

**Applications of Measurements at Permafrost Monitoring Sites for
Documenting Long-Term Change
in Denali, Wrangell-St. Elias, and Yukon-Charley Rivers
National Parks and Preserves**

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I. Summary

The extent and state of permafrost within the three park units of the Central Alaska Network (CAKN) are vital signs of interest to the National Park Service (NPS). This report explores potential applications of observations and measurements of permafrost in the CAKN-NPS monitoring program. Observations and measurements at a few sites illustrate how the data can be used. Since permafrost conditions vary significantly throughout Alaska, the recommendations made here may not be valid for other park units.

Air temperatures in Alaska warmed during the first half of the 20th century, cooled during the 3rd quarter and warmed sharply during the 4th quarter. Climate models predict that this recent warming will increase and continue well into the 21st century. Permafrost has generally warmed coincident with warming air temperatures. In many areas south of the Arctic Circle, permafrost is currently thawing with the formation of thermokarst terrain.

Thermokarst terrain drastically modifies and remolds the ground surface. This process can modify or totally change ecosystems, human activities, infrastructure, and the fluxes of energy, moisture and gases across the ground surface-air interface. In lowlands or relatively flat areas, a shift from boreal forests to shrubby wetlands or grasslands often occurs with concurrent changes in bird and animal populations. The new ecosystems favor aquatic birds and mammals.

This report makes recommendations to determine what changes have already occurred, to monitor these changes, to determine the current status (thermal regime) of the permafrost, and to monitor its thermal regime through observations and measurements. The specific, prioritized recommendations are:

- Conduct a literature search, especially of gray literature that exists in federal and state agencies that have performed permafrost related research in Alaska.
- Add permafrost observations and measurements to selected existing or proposed study sites within the parks.
- Determine the current extent of thermokarst by identifying areas where ice-rich permafrost is degrading using aerial photo analyses and field investigations.
- Determine the rates and characteristics of change associated with thermokarst terrain by establishing a thermokarst monitoring site in each park.
- Determine the current state (thermal regime) and recent changes in it by establishing at least one permafrost monitoring site in each park.
- Develop a predictive capability (thermal model) for each park that incorporates ecosystem characteristics.
- Archive data in the National Snow and Ice Data Center at Boulder, Colorado.

II. Introduction

A. Historical perspective

Permafrost is soil or rock and included ice and organic material that remain at or below 0 °C for at least two consecutive years. This is a thermal definition requiring, in some cases, temperature measurements for a period of two years to determine the presence or absence of permafrost. Temperature measurements are also required to determine the status of permafrost. Permafrost that is warm and warming is in danger of thawing.

Permafrost is a product of cold climates. The first permafrost on earth must have existed prior to or have formed coincidentally with the first glaciation about 2.3 billion years ago. Permafrost occurrences, distribution, and thicknesses must have increased during periods of cold climates and decreased during warm intervals. Permafrost may have disappeared in the Arctic about 50 million years ago. In Alaska, there is no reported evidence for the occurrence of permafrost in continental lowland areas prior to 2.5 million years ago. The current permafrost in Alaska appears to have been initiated during the climatic cooling that began about this time. During the last million years, there is evidence for repeated glaciations about every 10^5 years. Permafrost varied significantly in response to them (Osterkamp and Gosink, 1991). The last glacial period ended about 12 to 14 thousand years ago. About 8 to 10 thousand years ago, the climate may have been slightly warmer than present. There was a Medieval warm period followed by a "Little ice age" during the last millennia.

Global air temperatures have increased since the late 1800s (Hansen and Lebedev, 1987). Air temperatures in Alaska warmed from then until about 1940 (Hamilton, 1965), cooled during the third quarter of the 1900s, and warmed sharply at the beginning of the fourth quarter (Hartman and Wendler, 2003). Air temperatures in permafrost regions of Alaska are highly correlated (Hamilton, 1965; Hansen and Lebedev, 1987; Zhang and Osterkamp, 1993). After the sharp warming of 1977, Alaskan weather stations recorded annual mean air temperatures during the following two decades (1978-1997) that were typically 1 to 2 °C warmer than the previous two decades (Osterkamp and Romanovsky, 1999). However, trends in air temperatures over this time period were variable with some stations showing little or no change and others showing a warming or cooling (Osterkamp, submitted).

The regime shift that occurred in 1977 was characterized by warmer winter temperatures (Hartman and Wendler, 2003). Typically, December through April air temperatures warmed significantly with the greatest warming occurring in January. The rest of the year showed little or no warming. This seasonality of the warming also occurs in the active layer and permafrost (Osterkamp, submitted). Increases in air temperatures have resulted in an increase in permafrost temperatures. However, other climatic factors especially timing, duration and accumulation history of the annual snow cover and site wetness impact permafrost temperatures modifying the effects of changes in air temperatures (Zhang et al., 1996).

Twenty to 25% of the exposed land area of the Earth and about 80 % of Alaska are underlain by permafrost. Denali (DENA), Wrangell-St. Elias (WRST), and Yukon-Charley Rivers (YUCH) National Parks and Preserves are underlain by warm

discontinuous permafrost. This permafrost is typically within a few degrees of thawing and recent but sparse measurements indicate that much of it is within a degree of thawing (Osterkamp, 1983, 1994, 1995). These measurements also show that it has warmed significantly during the last quarter century (Osterkamp and Romanovsky, 1999; Osterkamp, 2003a; Osterkamp, submitted). Thawing permafrost, landslides, and thermokarst terrain (an irregular topography resulting from thawing of excess ground ice, see Figures 1 to 6) have been observed near these parks (Osterkamp et al., 2000; Jorgenson et al., 2001).

The climatic changes of the past century coupled with recent observations of warming and thawing permafrost have caused concern about the future of permafrost (NAS, 1983; CO2, 1984). Thawing permafrost in natural settings has been observed in Alaska (Osterkamp, 1994, 1995; Osterkamp et al., 1997; Osterkamp et al., 2000; Jorgenson et al., 2001) and the southern boundary of permafrost has moved northward in Canada. Recent observations show that warming of the permafrost has continued into the 21st century in Alaska, Europe including Svalbard, Canada, Russia, China, and Mongolia (ICOP, 2003). There are increasing reports of thawing permafrost and formation of thermokarst terrain in Alaska (Osterkamp et al., 2000; Jorgenson et al., 2001; Shur and Jorgenson, 2003) and thin permafrost is thawing from the bottom at some sites (Osterkamp, 2003a; Osterkamp, submitted). Ice wedges have been found to be thawing in the Alaskan Arctic in the region of continuous permafrost where permafrost temperatures were thought to be too cold for this to happen (Jorgenson et al., 2003).

Global circulation models predict that air temperatures in the Arctic will rise 2 to 5 °C in the next half century (Maxwell, 1992). Since continuous permafrost is typically colder than -5 °C, no widespread thawing is expected although some areas may experience localized thawing, slope instability and ice wedge thawing. Discontinuous permafrost is much warmer so that the effects of climatic warming there will be much more serious. Additional warming will cause more of it to thaw and a warming of several degrees would cause most of it to begin thawing. Thawing proceeds from the top downward and, eventually, from the bottom upward. Thawing rates are slow, initially on the order of 10 cm/year near the surface, and theoretically less than 2 cm/year at the base (Osterkamp, 1983) so that times on the order of centuries to millennia are required to thaw even thin discontinuous permafrost.

The combination of the above observations and conditions and the predicted climatic warming of the 21st century are cause for concern about the future condition of permafrost in Alaska. Thus, it is important to determine what changes have already occurred, to monitor these changes, to determine the current status (thermal regime) of the permafrost, and to monitor its thermal regime.

B. Cause for concern

Why should there be concern for thawing permafrost? Current climatic scenarios predict up to 5°C additional warming of the air temperatures in the next century for Alaska and the Bering Sea regions (Weller et al., 1995) although the uncertainty in these predictions is large. At the low end of the predicted warming (2 or 3°C), most of the discontinuous permafrost in Alaska would thaw, creating many attendant problems (Osterkamp, 1983; NAS, 1983; Nelson et al., 1994; Osterkamp et

al., 1997). Thawing of ice-rich permafrost and creation of thermokarst terrain has been identified as one of the primary problems facing northern ecosystems as a result of climatic warming (Osterkamp et al, 2000; Jorgenson et al, 2001).

Boreal forests typically cover discontinuous permafrost in Interior Alaska and below timberline in DENA, WRST and YUCH. Sparse data around these parks indicates that permafrost there is usually within 1 to 2°C of thawing. DENA and WRST are probably somewhat warmer than YUCH. In areas of discontinuous permafrost, the edges of isolated permafrost bodies are already at the thawing point and any additional warming will cause them to thaw and shrink. If the observed warming of the permafrost underlying boreal forest ecosystems in Alaska continues, then additional permafrost will thaw. Where the permafrost is ice-rich (roughly 50% of it), thawing changes the ice to water creating a mud slurry that cannot support the weight of any overlying soil or vegetation thus dissolving the physical foundation on which trees and ecosystems rest. As a result, the ground subsides and landslides and thermokarst terrain develops consisting of channels, pits, troughs, potholes, ponds, lakes, and "drunken forests" (trees leaning in random directions). Thermokarst drastically modifies and remolds the ground surface. This process can modify or totally change ecosystems, human activities, infrastructure, and the fluxes of energy, moisture and gases across the ground surface-air interface. Vascular and nonvascular plant species composition and distribution, plant community productivity, soil chemistry, biological activity and nutrient supply for plant use can be substantially altered by this geophysical phenomenon. Drainage conditions determine whether standing water will be present or not. The affected trees usually die and vegetation changes significantly. These changes in the flora have a direct impact on the fauna. In lowlands or relatively flat areas, a shift from boreal forests to shrubby wetlands or grasslands often occurs with concurrent changes in bird and animal populations (Osterkamp et al., 2000; Jorgenson et al, 2003). The new ecosystems favor aquatic birds and mammals. Figures 1 through 6 illustrate thermokarst terrain and some of its effects.



Figure 1. Thermokarst terrain in the Slana River valley northeast of WRST showing the destruction of this boreal forest ecosystem that previously supported terrestrial birds and mammals (e.g. caribou). It is being converted to wetlands with grasses and shrubs favoring moose and aquatic birds and mammals. Note the trees that are tilted and dying in the upper left background of the photo. (Photo by T. E. Osterkamp).



Figure 2. Open grass and sedge meadows and two remnant islands of spruce forest (across the center of the picture) that are underlain by ice-rich permafrost in the Slana River valley northeast of WRST. The islands are "inflated" up to 3 m above the present level of the meadows by the presence of excess ice in the permafrost. Thawing is "deflating" the soil destroying the boreal forest ecosystem that is being replaced with wetlands (wet grass and sedge meadows). (Photo by T. E. Osterkamp).



Figure 3. A close up view of the edge of an island covered by spruce trees and underlain by ice-rich permafrost that is thawing in the Slana River valley. (Photo by T. E. Osterkamp).



Figure 4. An area in the Tanana Flats showing thermokarst ponds, floating fens and remnant islands of birch forest underlain by ice-rich permafrost. The islands are "inflated" up to 2 m above the present level of the fens by the presence of excess ice in the permafrost. Thawing is rapidly "deflating" the soil with complete destruction of the forest ecosystem that is being converted into floating fens with ponds. Many dead birch trees standing in water are visible in the center and right half of the photograph. (Photo by T. E. Osterkamp).



Figure 5. A thaw slump along the edge of a river in northwestern Alaska created by thawing the ice-rich permafrost underlying this boreal forest. (Photo by an unknown Japanese photographer).



Figure 6. A thaw slump on a slight slope in tundra near the Yamal Peninsula, Russia. The left end of the headwall is about 10 meters high. The grass tundra ecosystem has been destroyed and a new one consisting primarily of shrubs is forming in the slump. These slumps are expected to become more common as the climate warms and may occur in both tundra and forested areas of parks. (Photo by T. E. Osterkamp).

Thus, the result of thawing ice-rich permafrost in a boreal forest ecosystem is not just a slight shift in the nature of the ecosystem but rather partial or total destruction of the ecosystem and its replacement by a new ecosystem.

Time scales to create thermokarst terrain are on the order of a decade but can range from several years to centuries. Time scales for recovery of the ecosystems appear to range from centuries to millennia although, in many cases, recovery may be impossible because of permanent changes in relief, drainage and other factors.

C. Need for monitoring

Little can be done about the terrestrial impacts associated with natural thermokarst formation. However, it is highly desirable to be knowledgeable about them, to anticipate their impacts, and to develop rational responses to them. This requires an understanding of permafrost conditions which must come from a detailed knowledge of its thermal state as derived from observations and temperature measurements. However, the totality of permafrost conditions throughout a park is not reasonably

attainable. A reasonable approach is to develop a series of carefully chosen monitoring sites in a few key areas where temperature measurements and other observations of permafrost can be made. The results can then be used to infer the general conditions of permafrost in the park.

Permafrost conditions in Interior Alaska within DENA, WRST, and YUCH depend on a number of factors ranging from regional to site specific (see section IV A). Thus, monitoring sites need to be developed for each park to span the range of conditions found there.

This report makes recommendations to determine what changes have already occurred, to monitor these changes, to determine the current status (thermal regime) of the permafrost, and to monitor its thermal regime through observations and measurements. Where possible, data from nearby existing permafrost monitoring sites will be used to illustrate the potential results to be obtained from the sites.

III. Use of existing data and research

A. Past research and existing data

Some research has already been done on permafrost in and near DENA, WRST, and YUCH in Interior Alaska. Examples include studies of permafrost conditions (Black, 1951), thermokarst (Wallace, 1948) and the interactions of thermokarst and the boreal forest ecosystem to the north and east of WRST (Osterkamp et al., 2000) and DENA (Jorgenson et al., 2001). Permafrost monitoring sites were established with funding from the now defunct Alaska Council on Science and Technology in the early 1980s near the northwest corner of WRST (Gulkana and Hogan Hill), northeast (Healy) and southeast (Cantwell, 1990s) of DENA, and to the west (Old Man, Yukon River bridge, Livengood) and southeast (Eagle) of YUCH (Osterkamp, 2003a; 2003b; submitted). The primary purpose of the sites was to investigate the effects of changes in climate on permafrost. The sites were placed in relatively flat terrain far from the influence of water bodies, springs and potential groundwater flow to avoid having to make corrections to the borehole temperatures. For this reason, thermal disturbances associated with the effects of surface morphology, vegetation, forests, burns, high wind areas, relatively recent volcanic ash flows, tectonic activity, major changes in thermal properties of the ground, and human activities were also avoided. Additional details about them can be found in Osterkamp (2003b).

It is recommended that a detailed literature search be conducted to determine if other studies have been done.

There is also a considerable amount of information in the gray literature. This ranges from agency reports with limited distribution to things like geological maps and drilling logs that may only reside within the agencies that did the work.

Some examples include:

1. USGS reports on research conducted since the late 1940s in Alaska. Apparently, they conducted a permafrost study near Glennallen sometime in the 1950s or 1960s and reports should exist about the study.
2. State geological survey reports and mapping projects.
3. Alaska Department of Transportation and Public Facilities (ADOTPF) drilling logs for roads and bridges in and near the parks. It is estimated that these

number in the thousands. Drilling must have been done for the DENA park road, Nabesna road, and McCarthy road in the parks and for the highways adjacent to the parks.

4. Water well logs recorded by the state. A record is kept of all wells drilled.
5. Drill and geophysical logs from oil exploration holes. I believe there was a hole near Glennallen and one somewhere in the Yukon River Flats or to the east of there. The USGS drilled a research hole somewhere near Ft. Yukon during the 1990s.
6. Information in the private sector. One obvious example is the work done by Alyeska to determine permafrost conditions in constructing the pipeline to the west of YUCH and WRST.

It is recommended that the libraries of the USGS and state of Alaska agencies be searched for reports and information on their activities involving permafrost.

B. Aerial surveys

Aerial surveys have been addressed in the report by Karle and Jorgenson (2004) and will not be addressed here.

C. Use of existing sites and current research efforts

A cost-effective way to obtain information on thermokarst terrain and permafrost is to make some of the necessary observations and measurements at established sites in the parks where other NPS research is being conducted. Data from permafrost monitoring sites outside of the parks has been and will continue to be archived at the National Snow and Ice Data Center (NSIDC) in Boulder, Colorado. This data is available online (<http://nsidc.org/data/arcss034.html> and <http://nsidc.org/data/arcss106.html>) at no cost. The author is also participating in a major proposal that extends beyond his planned retirement and will most likely be funded so that these measurements will continue into the future. Thus, the future of the project seems secure.

It is recommended that current and planned long-term research projects in the parks be examined to identify those that may have sites that would be compatible and suitable for permafrost-related observations and measurements.

IV. Monitoring site requirements

A. Factors affecting permafrost

Factors that have an effect on permafrost are those that can cause its surface or internal temperature to change. These changes are brought about by changes in the energy balance at the surface of the permafrost (including sides and bottom in isolated masses of permafrost) or interior to it. The factors can include climate (air temperature, precipitation as rain or snow, wind), physical terrain (topography, slope, aspect), hydrology (surface drainage and site wetness, proximity of nearby water bodies, presence of underground water, flooding), environmental (ecosystems, vegetation, fire events), geology (soil and rock, geothermal heat flow, tectonic setting) and human and animal disturbances. A consideration for investigations of changes in permafrost conditions is that these factors operate at different time scales ranging from days to

millennia. Our primary concern is with changes in permafrost conditions ranging from multi-year to a century or so. Consequently, we will be concerned with monitoring factors that vary significantly over these time scales. Finally, we note that observations, measurements, and reports are often made or summarized on an annual basis. Annual changes in permafrost temperatures are caused primarily by changes in air temperatures, snow cover (timing, duration and thickness) and site wetness.

B. Desirable site conditions

Much of the work on site selection can be done using existing information such as topographic and other maps, satellite images, and aerial photographs. However, ideally, two field trips to the proposed sites should be made to determine site conditions during summer and near the time of maximum snow thickness and to select the precise location of the site.

The site conditions discussed below are specific to permafrost observatories (including boreholes) designed to study the effects of climate change on permafrost. Some of the conditions are chosen to make data acquisition and analyses easier for the investigator (e.g. access, terrain). Sites for thermokarst studies must be selected where thermokarst exists. Measurements at these sites are discussed in Karle and Jorgenson (2004).

1. Existence of permafrost

Obviously, permafrost should exist at the site. This may not always be easy to determine (particularly in WRST and DENA) where there are substantial areas with no permafrost or with subsurface conditions that make the permafrost distribution sporadic. In some cases, probing and/or temperature measurements may be necessary to confirm whether or not permafrost exists at a site.

2. Access

Good access is a prerequisite for sites since drilling costs are very sensitive to access and the costs of other investigations are significantly reduced if helicopters or airplanes are not required to conduct investigations. This usually dictates placing them along existing road or trail systems or in areas that can be reached during winter with over-the-snow transport systems.

3. Availability of long-term climate data

It is desirable to have borehole sites near a long-term weather station. The availability of climatological data supplements the site measurements and, after a few years, the measurements can be used to conduct site-specific calibrations of models. Past climatological data can then be used to drive the calibrated models to calculate realistic values for the active layer and permafrost conditions for the period of record (Osterkamp and Romanovsky, 1999). The calibrated models can also be used to project permafrost conditions into the future using various climate scenarios.

4. Terrain

The sites should be placed in relatively flat undisturbed terrain as determined from aerial photographs and topographic maps. Field trips are needed to examine the area and to determine the precise location of the site. The terrain requirements (flatness) for a borehole site are much greater than for a site without a borehole.

5. Snow cover

The most desirable sites are those where snow cover is relatively uniform and where drifting is not a major consideration.

6. Hydrological

The sites should be placed far from the influence of water bodies, springs, potential groundwater flow, floods, icings, and areas of unusual ground wetness caused by surface drainage. Seeps can be identified during summer and icings will be obvious during late winter.

7. Geological

The soil or rock in the vicinity of a site should be relatively uniform. Geothermal heat flow should be uniform around a borehole site. This rules out areas with sharp topographical changes and makes those near active volcanoes or mud volcanoes suspect.

8. Environmental

Areas that have uniform conditions on the surface and in the sub-surface are the most desirable. Thus, boundaries between ecosystems, forest edges, and any sharp changes in vegetation should be avoided. Burned areas should also be avoided.

9. Security

It is necessary that the study sites be secure from human intrusion and disturbance over long time periods (a century or more). This insures that observed changes can be attributed to natural events.

The permafrost observatories developed by Osterkamp (2003b) were the first in Alaska specifically designed to investigate the effects of changes in climate on permafrost. While investigations at these sites have taught us much about the response of permafrost to changes in climate, this area of research is still relatively new. There are several important questions about permafrost observatories and thermokarst study sites that cannot be properly addressed given the present state of knowledge. These include questions about the representative nature of the sites, the area over which results from a site can be used to characterize conditions, how results between sites are correlated, the number of sites that are needed for a park and others.

Current research supported primarily by the National Science Foundation (NSF) is addressing the interactions between the air (climate) and the land (including vegetation and permafrost) in Arctic regions. The results from this research will help us better understand how the land responds to climatic change. A research project recently funded by NSF (Effects of ground ice on the evolution of permafrost-dominated landscapes under a changing climate by Shur, Jorgenson and Osterkamp, 2005) will help us develop a better understanding of the modes of permafrost degradation and thermokarst which will improve our ability to develop criteria for selection of thermokarst study sites and to interpret data from them.

V. Observations and measurements

A. Observations and mapping

1. Photographic stations

Photographic stations where periodic digital photographs are taken of fixed scenes are useful for monitoring vegetational changes and areas of active thermokarst and for recording any other temporal changes that may occur at monitoring sites. While

only sporadic photographs were taken at the Healy site, it is possible to observe thermokarst terrain that began developing there between 1985 and 1989 (Figure 7).

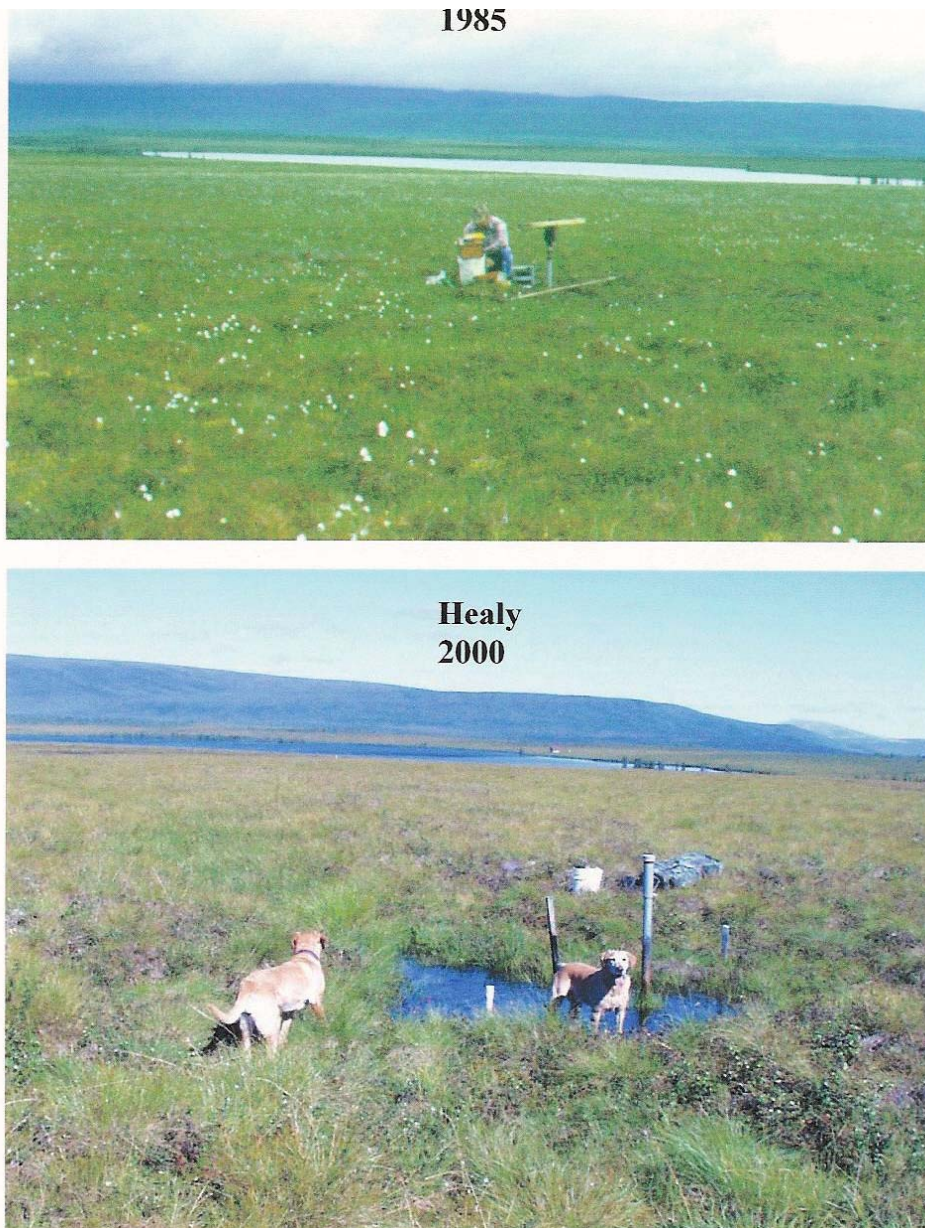


Figure 7. Photographs of the borehole pipe at the Healy site in 1985 and 2000 showing the thermokarst pit and changes in vegetation that have developed at the site.

A catalogue of annual photos taken from several viewpoints at fixed stations and with different spatial scales over a long period of time can be used to document changes in vegetation and terrain. Photographic systems are also available with cameras that can be mounted in small balloons or model airplanes to provide a birds-eye view of a site with very detailed spatial resolution.

2. Aerial photographs

Aerial photographs provide a detailed plan view of the terrain and can be obtained with sufficient spatial resolution to study the evolution of thermokarst terrain, particularly thermokarst pits, ponds, shores, landslides etc. These are useful over decadal time scales or longer. Thermokarst features near the Healy site are shown in the aerial photograph below (Figure 8).



Figure 8. Aerial photograph of the Healy site taken in 2003. Some of the larger thermokarst pits are marked by rectangles and the site by an ellipse.

3. Topographical surveys

Topographical surveys conducted every few years over active thermokarst terrain are useful for determining the ground subsidence or thaw settlement that is occurring. Figure 9 shows the thaw settlement that has occurred at the Healy site over a seven year period along an approximately east-west line across the borehole. This survey shows that up to 0.4 m of thaw settlement occurred along the line between 1996 and 2003 during the second decade of thawing at the site.

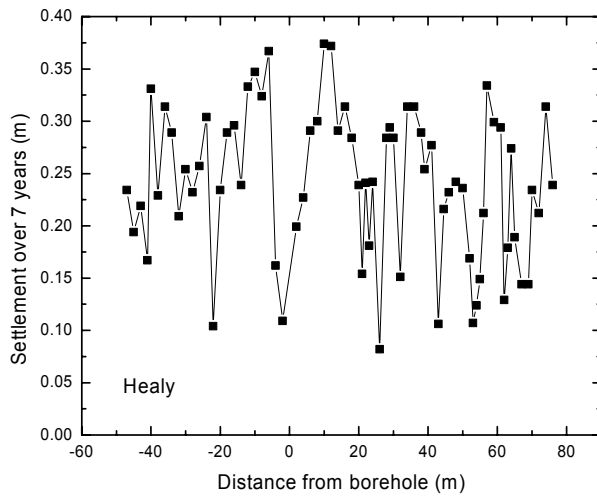


Figure 9. Thaw settlement at the Healy site over a seven year period.

Theory suggests that the thawing must have been much greater during the first decade. This is confirmed by measurements of the distance from the top of the pipe in the borehole to the ground surface (Figure 10). The pipe in the borehole is frozen in the permafrost to a depth of 28 m and serves as a fixed survey point. The data are fit with a square root of time line. Total thaw settlement since the late 1980s is more than 1 m allowing for the depth of the water puddle next to the pipe.

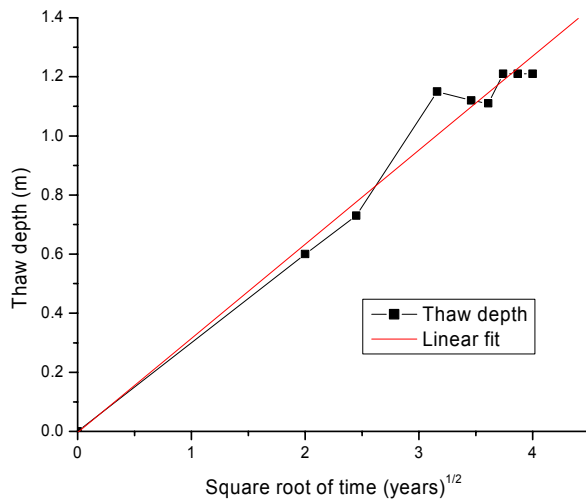


Figure 10. Thaw settlement vs square root of time and a linear fit to the data for the ground adjacent to the borehole at the Healy site.

4. Mapping

It would be desirable to have a map of air temperatures for each park but obtaining the necessary data would be expensive. However, developing a few sites for

air temperature measurements in some of the major ecosystems where other measurements are already being done might be feasible.

Information on the snow cover (especially thicknesses and types) is useful for permafrost investigations and also important for other studies (e.g. overwintering of large mammal populations). Snow survey sites could be set up along the routes that park rangers use to conduct winter patrols. They could be trained to identify snow cover types and to make thickness measurements. Snow survey sites can also be set up that can be read from the air using light aircraft.

Icings indicate the presence of subterranean water flow and the absence of permafrost locally. Those of primary interest are the ones that usually occur at the toe of slopes and in floodplains. Stream icings are not of interest. Park rangers are probably familiar with the locations of some icings and could map them. Aerial photographs taken about the time the snow cover disappears may also be useful in mapping them.

Ecosystems, geology and soil maps appear to have received attention as part of past and ongoing park studies. The geology of some areas is known from past mining activities. Deep boreholes with extensive sampling, identification of rocks, and measurements of their thermal properties have been conducted at Orange Hill on the headwaters of the Nabesna River by the USGS. Other sites are known to exist, need to be identified, and the information from them catalogued.

B. Physical measurements

1. Permafrost surface temperature

Since permafrost is a thermally conductive medium, the thermal history at the top of the permafrost determines its future thermal state. Permafrost surface temperature can be determined by placing a single temperature sensor there. With automatic data loggers, measurement frequencies are often a few hours although a few times daily is adequate for most purposes. Figure 11 shows sporadic permafrost surface temperature measurements at the Healy site for 1995 to 2003 made with inexpensive self-contained single sensor systems that have also been used to measure air and ground surface temperatures. This site was adjacent to the borehole but in an area that was not thawing. These data show that the undisturbed permafrost was warm from the summer of 1995 to the summer of 1998, was slightly cooler during the winter of 1999-2000, cooled strongly during the winter of 2000-2001, and was cold during the winter of 2002-2003.

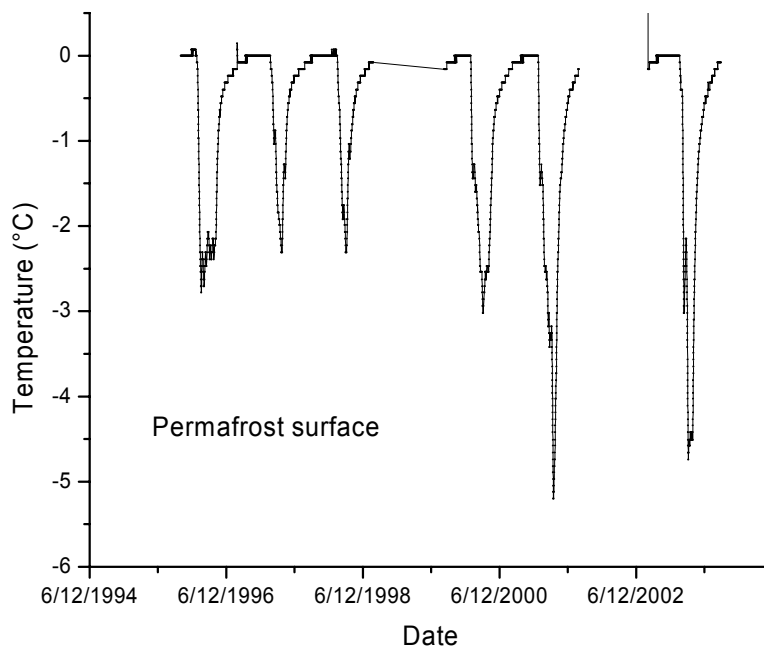


Figure 11. A time series of temperature measurements near the permafrost surface in undisturbed permafrost at the Healy site.

Figure 12 shows similar measurements made adjacent to the borehole where there is a talik (thawed layer) under the active layer and above the top of the permafrost. During winter, temperatures in the talik are constrained near 0 °C and in summer they can be warmer. Figure 12 also indicates that the accuracy of the measurements is about 0.2 °C.

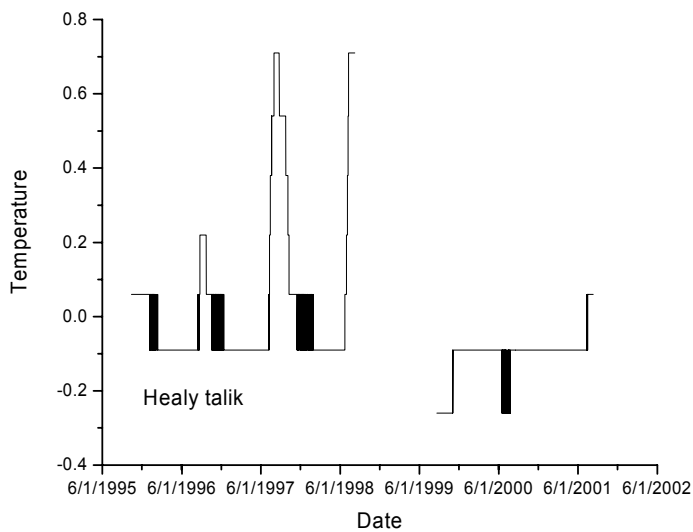


Figure 12. A time series of temperature measurements in the talik between the active layer and the thawing permafrost surface adjacent to the borehole at the Healy site.

2. Ground surface temperature

Annual mean values of ground surface temperatures are typically up to several degrees warmer than permafrost surface temperatures primarily because of the effects of snow cover and thermal offset. The two can be related using numerical and analytical modeling (Jorgenson and Kreig, 1988; Osterkamp and Romanovsky, 1999). Thus, ground surface temperatures can be used to predict permafrost surface temperatures, at least to the precision of the models. Measurement frequencies are typically every few hours since the ground surface temperatures change rapidly when snow is absent. Figures 13 and 14 show ground surface temperatures for both undisturbed and thawing permafrost. The range of the sensor for the ground surface temperature measurements made at the undisturbed site near the borehole is +5 to -15 °C resulting in data being truncated above and below those temperatures. Summer temperatures exceeded 5°C from 1997 to 2003. In early 2001 and 2003, the ground surface temperatures cooled below -15°C repeatedly. Summer ground surface temperatures next to the borehole were commonly in the 20 °C range. However, winter temperatures were rarely colder than -5°C. This is believed to be a result of snow drifting into the depression around the pipe.

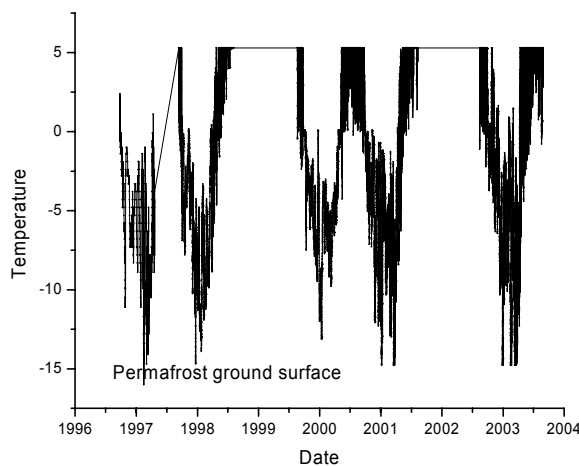


Figure 13. Ground surface temperatures in undisturbed permafrost at the Healy site. The truncations at +5 and -15 °C were caused by the range of the measuring instrument.

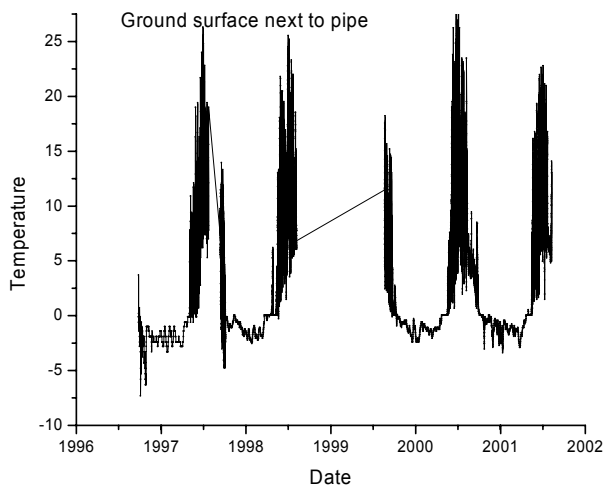


Figure 14. Ground surface temperatures next to the borehole at the Healy site.

Ground surface temperatures were also measured in an area of thermokarst pits and ponds to the northwest of the borehole site (Figure 8). These pits and ponds were generally filled with vegetation (mostly grass) that usually extended above the water surface. Paired sensors were placed just under the surface of the vegetation, one in the pit or pond and one a few meters distant on the tundra. Figure 15 shows results similar to those at the pipe site.

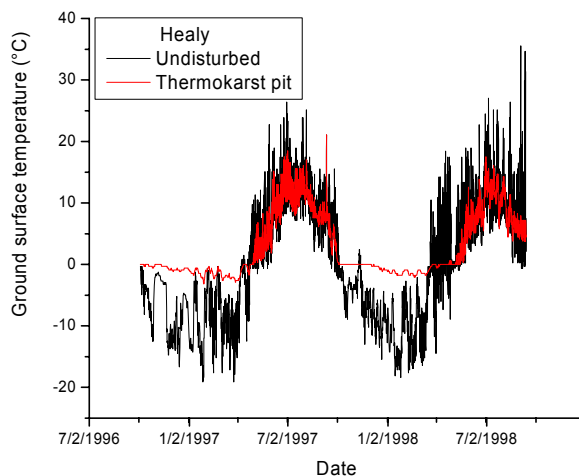


Figure 15. Ground surface temperatures in a thermokarst pit and on adjacent undisturbed permafrost.

Annual mean ground surface temperatures for the pits and adjacent undisturbed permafrost differ by 3 to 5 °C. These temperature differences are primarily a measure of the effects of drifted snow in the pits.

3. Air temperature

Air temperature, modified by the effects of intervening materials (vegetation, snow cover, active layer etc.), is the primary modifier for the thermal regime of permafrost. Measurements of air temperatures are usually made by automatic loggers in standard shelters every 1 to 4 hours. Given sufficient information about the intervening materials, numerical and analytical models can be used to predict the thermal regime of the permafrost in response to changes in climate. At the Healy site, air temperatures were measured sporadically (Figure 16).

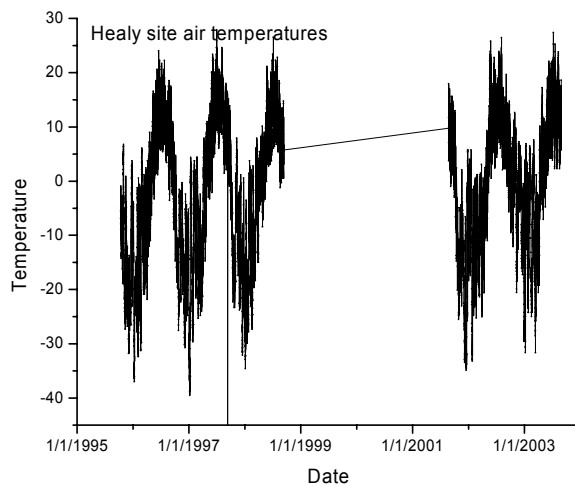


Figure 16. Air temperature measurements near the Healy borehole.

While not complete, these measurements can be used to do an approximate reconstruction of air temperatures at the site using data from the town of Healy. Figure 17 shows the mean monthly air temperatures for the site and town. There are three sets of values for each month, one for each year of measurements.

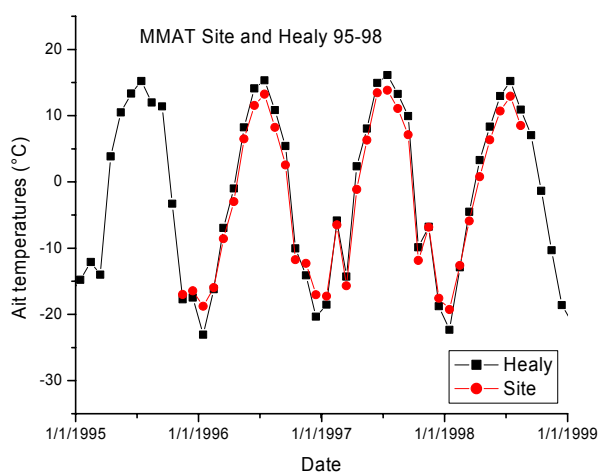


Figure 17. Monthly mean air temperatures (MMAT) for the site and the town of Healy. Site air temperatures are cooler in the summer and warmer in the winter.

An approximate air temperature history for the site for the period of record at Healy can be constructed. The first step is to calculate the average differences in monthly temperatures between the two places. These differences are then used to modify the Healy record so that it reflects site conditions. As the period of overlap for the data at the two places (Figure 17) increases, the reliability of the reconstructed record at the site increases.

4. Snow

Snow provides an insulating blanket that modifies the effects of air temperatures on the ground and underlying permafrost. The timing of the first snow in the fall, snowmelt in the spring (these give the duration of snow on the ground), the temporal history of snow depth during the year, and snow cover characteristics are important aspects of this insulation. However, wind, surface morphology and vegetation strongly influence snow depths, snow properties and the effects of the resulting snow cover on the permafrost (Zhang et al., 1996). Snow depths were not measured at the site; however, maximum annual snow depths are available from the town of Healy (Figure 18). While snow depths at the site and at Healy are undoubtedly different, the trends are likely to be similar considering that they are separated by only 15 km. The data show larger than average snow depths during the 1990s. These increased snow depths were primarily responsible for the permafrost warming that occurred at the Healy site.

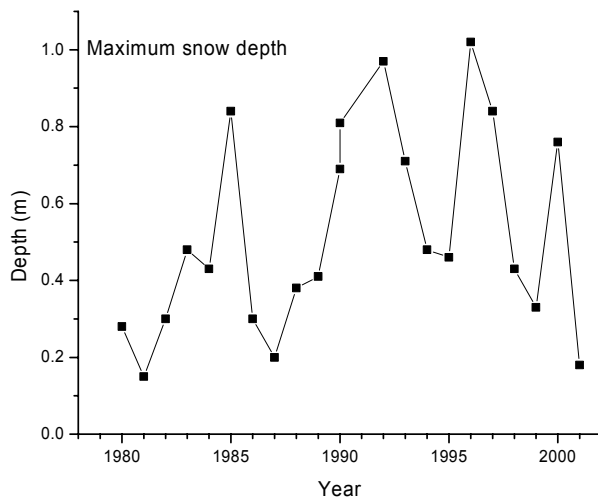


Figure 18. Maximum snow depths at the town of Healy.

5. Active layer monitoring

The measured ground and permafrost surface temperatures described above are also the temperatures at the top and bottom of the active layer. No attempt has been made to monitor intervening temperatures in the active layer at the Healy site although this has been done at other sites using a multi-point logging system. A common configuration uses sensors in the air, at the ground surface, and three each in the active layer, straddling the permafrost surface and in the permafrost. Figure 19 shows some of this type of data for the 1986 to 2000 period from the Hogan Hill site, about 40 km north of the northwest corner of WRST.

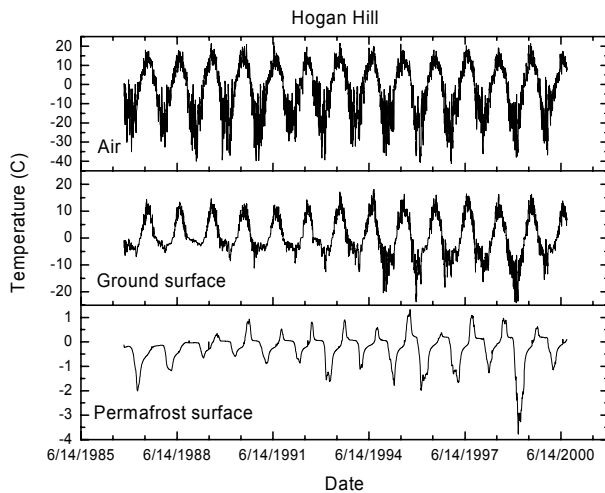


Figure 19. Air, ground surface and permafrost surface temperatures for a fourteen year period, 1986-2000, at Hogan Hill.

These data and that from different levels in the active layer can be used in analyses of the thermal regime of the permafrost. The data are especially useful to calibrate and verify the predictions of models. Another interesting aspect of the data is that ground surface temperatures can exceed 0°C by several degrees while the permafrost surface temperatures remain below 0°C, an effect termed the thermal offset. This is a result of changes in the thermal conductivity of the active layer when it freezes. Figure 20, for the Hogan Hill site, shows annual mean ground surface temperatures that were up to 2 ½ °C while permafrost surface temperatures remained below 0°C. A result of thermal offset is that positive annual mean ground surface temperatures cannot be used as a criterion for the absence of permafrost.

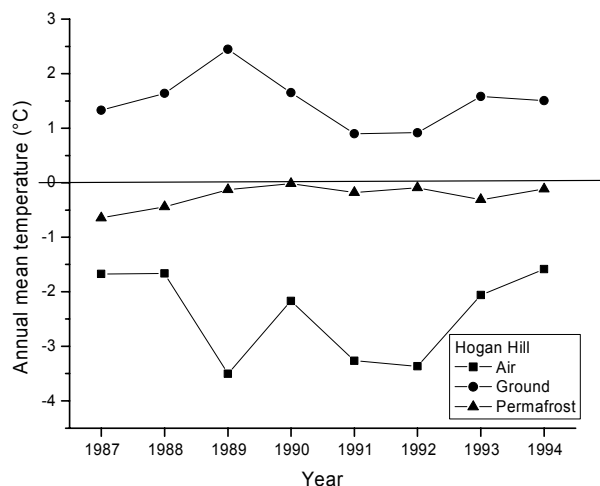


Figure 20. Annual mean air, ground surface, and permafrost surface temperatures at the Hogan Hill site demonstrating that ground surface temperatures can remain positive for extended periods without thawing the permafrost.

Active layer thicknesses and temperatures during the summer season are not necessarily indicative of climatic change or changes in permafrost conditions. For example, the most recent warming of the permafrost (since the mid 1980s) was caused by changes in “winter conditions”. Maximum snow cover thicknesses increased and warming of air, ground and permafrost temperatures were greatest in winter and spring and least in summer and fall (Figure 21). Since active layer thicknesses depend primarily on the thermal history of the ground surface during the thaw period, the recent “winter” warming of air, ground and permafrost temperatures has produced little change in annual maximum active layer thicknesses. Thus, active layer trends reflect summer conditions and do not necessarily follow trends in permafrost temperatures that are a result of the full annual cycle. Consequently, trends in active layer thicknesses cannot be used as an indication of climatic warming or cooling.

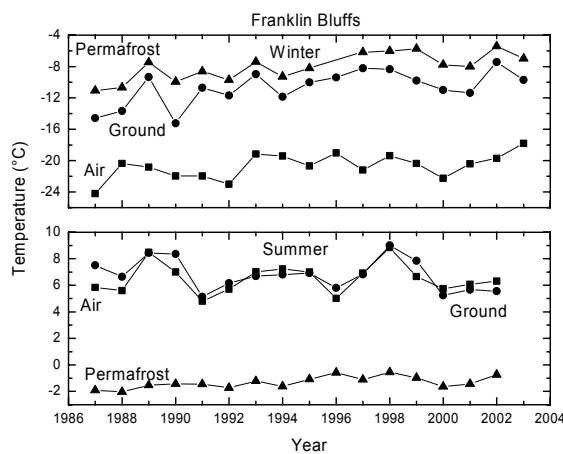


Figure 21. Calculated air, ground surface, and permafrost surface temperatures at the Franklin Bluff site for “winter” months (October through May) and “summer” months (June through September). Summer trends are not correlated with the observed warming of the permafrost.

6. Borehole Temperatures

The temperature distribution in permafrost defines its state and can only be obtained from a temperature profile measured in a borehole. Figures 22 and 23 show temperature profiles for the Healy and Gulkana sites. These profiles are usually measured annually. Seasonal temperature changes penetrate from about 5 to 20 m in depth so that temperatures there reflect the events of the past season. Changes in soil strata with depth can often be seen from breaks in the profile such as the one for Gulkana near the 29 m depth.

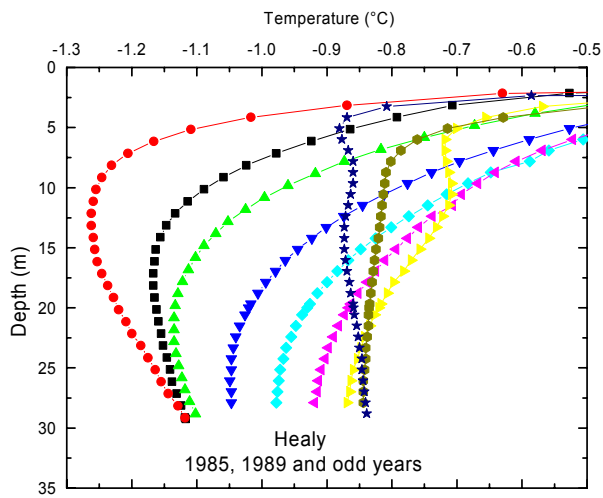


Figure 22. Temperature profiles at the Healy site for 1985, 1989 and later odd years. The permafrost here is within 0.9 °C of thawing.

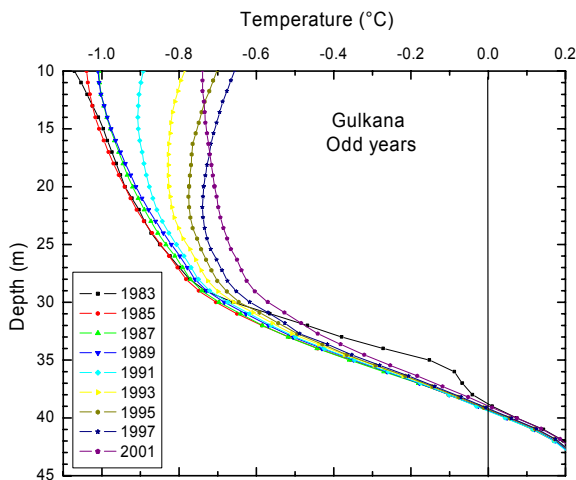


Figure 23. Selected temperature profiles at the Gulkana site. The 1983 profile shows the disturbance due to drilling at the 30 to 40 m depths. The permafrost here is within 0.8 °C of thawing.

Depth to the base of the permafrost (0°C) can be determined precisely from the profile (38.8 m). Depth to the base of ice-bearing permafrost and the freezing point depression there can also be determined (about 37.4 m and -0.10°C). Repeated annual measurements of the temperature profile provide the temporal history of the thermal regime of the permafrost showing for these sites that the permafrost is warming and is currently within less than 1 °C of thawing. The magnitude of the warming at any depth for a given time period and the rate of warming can be obtained by graphing the temperatures at that depth as shown in Figure 24 (e.g. 0.66°C for 1989 to 1998 or

0.07°C per year) at the Healy site. If the thermal conductivity of the soil or rock is known the heat flow can be calculated using the measured temperature gradient.

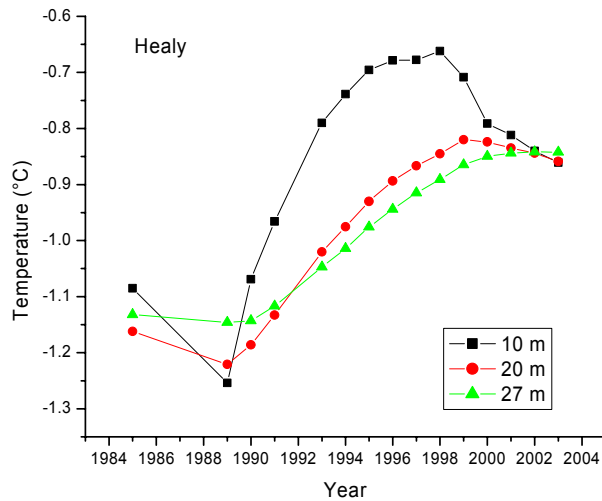


Figure 24. Time series of temperatures at the 10, 20, and 27 m depths at the Healy site. Temperatures nearer the surface started cooling in 1999 while those at depth lag.

When equilibrium permafrost warms at its surface, thawing at the bottom cannot begin until the warming penetrates there which requires a time scale $\tau \sim X^2 / 4D$, where X is the permafrost thickness and D is the thermal diffusivity (Osterkamp and Burn, 2002). For thin discontinuous permafrost, τ is a few years but for thick continuous permafrost it may be two millennia. The timing of the recent warming (late 1980s) suggests that thin discontinuous permafrost should be thawing from the bottom at some sites. Figure 25 shows the position of the bottom of the permafrost (0°C) at the Gulkana site obtained by extrapolation between measured temperatures. The mean thawing rate was about 4 cm/year (1989-2002) with a value of 9 cm/year 2000 to 2002. More than ½ m of permafrost has thawed at its base since 1991.

The thawing rates are larger than expected theoretically. The amount of heat available from normal geothermal heat flow can only thaw on the order of 2 cm/year if ice fills the soil pores and all the geothermal heat is available for thawing. Possible reasons for the large observed thaw rates include heat flow that is much larger-than-normal, pore spaces that are not saturated with ice, a significant amount of unfrozen water in the pore spaces or some combination of these. The presence of a volcano (Mt. Wrangell) in the area suggests potential larger-than-normal heat flow values but there does not appear to be a heat flow measurement near the Gulkana site.

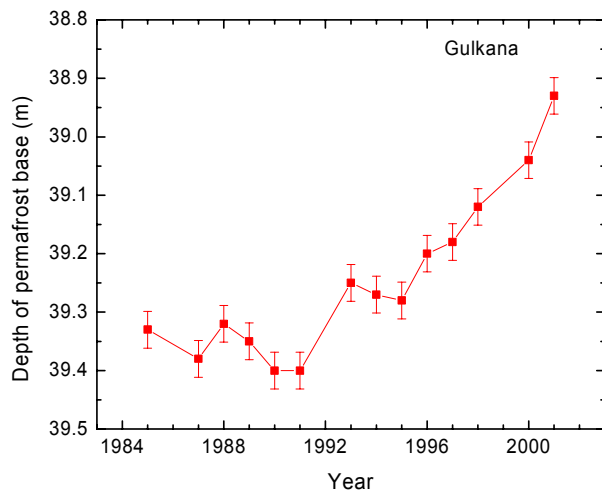


Figure 25. Permafrost thicknesses at the Gulkana site have been decreasing with permafrost thawing at the base. About ½ m of permafrost has thawed at its base since 1991.

If there is sufficient information available on air temperatures, snow cover, soil temperatures and temperature profiles, soil characteristics, permafrost boundary conditions, and initial conditions, then models can be calibrated to reproduce the measured temperature profiles. For sites with nearby meteorological stations that have information on air temperatures and snow cover, hindcasts of the thermal regime of the permafrost for the period of record can be made using the calibrated model. Forecasts can also be made but these require, at the least, both air temperatures and snow cover information for the future climatic scenario. Unfortunately, while air temperatures are commonly forecast, snow cover depths are not. This is an obstacle since permafrost temperatures are sensitive to snow cover depths.

7. Miscellaneous measurements

Soil samples can be taken to determine the soil moisture content in the laboratory. Field measurements of the dielectric coefficients of the soil using time domain reflectometry (TDR) and Vitel probes (with data loggers) can be made to determine the soil moisture in the active layer and near surface permafrost. Neutron logging has been used to measure the soil moisture (ice and unfrozen water content) in drilled holes in the permafrost. A well point driven into the active layer allows measurements of the water table level. This is a pertinent parameter for gas emission studies and also provides an indication of drying of the active layer.

The thermal conductivity of the active layer and near-surface permafrost can be determined by direct measurements. A portable needle probe system can be used to measure the thermal conductivity of soils in the field in the sidewalls of pits and on samples returned to the laboratory. A method has been developed to determine the thermal diffusivity from temperature measurements and conditions delineated for its use (Zhang and Osterkamp, 1995).

The pipe in the borehole can be used as a survey marker (reference point). It is used (by leveling) to determine heave or settlement in the vicinity of the hole. Another method involves placing magnetic disc markers on the outside of plastic pipes in the permafrost. A magnetic switch is lowered down the pipe to measure the position of the markers over time, which determines any soil movement.

Investigations of vegetation and of the morphological, chemical, and physical properties of the active layer and permafrost are desirable and have been conducted at several of the permafrost observatories (Romanovsky and Osterkamp, 1995; Zhang et al., 1997; Ping et al., 1998; Walker et al., 2003; Osterkamp, 2003b).

Temperature profiles (Lachenbruch et al., 1982; Osterkamp, 2003a) and well logs from petroleum exploration and production wells (Osterkamp and Payne, 1981; Osterkamp et al., 1985) and a surface transient electromagnetic method have been used to determine permafrost thicknesses. Gamma-gamma density and neutron porosity logs have been used to determine the fractional volumes of ice, unfrozen water, ash and organics and to estimate potential thaw settlement in boreholes. Surface D.C. resistivity and magnetic induction methods have been used to investigate the presence of ice-rich soils, massive ice and unfrozen zones near some of the observatories (Kawasaki and Osterkamp, 1985).

VI. Specific parks

Hartmann and Wendler (2003) examined the recent warming in Alaska (since 1976) dividing the state into four meteorological regions (Arctic, Western, Interior, and Southern). DENA straddles the boundary (Alaska Range) between the Interior region and the Southern region. WRST is in the Southern region and YUCH is in the Interior region. Comparing the decade prior to 1976 and the decade after, they reached the following primary conclusions: a) all the regions warmed significantly, b) the warming was largest in winter and smallest in summer. Precipitation increases during the last half of the 20th century were found at the majority of stations for the winter, spring and autumn seasons. While there are no analyses available for the exact time period when permafrost temperatures were warming, their conclusions are consistent with warming of the permafrost.

There are some considerations specific to each park based on very limited observations. Sparse data indicates that DENA and WRST have the warmest permafrost. If all other factors are equal (magnitude of warming, areas of ice-rich permafrost etc.), then DENA and WRST ecosystems will be subjected to thermokarst problems earlier than YUCH.

The timing and magnitude of the permafrost warming at the Healy site is similar to the warming at three other sites in the Tanana River valley (near Fairbanks and Birch Lake). All four of these sites are in the southern and western portions of the Interior region suggesting a correlation between them. However, the Eagle site near the town of Eagle near the southeast corner of YUCH is also in the Interior region although farther to the north and east. Mean permafrost surface temperatures are near -3°C (Figure 26) and there is no indication of permafrost warming just prior to the time it was drilled and at least through 1994, the time of the last measurements.

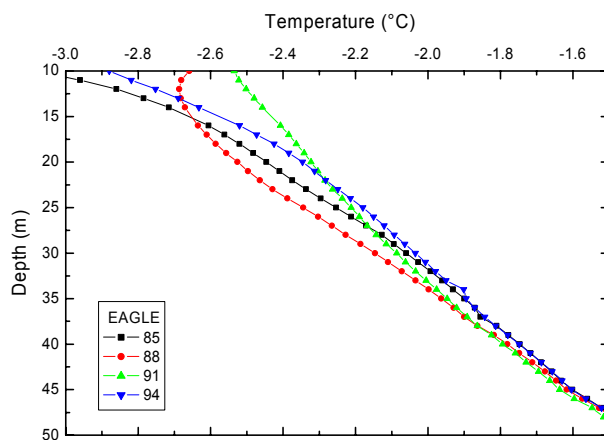


Figure 26. Temperature profiles measured at Eagle.

Current knowledge of permafrost conditions within YUCH is poor, almost non-existent. There are three sites to the west of YUCH along the Hickel Highway. Two of these sites show a cooling trend and one shows a warming trend. The two sites that show a cooling over the last two decades are the only ones to do so along a north-south transect from Prudhoe Bay to Glennallen. The reasons for this behavior are not clear but it suggests that permafrost conditions in YUCH may be very complex.

Figure 23 shows temperature measurements from the Gulkana site about 3 km from WRST in the Southern climatological region. The temperatures are similar to those at the Healy site. However, the magnitude of the warming here is smaller and the timing of the warming is different. Gulkana has been warming slowly since it was drilled in 1983.

In the Slana River drainage to the northeast of WRST, there are extensive areas with thermokarst terrain (Osterkamp et al., 2000). Some of this thermokarst dates to the late 1800s. The primary impact of the recent thawing of permafrost and thermokarst development in the boreal forest of the Mentasta Pass area is the destruction of valley spruce and birch forests and their conversion to wet sedge meadows, ponds, and lakes. The meadows have remnant masses of permafrost that are degrading from within by thermokarst formation and along their edges by lateral heat flow. Islands of permafrost in Mineral Lake and Mentasta Lake and their shorelines are degrading by the same processes. Some small islands disappeared between 1948 and 1981 and small thermokarst lakes are growing and coalescing. Measurements in soil profiles and field observations indicate that the average thaw settlement is about 2 m with maximum values about 6 m.

VII. Recommended strategy

The proposed strategy seeks to provide information on permafrost within the parks. We need to determine what has already happened to the permafrost, its current state, and what is likely to happen to it in the future. Recommendation A is listed first but need not be a separate study since it could be incorporated into C, D, or E. Recommendation B is a high priority but should be more of an ongoing consideration

when other park projects are being developed. Recommendations C through F are the essentials of the strategy.

A. Conduct a literature search, especially of gray literature that exists in federal and state agencies that have performed permafrost related research in Alaska. The items addressed in section V above are those for which information is sought. See section III for more details.

B. Add permafrost observations and measurements to selected existing study sites in the parks.

It is necessary to understand current environmental and permafrost conditions, especially its thermal regime, to fully assess the risks of future changes. It appears that a variety of measurements are being made or planned within the parks. It is recommended that:

- Permafrost observations and measurements be added to those made at existing and planned sites in the parks. Not all sites would be suitable or necessary and only selected measurements would be made at the sites. At the least, measurements of air, ground surface and permafrost surface temperatures should be made in the major ecosystems in each park. If existing meteorological sites could be used, it should be possible to realize significant savings.

C. Determine the current extent of thermokarst in the parks by identifying areas where ice-rich permafrost is degrading.

Evidence of ice-rich permafrost degradation includes thermokarst and kettle lakes, collapse scar fans, bogs and pits, polygonal features, gullies, sink holes, and certain types of landslides. Most of these features can be observed on existing aerial photographs. The following is recommended.

- Conduct an aerial photo analyses of each park to identify and classify areas where ice-rich permafrost is degrading. The aerial photo analyses should be repeated to determine decadal changes in thermokarst terrain and identify new areas of thermokarst.
- This study should include a field investigation component for verification and to determine the type and volumes of ice associated with various ice-rich permafrost ecosystems. This would allow future “calibration” of existing ecological maps and their use to determine terrain susceptibility to thermokarst.

D. Determine the rates and characteristics of change associated with thermokarst terrain by monitoring.

Documentation of thermal, physical and biological changes in active thermokarst areas are necessary to provide information on their characteristics and rates of change.

This can be done by establishing observation, sampling, and measurement points within a site (usually along a line transecting the site). It is recommended that:

- At least one thermokarst monitoring site be established in each park to determine thermal, physical and biological changes. At the least, measurements of temperatures in the air, at the ground surface and at the permafrost surface should be made. The ground surface and permafrost surface measurements should include a place that is thawing and one that is not. Thaw depths should be measured annually at a few selected points. A survey of ground and water surface elevations should be made at about 5 year intervals. Shallow cores (2-3 m) should be taken along the transect to quantify ice volume and structure to be used to evaluate modes of thermokarst development. Additional measurements should be done as funding allows (Karle and Jorgenson, 2004, p.30, field monitoring, items one and two)

E. Establish at least one permafrost monitoring site in each park.

It is desirable to have a full complement of measurements made on permafrost at one site since there are often significant differences between sites. This would allow future calibration of models using a consistent set of input data. The recommendation is to:

- Establish at least one permafrost monitoring site in each park. Osterkamp (2003b) has provided detailed information for establishing monitoring sites. A full complement of measurements should be conducted. These include air, ground, active layer, and permafrost surface temperatures using a multi-point data logger. A borehole (30 to 60m depth) is needed for determining deeper permafrost temperatures that will allow trends in permafrost temperatures to be determined. Once the site has been selected and drilled, individual components of the monitoring system could be added annually spreading the costs over several years.

F. Develop a predictive capability.

It is recommended that a thermal model of ground temperature distribution that incorporates ecosystem information be developed for each park. The measurements of air, ground surface and permafrost surface temperatures (above) would be used to calibrate the model. The model should then be used to map the spatial distribution of these temperatures throughout the park ecosystems. It would identify areas with and without permafrost and those areas of warm permafrost that are most vulnerable to change. When coupled with the above recommended observations and measurements, the areas most likely to develop future thermokarst terrain could be identified.

VIII. Data archiving

Beginning in the mid-1980s, data from ecosystem and permafrost studies in Alaska have been archived at the National Snow and Ice Data Center (NSIDC) in

Boulder, Colorado. Since the mid-1990s, the National Science Foundation (NSF) has required that NSF funded studies have a plan for archiving data. Data from Alaskan studies are now routinely archived at NSIDC and it would be beneficial to have any studies in Alaskan parks also archived there.

XI. Acknowledgements

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