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A thermal history of permafrost in Alaska

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ABSTRACT: There has been a widespread warming of air temperatures in Alaska since 1977 and some warming of permafrost. Constant or cooling permafrost temperatures followed this in the early 1980s, probably due to thin snow covers and a short cooling trend. Permafrost temperatures along a north south transect from Prudhoe Bay to Gulkana and at other sites have generally warmed since the late 1980s, initially in response to thicker snow covers. The warming north of the Brooks Range is comparable in magnitude to the century long warming there (2 to 4°C). The trend has not been followed at Eagle and the Yukon River bridge. Warming of the discontinuous permafrost is typically ½ to 1½°C. Thin discontinuous permafrost is thawing at the base at a rate of 0.04 m per year at one site. New thermokarst and thawing permafrost have been observed at several sites.

1 INTRODUCTION

Current information on permafrost suggests that, during the last ice age, the occurrence, distribution and thickness of terrestrial permafrost increased and, with low sea levels, thick permafrost formed in the exposed continental shelves of the Arctic and Antarctic Oceans. Warm global temperatures of the last 10,000 years have relegated permafrost to polar and high mountain regions and thick terrestrial permafrost is thinning from the bottom (Osterkamp and Gosink, 1991). Permafrost temperatures warmed coincident with the warming since the "little ice age" and there has been an accelerated warming during the last two decades.

This paper reviews the thermal history of permafrost in Alaska based on modeling and measurements and reports the results of precise temperature measurements made over the last twenty five years.

2 REVIEW

2.1 *The last century*

The U.S. Geological Survey has measured temperatures in deep drill holes in permafrost in Northern Alaska since the late 1940s. Their results (Lachenbruch et al., 1982; Lachenbruch and Marshall, 1986; Lachenbruch et al., 1988) show that the permafrost in this region warmed, typically 2 to 4°C although some holes show little or no change or a cooling. Penetration of the warming signal indicates that the warming began about 40 to 80 years ago. Warming of air temperatures in the late 1800s and early 1900s in North America may have preceded warming of the permafrost. However, Zhang and Osterkamp (1993) showed that, at Barrow, air temperature variations alone (since 1923) couldn't account for the observed warming of the permafrost thus implicating changes in snow cover or perhaps an earlier warming.

Some evidence indicates that the discontinuous permafrost in Alaska warmed coincident with warming air temperatures since the "little ice age". Air temperatures at stations throughout mainland Alaska are correlated (Hamilton, 1965; Hansen and Lebedev, 1987; Zhang and Osterkamp, 1993). Sparse data from thermokarst studies in undisturbed areas in Interior Alaska using tree rings have shown that the earliest thermokarst dates to the late 1880s (Barber and Osterkamp, 1998). The studies also show that thermokarst was initiated in the late 1930s and early 1940s in permafrost in Anchorage where there is no permafrost today (at least near the surface). This suggests that some of the discontinuous permafrost in Alaska should be thawing from the bottom at present and that its southern boundaries should have moved northward during the last century.

2.2 *The last five decades*

Information for the last half-century comes from deep borehole data and modeling. Calibrated models for the Barrow and Fairbanks areas have been used to investigate the behavior of the active layer and permafrost during the latter half of the 20th century (Romanovsky and Osterkamp, 1996; Osterkamp and Romanovsky, 1999). The results show that the continuous permafrost at Barrow generally cooled from 1950 until the latter 1970s and have generally warmed since then. At the 10 m depth, temperatures have warmed about 1½°C since 1976. At depths of 40 m or more, temperatures have warmed continuously since 1950 as a result of the warming earlier in the century.

For discontinuous permafrost, these studies show that ground surface temperatures varied about 0°C from 1971 to 1987 and since then have remained warmer than 0°C. Warming totaled about 3°C over thirty years.

Near-surface permafrost temperatures began warming in the 1970s with a warming of about 2°C over thirty years. Permafrost remains stable and survives only because of the insulating effect of the organic mat at the ground surface and the related thermal offset in the active layer.

3 METHODS

The data used in this study come from permafrost observatories located along a north south transect of Alaska that follows the trans-Alaska pipeline with a few sites located elsewhere (Fig. 1).

Access holes, typically 60 m in depth (range 30–90 m), were drilled and instrumented for measuring permafrost temperatures annually at all the sites. Additional shallow holes ($<$30 m) were drilled for seasonal measurements at some of the sites. At seven sites, daily temperatures have been recorded since 1986 at eleven levels (air, ground surface, three in the active layer, three straddling the permafrost table and three in the permafrost to a maximum depth of 1 m) using an automated temperature logger attached to thermistor sensors in a plastic rod installed in the ground (Osterkamp et al., 1987; Romanovsky and Osterkamp, 1995; Osterkamp and Romanovsky, 1999).

The permafrost observatories were placed in undisturbed areas in flat terrain far from water bodies where the surface vegetation was relatively uniform. Drilling methods included rotary air and mud drilling, augering, coring and water jetting. Some sites have supplementary information such as soil samples, soil thermal conductivities, active layer thicknesses, extent of taliks and thawed layers and water table levels.

Annual temperature profiles were measured with a thermistor sensor on the end of a cable that was lowered into the pipe to discrete levels (1 m intervals) using the procedures and equipment described by Osterkamp (1985). Accuracy of these measurements is typically between 0.005 and 0.01°C. Precision of the depth measurements was typically better than 3 cm. Warming at the permafrost surface was determined from daily temperature measurements there and also from time series of temperature profiles in the permafrost below the depth of seasonal variations where the profiles showed increased curvature toward warmer temperatures. Additional information is provided in Osterkamp and Romanovsky (1999).

4 RESULTS AND DISCUSSION

4.1 *West Dock (WD)*

Figure 2 is a time series of permafrost temperatures for the 20 m depth at WD and other sites southward to the Brooks Range. Values of −10.05°C in 1978 and −9.56°C in 1980 were measured at the 19.4 m depth in a hole less than 400 m distant from WD. This half-degree warming in two years may be the result of increasing air temperatures in the late 1970s (Fig. 3). Data from the current site began in 1983 and indicate a slight cooling for the first four years followed by a general trend of increasing temperatures. Net warming

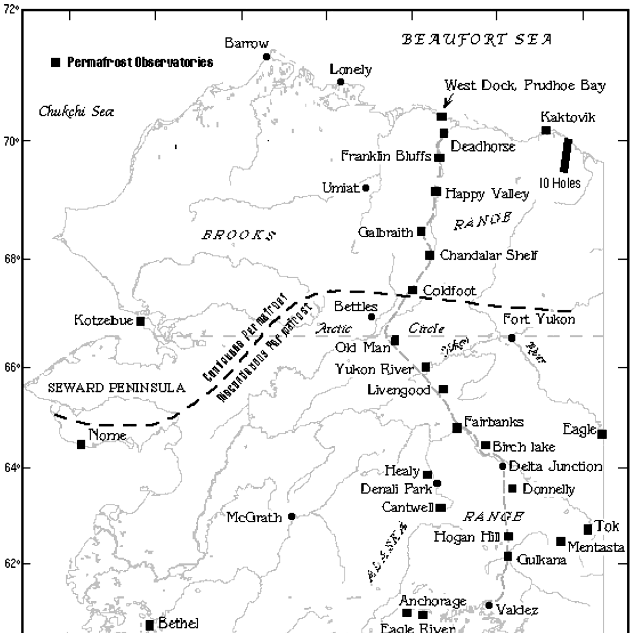

Figure 1. Locations of the permafrost observatories in Alaska. College Peat and Bonanza Creek are in the Fairbanks area.

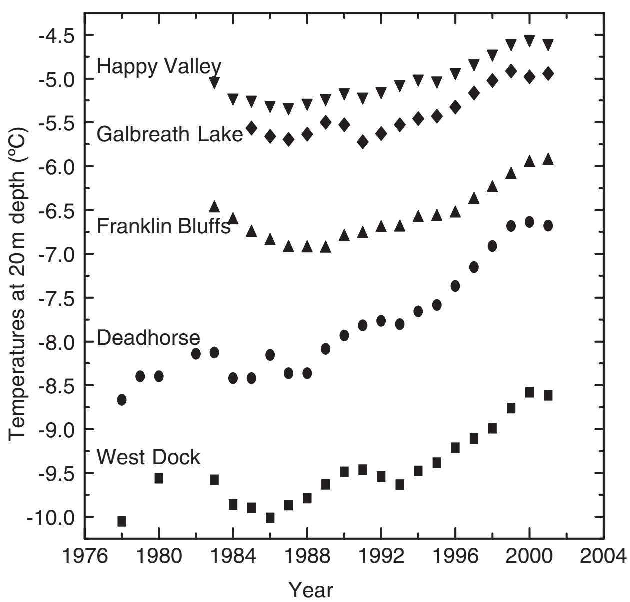

Figure 2. Time series of temperatures at the 20 m depth for sites from Prudhoe Bay south to the Brooks Range in Alaska.

at the 20 m depth (1986–2001) was 1.40°C. Annual mean air temperatures at all sites on the coastal plain agree within 1°C, typically (Fig. 3). For years of overlap (1987–1998) Deadhorse and ARCO airports are the same within a few tenths degree except for 1996 and 1997 where the ARCO data appear to be in error. Both are typically within 1°C of the other sites.

Annual mean air temperatures at the ARCO Airport warmed about 1.8°C in a step-like fashion in 1977 and cooled somewhat in the 1980s. There was a general warming from the lows of the late 1980s to the extreme high of 1998. The warming has been greatest in winter. Increases in monthly mean temperatures of 2.2 to 3.3°C occurred in December through March. September and November were slightly cooler (<1°C) while the rest of the months were warmer by 0.1 to 1.7°C. Temperatures just below the permafrost table have warmed about 3°C (1992–2001). Deeper data are consistent with a surface warming between 1979 and 1981. Except for Franklin Bluffs, holes on the coastal plain show a slight cooling for the last year or two.

4.2 *Deadhorse (DH)*

Temperatures measured at a site near the airport at a depth of 20 m indicate a warming of 0.6°C (1978–1982). At the current site, about 3 km distant, temperatures at the 20 m depth were variable (1983–1988) with a general trend of increasing temperatures starting in 1988. The net warming was 1.69°C (1988–2001), larger than the coastal site (WD) and inland sites. Deeper temperatures are consistent with a warming near 1980. The magnitude of the warming at the permafrost surface is estimated to be between 3 and 4°C. Annual mean air temperatures at the DH site average about 0.6°C colder than the Deadhorse Airport.

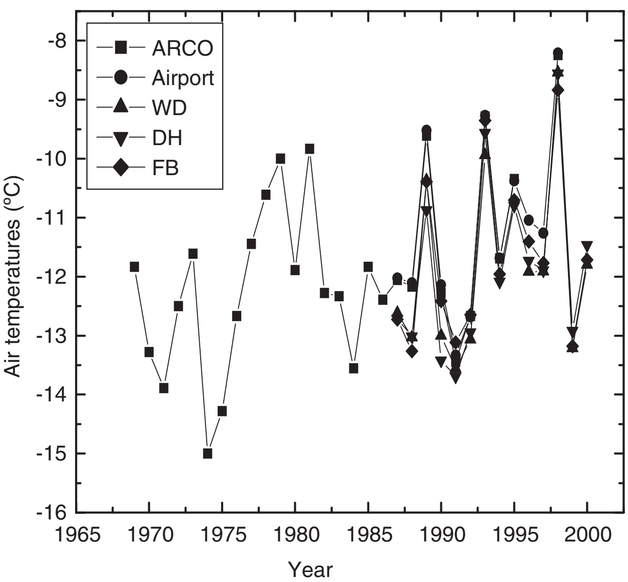

Figure 3. Annual mean air temperatures at the ARCO and Deadhorse airports and at the WD, DH, and FB sites. ARCO data for 1996 and 1997 have been deleted.

4.3 *Franklin Bluffs (FB)*

The data at 20 m depth show a cooling (1983–1987) with continuously warming temperatures beginning in 1989. At 50 m depth, temperatures cooled slightly until 1985 and then warmed continuously (1985–2001). A net warming of 1.00°C (1989–2001) at the 20 m depth was observed. The estimated magnitude of the warming at the permafrost surface is about 3°C. Deeper temperatures are consistent with a warming around 1980.

4.4 *Happy Valley (HV) and Galbreath Lake (GL)*

HV and GL are in the northern foothills of the Brooks Range with GL adjacent to the mountains. Data at HV began in 1983 and indicate a slight cooling until 1987 followed by a general trend of increasing temperatures. Data from GL began in 1985, indicate a cooling until 1987 followed by a warming until 1989, a cooling until 1991 followed by a general warming. The net warming was 0.71°C at HV (1987–2001) and 0.75°C at GL (1987–2001). Estimated magnitude of the warming at the permafrost surface is about 2°C. At HV, deeper temperatures are consistent with a warming prior to 1982. At GL, temperatures below 50 m have warmed continuously (1985-2001).

4.5 *Chandalar Shelf (CS), Coldfoot (CF), Old Man (OM) and Yukon River (YR)*

Figure 4 shows a 19 year time series for these holes. At the 20 m depth, there was an initial cooling until 1986 or 1987 in all 4 holes followed by a general warming trend at CS, CF and OM. This timing of the warming is about the same as that north of the Brooks Range. Net warming at the 20 m depth was CS, 0.52°C (1986–1996), CF, 0.39°C (1987–1995) and OM 0.41°C (1987–2001). Deeper temperatures at CS and CF show continued warming after 1995. At the YR site, 20 m permafrost temperatures behaved similarly with CS until 1996 but then cooled with a net cooling of 0.187°C (1985–2001). The reasons for this behavior are not clear. Deeper temperatures showed a warming trend in all the holes except YR where there was a cooling trend. The estimated magnitude of the warming at the permafrost surface is about 2°C at CS and about 1°C at CF and OM.

Warming of the deep permafrost temperatures at CS, CF, and OM appears to be associated with the step increase in air temperatures around 1977. However, this warming did not have a significant effect on permafrost

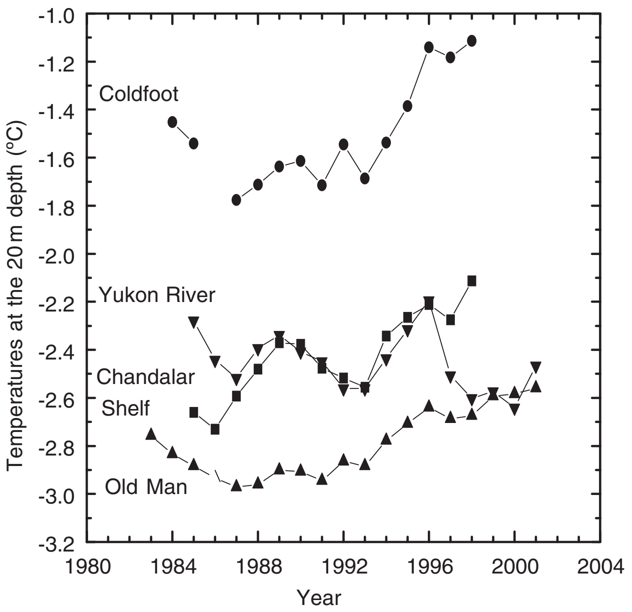

Figure 4. Time series of temperatures at the 20 m depth for sites from the Brooks Range to the Yukon River in Alaska.

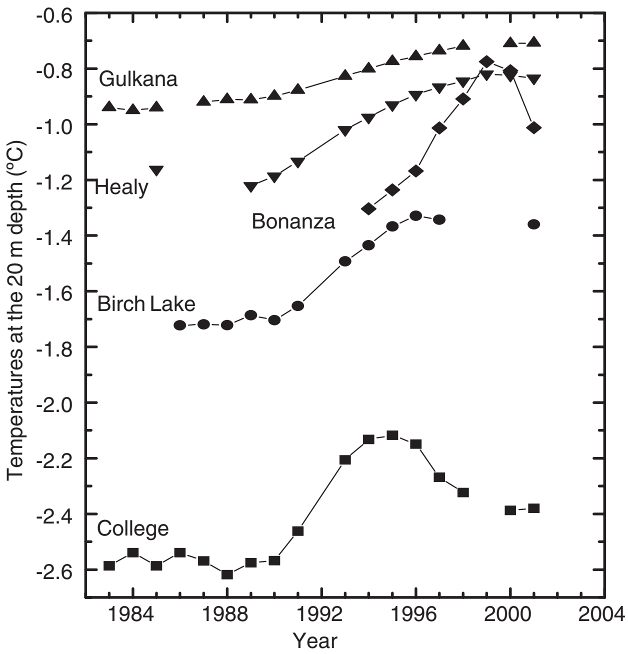

Figure 5. Time series of temperatures at the 20 m depth for sites south of the Yukon River in Alaska.

temperatures at the 20 m depth until the late 1980s. The initial cooling in the holes (1983–1987) appears to be associated with thin snow covers and a short cooling trend in the early 1980s.

4.6 *College Peat (CP), Bonanza Creek (BC), Birch Lake (BL), Healy (HE), and Gulkana (GU)*

Figure 5 is a 19 year time series of temperatures at the 20 m depth for discontinuous permafrost from 1983 to 2001 for the CP, BC, BL, HE, and GU sites.

At the CP site, temperatures were nearly constant from 1983 to 1990, warmed until 1995 and then cooled about one half of the warming. Temperatures at the 50 m depth were stable except for a slight increase from 1994 to 1998. Temperatures at the BL site were stable through 1990, warmed until 1996 and appear stable since then. Deeper temperatures were stable until 1991 and then increased. At the BC site, temperatures increased from 1994 to 1999 and then decreased the last two years. Deeper temperatures (40 m) have continuously increased.

Temperatures at the HE site at the 20 m depth decreased slightly from 1985 to 1989, warmed to 1999 and now show a slight cooling. At the GU site, temperatures increased slightly (1983–1989), and then warmed until about 2000.

The net warming was CP, 0.24°C (88-01), BL, 0.36°C (88-01), BC, 0.29°C (94-01), HE, 0.39°C (89-01), and GU, 0.24°C (84-01). The warming at the permafrost table was estimated to be about ½ to 1½°C for these sites. A site near Donnelly Dome that is not in permafrost shows a similar pattern but with a larger warming of 0.56°C. A site near Eagle did not show a warming trend prior to 1997 (Osterkamp and Romanovsky, 1999).

5 IMPLICATIONS OF THE WARMING

5.1 *Thawing of isolated permafrost bodies*

In discontinuous permafrost, the lateral boundaries of permafrost bodies are in contact with the adjacent unfrozen ground. These boundaries are constrained to be at the phase equilibrium temperature, typically slightly <0°C. At equilibrium, the energy balance at a boundary is zero and the boundary is stationary. Thus, any warming of the permafrost will upset the energy balance and will cause thawing at these boundaries and contraction of the permafrost bodies. Consequently, the boundaries of permafrost bodies in the discontinuous permafrost that has warmed must be thawing.

5.2 *Thermokarst*

If the surface temperature of permafrost exceeds 0°C, then the permafrost must thaw and, where the permafrost is ice-rich, thermokarst will form. New thermokarst has been observed in several areas since the late 1980s. At the HE site, a meter or more of subsidence has occurred. Thermokarst drastically modifies and remolds the ground surface. This process can severely change or disrupt ecosystems, human activities

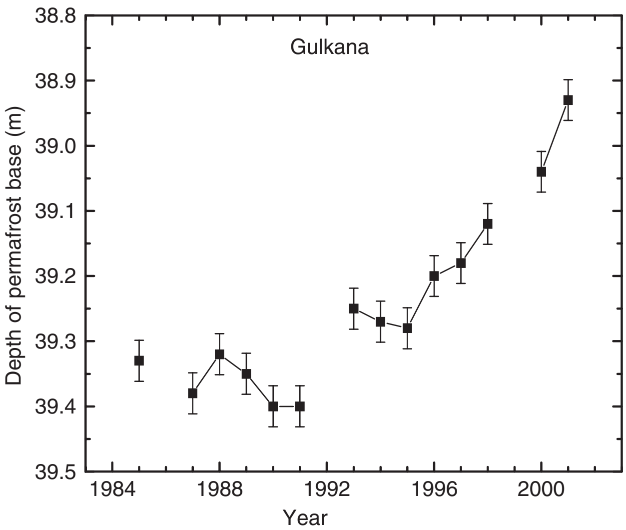

Figure 6. Depth of the permafrost base at Gulkana where the permafrost is thawing at a mean rate of about 0.04 m per year.

(particularly subsistence hunting, fishing and gathering), infrastructure, and the fluxes of energy, moisture and gases across the ground surface-air interface (Osterkamp et al., 1997). These results and other observations in Alaska (Jorgenson et al., 2000; Osterkamp et al., 2000) indicate that thawing of discontinuous permafrost is becoming widespread and extensive areas of thermokarst terrain are being created as a result of climatic change.

5.3 *Basal thawing*

Warming at the surface of the permafrost eventually penetrates to the base of the permafrost. Thawing at the base of the ice-bearing permafrost then begins, accelerates and, if the new surface temperature remains stable, eventually slows approaching an asymptotic value (Osterkamp, 1983). The warming described above should be causing basal thawing of thin discontinuous permafrost. Figure 6 shows the depth of the 0°C isotherm at the GU site. There was little change in its position until about 1992 when it began to move upward. This movement implies thawing at the base of the ice-bearing permafrost. The mean thawing rate is about 0.04 m per year. Such a large thawing rate suggests a larger than normal heat flow and/or a small latent heat, perhaps as a result of unfrozen water near the base of the ice-bearing permafrost.

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