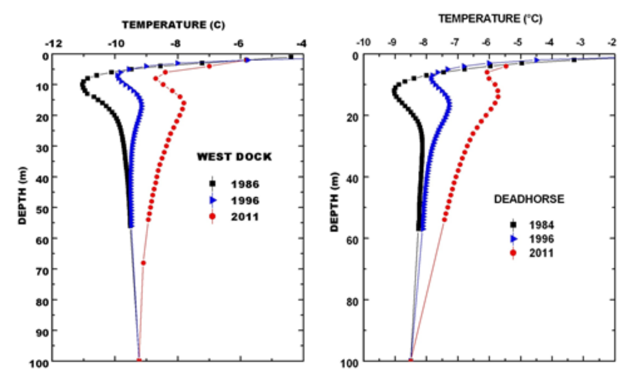

Figure 6. Selected permafrost temperature profiles measured in 1986, 1996, and 2011 at West Dock (left) and in 1984, 1996, and 2011 at Deadhorse (right).

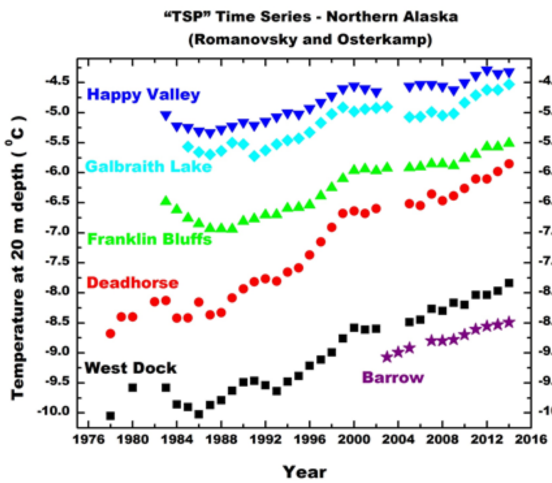

Figure 7. Time series of mean annual permafrost temperature on the Alaska North Slope including the records from Barrow.

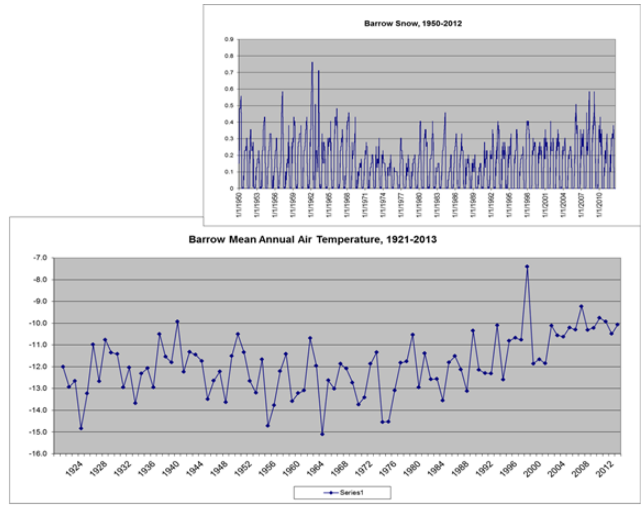

Figure 9. Time series of mean annual air temperature (lower graph) and daily depth of snow on the ground (upper graph) measured at the Barrow meteorological station in 1921-2013.

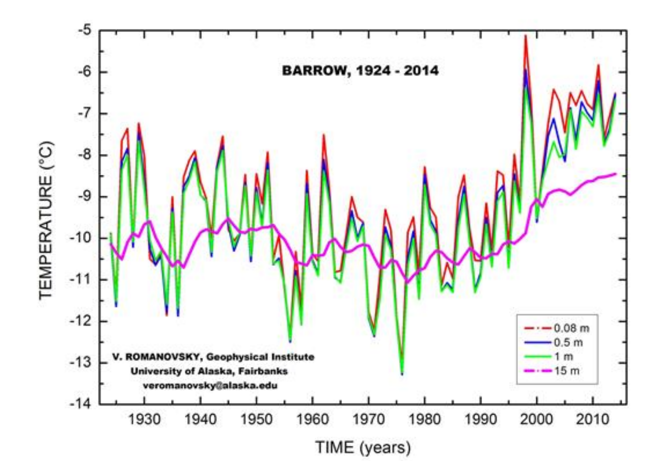

Figure 8. Time series of mean annual ground temperature at several depths measured since 2002 and modeled for the 1924-2001 time period.

Permafrost temperatures in Interior Alaska (Fig. 1a) generally continued to decrease slightly in 2014 (Fig. 1c), a cooling that dates back to 2007. Consequently, temperatures in 2014 at some sites in Interior Alaska were lower than those located much further north, e.g., temperatures at College Peat are now lower than at Old Man (Fig. 1c). However, at two sites, Birch Lake and Healy, this cooling trend was interrupted in 2014 by a warming of 0.1°C and 0.05°C, respectively (Fig. 1c).

Data presented in Fig. 10 clearly indicate that the warming phase in permafrost temperature variations observed in the 1980s and 1990s in Interior Alaska was replaced by a cooling trend sometime in the late-1990s or early-2000s. Analysis of the climatic records obtained from the Fairbanks meteorological station (Fig. 11) show that there was no significant air temperature increase during the last 40 years. The decrease in snow depth during the last 15 to 20 years may be responsible for the observed decrease or steady permafrost temperatures in the Central Interior (Fig. 12).

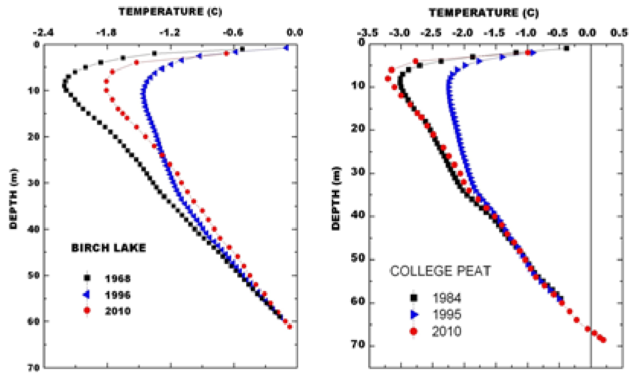

Figure 10. Selected permafrost temperature profiles measured in 1986, 1996, and 2010 at Birch Lake (left) and in 1984, 1995, and 2010 at College Peat (right) in Interior Alaska.

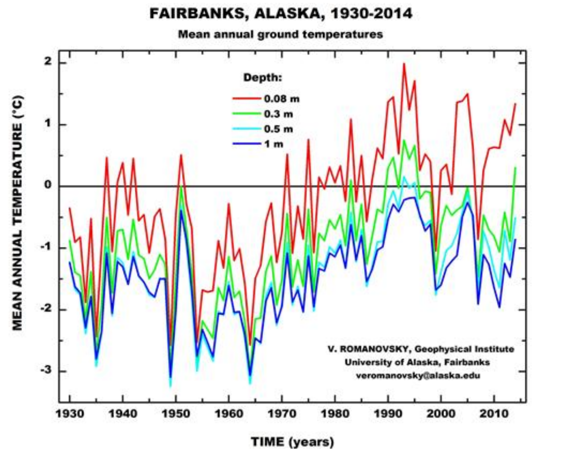

Figure 12. Time series of mean annual ground temperatures at several depths measured since 1996 and modeled for the 1930-1995 time period in Fairbanks, AK area.

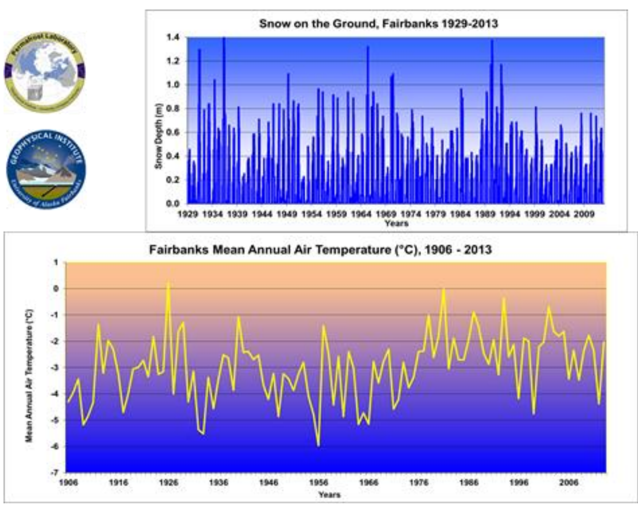

Figure 11. Time series of mean annual air temperature (lower graph) and daily depth of snow on the ground (upper graph) measured at the Fairbanks meteorological station in 1906-2013.

4 DISCUSSION AND CONCLUSIONS

Most of the permafrost observatories in Alaska show substantial warming of permafrost since the 1980s. The magnitude of warming varies with location, but is typically from 0.5 to 3°C. However, this warming is not linear in time and not spatially uniform. A short warmer period in the very early 1980s was followed by a relative cooling in the mid-1980s. Since the late-1980s, the permafrost and active layer temperatures were increasing up to the late-1990s. During the first half of the 2000s, permafrost temperatures were relatively stable at almost all of the sites in Alaska, except for the sites in the Brooks Range and at its southern foothills where the temperature was still increasing. Interesting dynamics in permafrost temperatures have been observed in Alaska since the mid-2000s until the present. While permafrost warming resumed on the North Slope of Alaska with a rate between 0.2 to 0.5°C per decade, permafrost temperatures in the Alaskan Interior have experienced a slight cooling that has continued through the first half of the 2010s. The observed climate warming has triggered permafrost degradation in Alaska, especially at locations which have been affected by human activities. The combination of thawing permafrost and erosion is damaging the local community infrastructure such as buildings, roads, airports, pipelines, water and sanitation facilities, and communication systems.

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