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Evidence for Warming and Thawing of Discontinuous Permafrost in Alaska

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ABSTRACT

Data show that permafrost temperatures along a north–south transect of Alaska from Old Man to Gulkana and at Healy generally warmed in the late 1980s to 1996. This trend was not followed at Eagle, about 330 km east of the transect. Estimates of the magnitude of the warming at the permafrost table ranged from 0.5 °C to 1.5 °C. Warming rates near the permafrost table were about 0.05 to 0.2 °C a^{-1}. No reliable trends in the depth of the base of ice-bearing permafrost or in the depth of the 0 °C isotherm could be detected. Thermal offset allowed mean annual temperatures at the permafrost table to remain below 0 °C with ground surface temperatures up to 2.5 °C for a period of 8 years. The observed warming has probably caused discontinuous permafrost in marginal areas to begin thawing. Thawing permafrost and thermokarst have been observed at several sites. Thawing rates at the permafrost table at two sites were about 0.1 m a^{-1}, indicating time scales of the order of a century to thaw the top 10 metres of ice-rich permafrost. Calculated thawing rates at the permafrost base are an order of magnitude smaller. Calibrated numerical models indicate that the permafrost warmed in the late 1960s and early 1970s in response to changes in air temperatures and snow covers. Additional warming in the late 1970s was caused by an increase in air temperatures beginning in 1977. Permafrost temperatures were nearly stable during the 1980s and then warmed again from the late 1980s to 1996, primarily in response to increased snow depths. This interpretation appears to be valid for all the sites in the region of the transect and at Healy. Copyright © 1999 John Wiley & Sons, Ltd.

RÉSUMÉ

Des données montrent que les températures du pergélisol selon un transect Nord–Sud au travers de l'Alaska de Old Man jusqu'à Gulkana et à Healy se sont généralement élevées depuis la fin des années 80 jusqu'à 1996. Cette tendance ne se retrouve pas à Eagle, environ 330 km à l'Est du transect. Des estimations de l'amplitude du réchauffement au niveau de la table du pergélisol varient de 0.5 °C à 1.5 °C. Les vitesses du réchauffement près de la table du pergélisol ont été d'environ 0.05 à 0.2 °C par an. Aucune tendance certaine à la base du pergélisol riche en glace ou à la profondeur de l'isotherme de 0 °C n'a pu être détectée. La compensation thermique a permis de maintenir la table du pergélisol sous 0 °C bien que les températures de surface aient été supérieures à 2.5 °C pendant une période de 8 ans. Le réchauffement observé a probablement causé un début de fonte dans des régions marginales du pergélisol discontinu. Le dégel du

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pergélisol ainsi que des phénomèes thermokarstiques ont été observés dans plusieurs sites. Les vitesses de dégel à la table du pergélisol en deux sites ont été de l'ordre d'environ 0.1 m par an, indiquant une échelle de temps de l'ordre de un siècle pour dégeler les 10 m sommitaux de pergélisol riche en glace. Les vitesses de dégel calculées pour la base du pergélisol sont un ordre de grandeur plus petit. Des modèles numériques calibrés indiquent que le pergélisol s'est réchauffé dans les dernières années 60 et au début des années 70 en réponse aux changements des températures de l'air et ceux de la couverture de neige. Un réchauffement supplémentaire à la fin des années 70 a été causé par une augmentation de la température de l'air qui a débuté en 1977. Les températures du pergélisol ont été presque stables pendant les années 1980 et se sont réchauffées de nouveau depuis la fin des années 1980 jusqu'à 1996, principalement à la suite d'une augmentation de l'épaisseur de neige. Cette interprétation paraît valable pour tous les sites dans la région du transect et à Healy. Copyright © 1999 John Wiley & Sons, Ltd.

KEY WORDS: permafrost; active layer; climatic change; thermokarst; thermal offset; modelling

INTRODUCTION

Permafrost is a product of cold climates. Its occurrence and thickness increase during colder climatic periods and decrease during warmer periods. Discontinuous permafrost is relatively warm with mean annual surface temperatures (MAST) typically warmer than −5 °C. In Alaska, south of the Yukon River and on the south side of the Seward Peninsula (Figure 1), MAST of the discontinuous permafrost are typically warmer than −2 °C. Therefore, the discontinuous permafrost is likely to thaw in response to climatic warming and its occurrence and distribution are especially sensitive to climatic changes. For time scales of a decade or less, the climatic changes that are of primary importance are changes in air temperatures and snow cover.

Global air temperatures have increased since the late 1800s and increases in the Arctic have been larger than in the temperate latitudes (Hansen and Lebedev, 1987). Recorded air temperatures in Alaska show a general warming trend from the late 1800s until about 1940 (Hamilton, 1965) with a general cooling after 1940 to the mid 1970s. An air temperature shift to a warmer regime began with the winter of 1976–77 (Hoffman and Osterkamp, 1986; Bowling, 1990, Osterkamp and Lachenbruch, 1990) and most Alaskan weather stations (including Anchorage, Barrow, Bethel, Bettles, Gulkana, Kaktovik, McKinley, Nome, Northway and Valdez) have reported warmer air temperatures since then. MAAT for the last two decades were typically about 1 °C warmer than the previous two to three decades. Figure 2 shows the pattern for Fairbanks where mean annual air temperatures (MAAT) for the 20 year period after 1976 increased 1.5 °C over the prior 20 year period. The increases at Bettles and Gulkana (Figure 3) were 1.4 °C and 1.3 °C, respectively. Such large increases in MAAT should have led to an increase in permafrost temperatures. However, other factors, especially depth, timing and duration of the annual snow cover, can also have a major impact on permafrost temperatures (Zhang *et al.*, 1996). Near Fairbanks, the period from 1978 through 1988, except for 1985, had less than average maximum snow depths on the ground (Figure 2), which may have reduced the impact of warmer air temperatures on the permafrost during that time. The period from 1989 to 1997 was one of thicker than normal snow covers and relatively warm temperatures. This last period is the primary focus of the paper.

There is considerable scientific concern about the future of permafrost. Changes in climate over the past century have caused permafrost to warm in major portions of the Arctic and sub-Arctic (Lachenbruch and Marshall, 1986; Burn, 1992; Pavlov, 1994; Wang and French, 1994; Osterkamp, 1994). Thawing permafrost has been observed in Alaska (Osterkamp, 1994; 1995; Osterkamp and Romanovsky, 1996a; 1996b; Osterkamp *et al.*, 1997a; 1997b) and the southern boundary of permafrost has moved northward in Canada (Kwong and Gan, 1994). Current global circulation models predict that air temperatures in the Arctic will rise 2 to 5 °C in the next half century (Maxwell, 1992). A climatic scenario for the Bering Sea region (Weller *et al.*, 1995) predicts about 5 °C warming with the winter warming larger than the summer warming and with more precipitation in both the summer and winter. Given the above conditions and the predictions of current models of climate, it is important to determine the current

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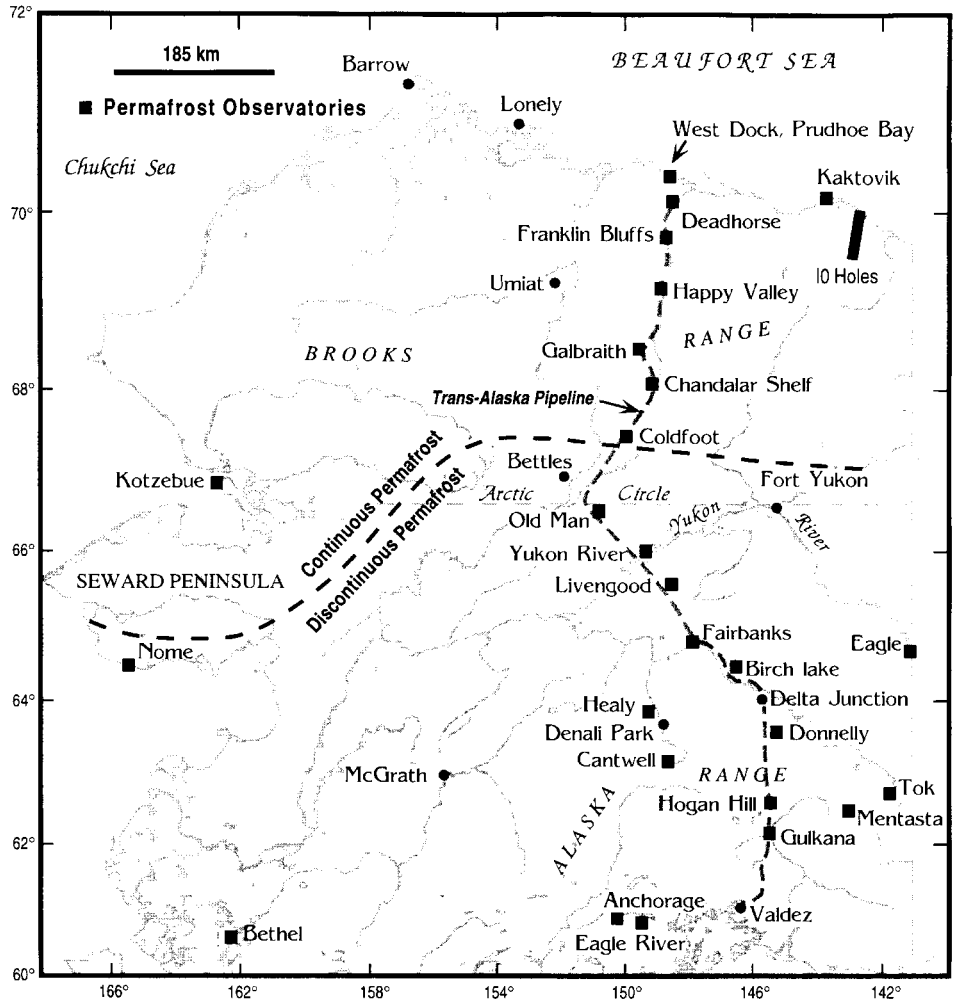

Figure 1 Continuous and discontinuous permafrost zones in Alaska and locations of the permafrost observatories.

thermal regime of discontinuous permafrost and to assess the effects of recent climatic variations on permafrost.

This paper presents evidence for warming and thawing of permafrost over the last several decades in the discontinuous zone in Alaska and explores the effects of changes in air temperatures and snow cover on the permafrost temperatures.

REVIEW

Changes in climate may be expected to produce changes in the energy balance at the ground (active layer) surface and at the permafrost table, causing the permafrost to become warmer or cooler. However, permafrost is usually buffered from the effects of climate by trees and shrubs, a seasonal snow cover, and an active layer which often consists of surface vegetation (especially moss) and organic soil overlying mineral soil. Changes in climatic variables (air temperature, snowfall, precipitation, and wind), vegetation and surface morphology produce changes in the energy balance and ground surface temperature that are complex and difficult to predict. Mean annual ground surface temperatures are often warmer than those a few decimetres in the ground because of the effects of thermal offset (Kudryavtsev *et al.*, 1974; Burn and Smith, 1988; Romanovsky and Osterkamp, 1995).

The US Geological Survey has measured temperatures in deep drill holes in permafrost in northern Alaska since the late 1940s. Their results (Lachenbruch *et al.*, 1982; 1988; Lachenbruch and

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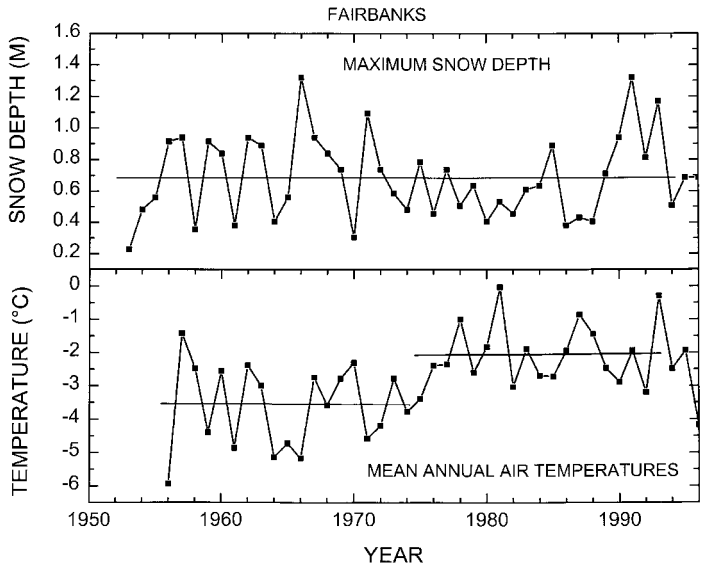

Figure 2 Mean annual air temperatures and maximum snow depths at Fairbanks, Alaska. The horizontal lines for the air temperatures are 20 year averages and the line for the snow cover is the average for the period.

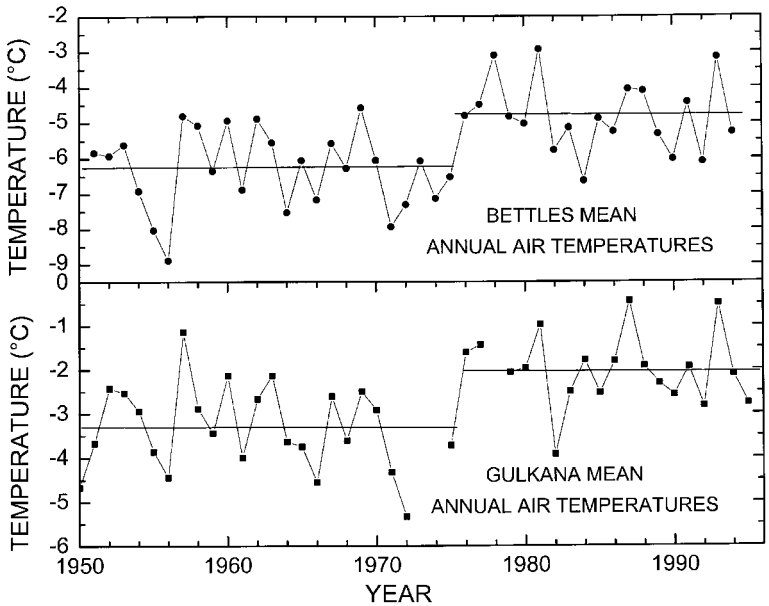

Figure 3 Mean annual air temperatures at Bettles and Gulkana, Alaska. The horizontal lines are averages for the period.

Marshall, 1986) show that the permafrost in this region has generally warmed. The magnitude of the warming is 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. It was also suggested that warming of air temperatures in the late 1800s and early 1900s in North America preceded warming of the permafrost. However, Zhang and Osterkamp (1993) showed that, at Barrow, air temperature variations alone (since 1923) could not account for the observed warming of the permafrost, thus implicating changes in the snow cover or perhaps an earlier warming.

Since air temperatures at stations throughout Alaska are highly correlated (Hamilton, 1965;

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Hansen and Lebedev, 1987; Zhang and Osterkamp, 1993), air temperatures in the interior of Alaska are also likely to have warmed coincident with the warming of the late 1800s and early 1900s in North America. If this is true, then most of the discontinuous permafrost in Alaska should be thawing from the bottom at present and the southern reaches of discontinuous permafrost should have moved northward in Alaska during the last century.

Permafrost is extremely sensitive to changes in its surface energy balance, where very small changes can produce large and easily measured changes in permafrost temperatures. If the thermal properties and the permafrost temperature changes are known, then the permafrost can be used as a 'calorimeter' to determine the change in energy balance at its surface over long periods. Lachenbruch and Marshall (1986) have shown that the 2 to 4 °C warming of the last century was produced by a change in the energy flux at the permafrost table of a few tenths of a watt per square metre. Osterkamp *et al.* (1994) have shown that a more recent warming of the same magnitude near Prudhoe Bay was produced by a change of 0.6 to 0.7 W m^{-2} over one decade. Direct measurements of such small changes in surface energy balance over long periods are not possible. These considerations indicate that temperature measurements in permafrost are an extremely sensitive method for detecting systematic changes in its surface heat balance and surface temperature over annual to century time scales.

In the late 1970s, a programme for measuring the thermal regime of undisturbed permafrost in Alaska was initiated to determine the effects of climate and environmental conditions on permafrost (Osterkamp *et al.*, 1987). Holes were drilled along a north–south transect of Alaska and in other areas of the state. A programme for measuring temperatures and other quantities was initiated at these permafrost observatories beginning in 1977, and this paper is based on these measurements.

METHODS

According to Brown and Péwé (1973), the northern boundary of the discontinuous permafrost zone in the interior of Alaska lies south of Coldfoot and, in the western portion of the state, on the Seward Peninsula. Figure 1 shows the continuous and discontinuous permafrost zones and the locations of the permafrost observatories.

Access holes, typically 60 m in depth (range 30–90 m), were drilled and instrumented for measuring permafrost temperatures annually at all the sites. Shallow holes, up to 6 m in depth, were drilled for seasonal measurements at some of the sites. At four sites in the discontinuous zone, temperatures have been recorded daily since 1986 at 11 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 automatic temperature logger attached to thermistor sensors in a plastic rod installed in the ground (Romanovsky and Osterkamp, 1995). A few sites have supplementary information such as soil samples, vertical moisture (water and ice) profiles, soil thermal conductivities, active layer thicknesses, extent of taliks and thawed layers and water table levels.

The permafrost observatories were placed in undisturbed permafrost except for four sites in an agricultural field underlain by permafrost and one in an area without permafrost. The sites were placed in flat terrain far from water bodies where the surface vegetation was relatively uniform. There was a tendency to select the coldest-appearing site in an area to ensure that permafrost would be encountered during drilling.

Drilling methods included rotary air and mud drilling, augering, coring and water jetting (Osterkamp and Harrison, 1982). A 2 cm (0.75 in) diameter galvanized iron water pipe filled with non-freezing fluid was placed in the holes which were backfilled with the cuttings and sand. Additional information is provided in Table 1.

The annual temperatures profiles were measured with a thermistor sensor on the end of a cable that was lowered into the pipe to discrete levels using the procedures and equipment described by Osterkamp (1985). Accuracy of these measurements is typically between 0.005 and 0.01 °C. Spacing between measurements was normally 1 metre although other spacings were used (0.1 m, 0.5m, and 2 m). Precision of the depth measurements was estimated from repeated measurements of the total depths of the drill holes and was typically better than 3 cm.

Warming at the permafrost surface was inferred from time series of temperature profiles in the permafrost below the depth of seasonal variations where the profiles showed increased curvature toward warmer temperatures. Temperature profiles without any curvature below the depth of seasonal variations are not necessarily equilibrium profiles. After a change in the surface temperature of

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Table 1 Drilling and site information.

Site	Location	Dates	Method	Depth (m)	Description
Old Man	0.3 km N of airport access road	6 May 1983	Rotary, air	63	Tundra, grass, patterned ground
Yukon River	0.3 km N of river and E of bridge	5–7 May 1985	Rotary, air	61	Tussocks, shrubs, black spruce
College	UAF, College Peat site	11–14 April 1983	Rotary, air	69	Tussocks, shrubs, black spruce
Birch Lake	0.7 km N of highway, 1.0 km E of lake	1–2 May 1985	Rotary, air	62	Dense black spruce
Bonanza Creek	Bonanza Creek LTER site	13–15 March 1994	Air, reverse circulation	45	Tussocks, shrubs, black spruce
Gulkana	0.3 km N, 0.7 km W of airport	2–3 Feb. 1983	Rotary, mud	89	Tussocks, shrubs, black spruce
Healy	0.5 km S, 0.2 km W of Eight Mile Lake	24–25 April 1985	Rotary, air	28	Tundra, grass
Donnelly	0.3 km S, 0.4 km E of radar access road	30 April 1985	Rotary, mud	63	Low, high shrubs, bare gravel
Eagle	0.8 km off W end of airport runway	3 May 1985	Rotary, air	63	Tussocks, shrubs, black spruce

permafrost to a new constant value, a formerly linear profile will eventually become linear again but will not be an equilibrium profile since the permafrost will be freezing or thawing at its base. For sudden changes in the MAST of the permafrost, the time constant for this to happen is about $X^2/4D$, where X is the thickness of the permafrost and D is the thermal diffusivity (Lachenbruch *et al.*, 1982). In discontinuous permafrost that does not contain unfrozen water, this time constant is typically a few decades or less (Osterkamp, 1983). When unfrozen water is present, D becomes smaller and the time constant increases. With these considerations, linear profiles can be used to imply that no changes have occurred in the recent past. MAST of the permafrost prior to warming were obtained by extrapolating linear temperature profiles at depth (where these exist) to the surface. Because of small thermal gradients, these MAST are about the same as the mean annual temperatures in the lower portion of the active layer prior to warming. As a result, the warming reported below for the permafrost surface could be considered to be about the same as the warming in the lower portions of the active layer.

The upper part of the temperature profiles is influenced by seasonal temperature variations and is less ideal for analysis of interannual to decadal time scale permafrost temperature dynamics. However, the depths of penetration of seasonal variations in the discontinuous permafrost zone are smaller than for cold permafrost where the seasonal thermal signal can penetrate to depths of 20 to 25 metres (Osterkamp *et al.*, 1994; Osterkamp and Romanovsky, 1996a). The depth of seasonal temperature variations generally decreases with increased MAST and is limited by the depth of the active layer when the MAST approaches 0 °C (Kudryavtsev *et al.*, 1974, p. 147). Measurements and modelling at Bonanza Creek where the MAST ≈ -0.6 °C show that it is less than 4 m, and at a site adjacent to the Geophysical Institute where MAST is slightly less than 0 °C it is less than 1 m or about the depth of the active layer (Figure 4). For the sites discussed in this paper, this depth was usually less than 10 m. Hence, in the following, annually measured temperature changes at depths of 20 m or more will be reported.

A temperature profile can be used to determine the depth of permafrost (0 °C) by linear extrapolation between two points and the position of the base of the ice-bearing permafrost (IBP). The latter is indicated by a change in the gradient of the temperature profile between IBP and the underlying non-IBP. Changes in lithology near the base of IBP complicate the latter procedure since these introduce corresponding changes in the gradients. However, a more serious problem is the presence of unfrozen water that is common near the base of the IBP where temperatures are very close to the phase equilibrium temperature. This unfrozen water introduces a curvature in the temperature profile

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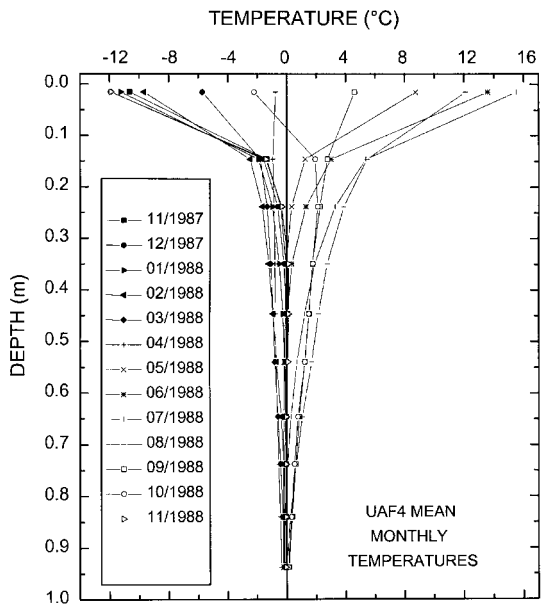

Figure 4 Measured mean monthly temperatures in the active layer at the UAF4 site adjacent to the Geophysical Institute.

above the base of the IBP (Figure 5) that tends to mask the exact point where IBP begins.

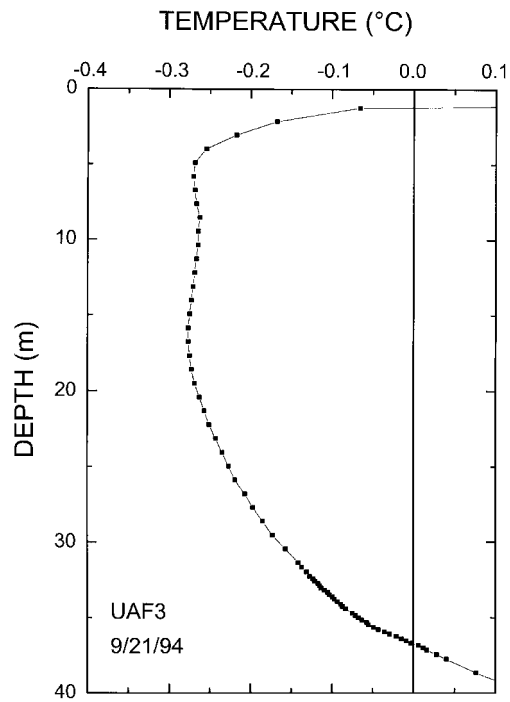

Figure 5 Temperature profile in permafrost at the UAF3 site showing the curvature above the base of the ice-bearing permafrost that is a result of the presence of unfrozen water in the permafrost.

RESULTS AND DISCUSSION

Permafrost Temperatures

Old Man. Selected temperature profiles and temperature–time series at selected depths are shown in Figures 6 and 7. From an extrapolation to the surface, the MAST in the decade beginning in 1983 was about −3.5 °C, significantly colder than Coldfoot (−2 °C) some 100 km farther north (Figure 1). Temperatures at depth have warmed slowly (e.g. 0.07 °C at 50 m since 1983). Temperatures at the permafrost surface cooled from 1983 until 1987, warmed slightly until 1991 and then warmed more rapidly through 1996. The increase in MAST at the 20 m depth between 1991 and 1996 was 0.33 °C. Temperatures above 15 m were cooler in 1996 than 1995. This was caused by a cold autumn in 1995 and an unusually thin snow cover prior to February 1996. Several sites show this effect.

Yukon River Bridge. MAST were near −3 °C from 1985 to 1993. Temperatures at depth generally cooled over the period from 1985 to 1996 (Figure 7). This is the only site where there was a distinct cooling at depth (30 to 50 m). Temperatures at the permafrost surface cooled until 1987, warmed until 1989 and then cooled until 1992. There was a rapid warming beginning in 1993 to 1996 of 0.37 °C at 20 m. The cooling effect of the latter part of 1995 and early 1996 can be seen above 18 m (Figure 6).

College. Figures 8 and 9 show that temperatures below the depth of seasonal variations (about 15 m) were nearly constant from 1983 to 1990 with MAST near −3.5 °C, similar to Old Man about 225 km north-west of College. This is the coldest site south of the Yukon River. At the 50 m depth, temperatures were nearly constant for the period of observation. MAST warmed rapidly from 1990 to 1995 (about 0.45 °C at the 20 m depth) and then cooled about 0.03 °C owing to the cooling effects of 1995 and 1996 noted above. This warming has now penetrated to the 50 m depth.

Birch Lake. Temperatures at depth warmed slowly throughout the period of observation. MAST were nearly constant at about −2.5 °C

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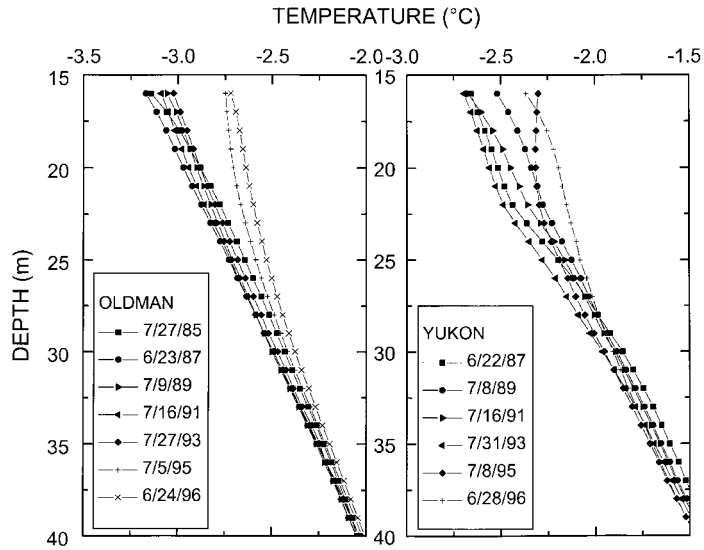

Figure 6 Selected temperature profiles at the Old Man and Yukon River bridge sites.

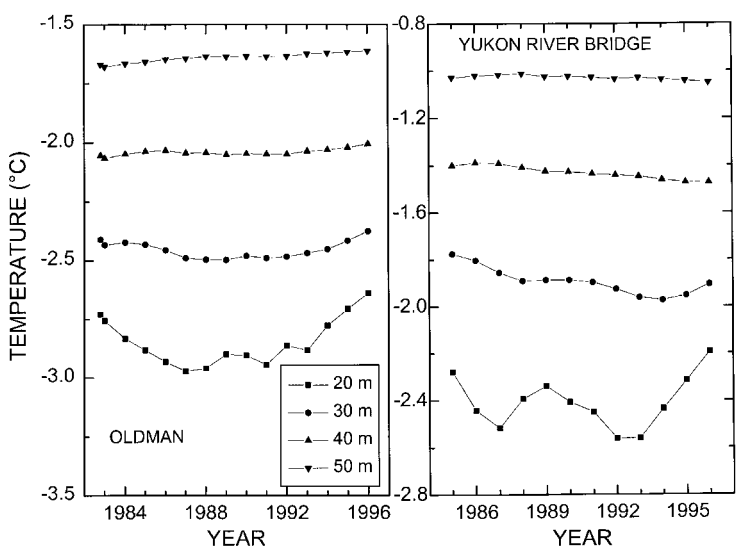

Figure 7 Temperature–time series for selected depths at the Old Man and Yukon River bridge sites.

from 1986 to 1990 when a rapid warming began (Figures 8 and 9). At the 20 m depth, the warming was 0.38 °C from 1990 to 1996 and it has penetrated to the 50 m depth. The cooling effects noted above for the latter part of 1995 and early 1996 can be seen above the 17 m depth (Figure 8).

Bonanza Creek. Figure 10 shows the three temperature profiles available for the Bonanza Creek site. Some depths still show a slight thermal disturbance, possibly due to a water blowout from the 51 m depth during drilling. The MAST prior to warming was estimated to be about −2.5 °C but the error in this estimate is larger than at other sites. The current (1996) MAST ≈ − 0.5 °C. Temperatures warmed about 0.14 °C at the 20 m depth from 1994 to 1996. The temperature profiles also show strong curvatures toward warmer temperatures, indicating that a warming which has penetrated to the 45 m depth occurred at the site prior to the time of drilling. Cooling associated with the latter part of 1995 and early 1996 cannot be seen in the temperature profiles because of the small penetration depth (less than 4 m) of the seasonal

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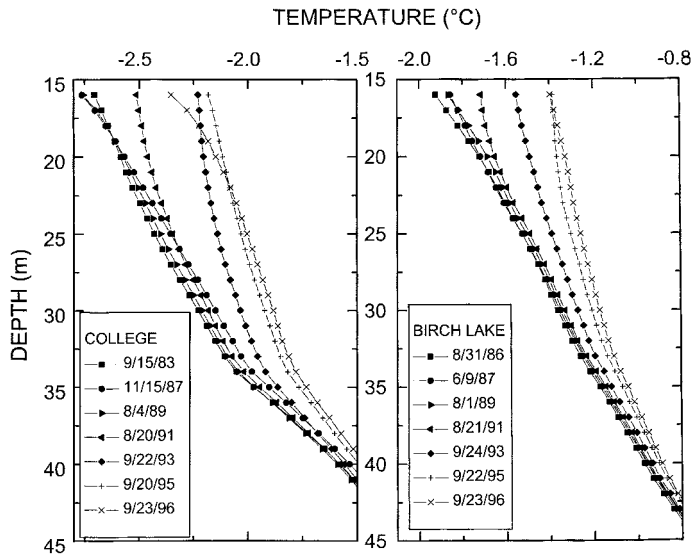

Figure 8 Selected temperature profiles at the College and Birch Lake sites.

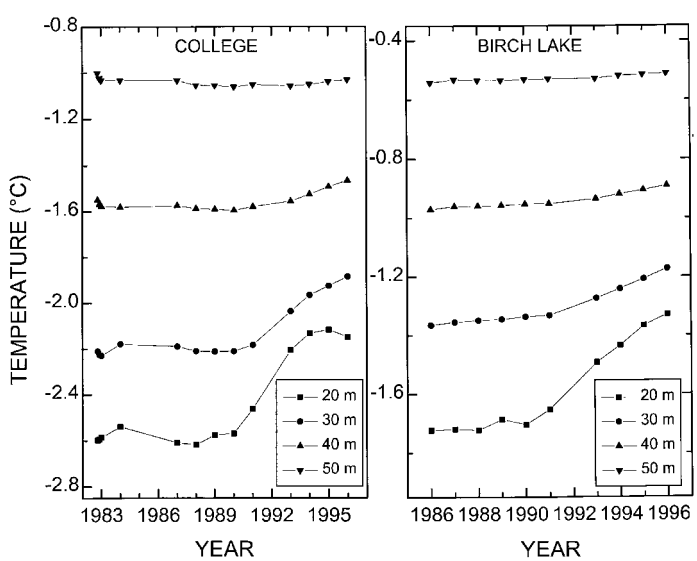

Figure 9 Temperature–time series for selected depths at the College and Birch Lake sites.

variations. A numerical model was calibrated for this site and the results of applying this model will be discussed below.

Gulkana. The 1983 and 1984 temperatures show a cooling in response to the thermal disturbance of drilling with water and mud. Temperatures at all depths (Figures 11 and 12) warmed slowly from 1984 (MAST $\approx -1.2\,^{\circ}$C) to 1989 and then more rapidly to 1996. The total warming at the 20 m depth was 0.19 °C from 1984 to 1996 with about 0.16 °C occurring from 1989 to 1996. There is no evidence for the cooling associated with 1995 and 1996 that was observed in holes farther north, possibly because of the small penetration depth of seasonal variations (less than 6 m). At the 29 m depth, there is a change in thermal gradient associated with a change in lithology from clay above to sand and gravel below (Figure 11). Continuous warming at depth (30 m, Figure 12) indicates that this site was already undergoing an earlier warming when the hole was drilled but this

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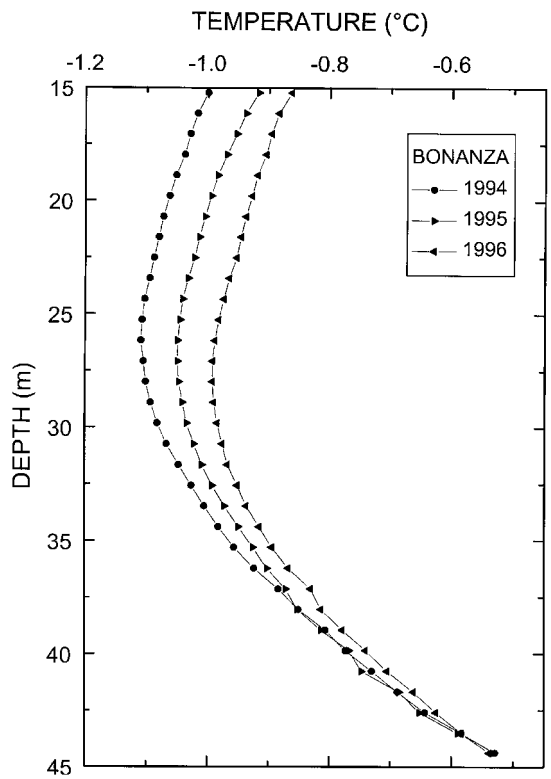

Figure 10 Three consecutive annual temperature profiles at the Bonanza Creek site.

change in lithology precludes estimating the MAST prior to the earlier warming. The warming that occurred since observations began has penetrated to the base of the IBP at 37.28 m. Thus, thawing at the base of the IBP must be increasing at present.

Healy. The first (1985) and second (1989) temperature profiles (Figure 11) were nearly identical at the bottom of the hole (29 m) indicating little change over this period with MAST near −1.3 °C. Since 1989, the profiles show a continuous and rapid warming to 1996 (about 0.33 °C at the 20 m depth, Figure 12). The cooling effect of the latter part of 1995 and early 1996 can only be seen above the 10 m depth. Thermokarst has developed around the hole and in much of this area where there are no apparent surface disturbances due to human activities.

Donnelly. There is no permafrost at the Donnelly site. The vegetation is sparse and this site often has areas of bare ground in the winter because of wind. Temperatures profiles measured from 1985 through 1989 (Figure 13) are similar and indicate the presence of flowing water in the formation (Osterkamp and Gosink, 1984). The temperature profile measured in 1995 shows that the site has warmed significantly since 1989 (about 0.28 °C at the 20 m

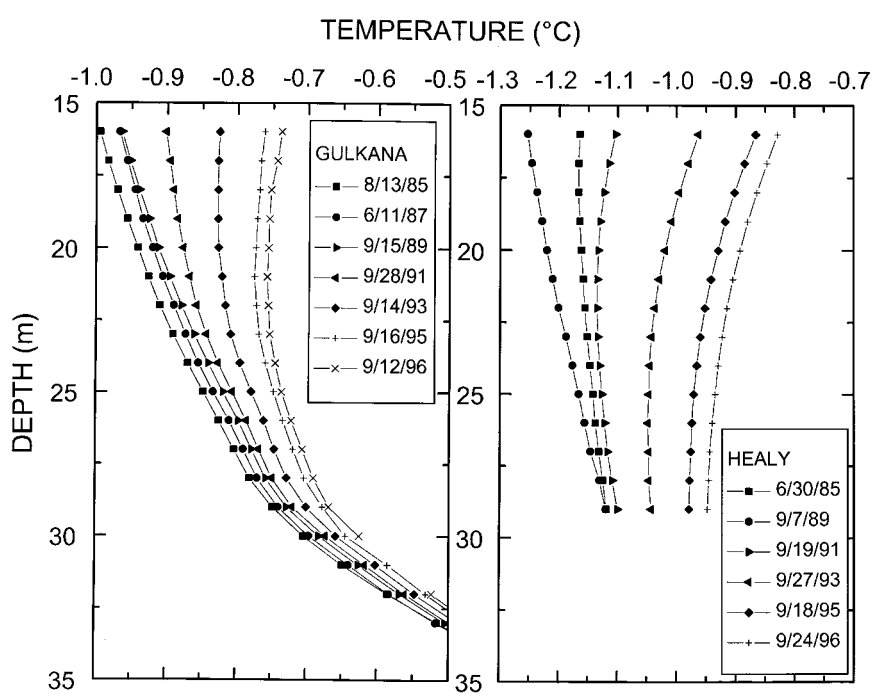

Figure 11 Selected temperature profiles at the Gulkana and Healy sites.

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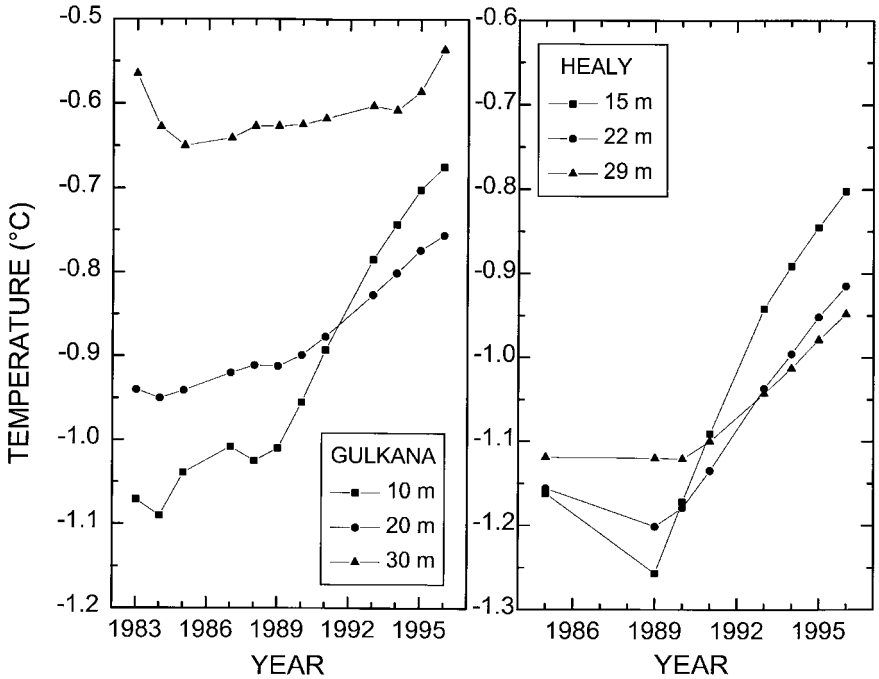

Figure 12 Temperature–time series for selected depths at the Gulkana and Healy sites.

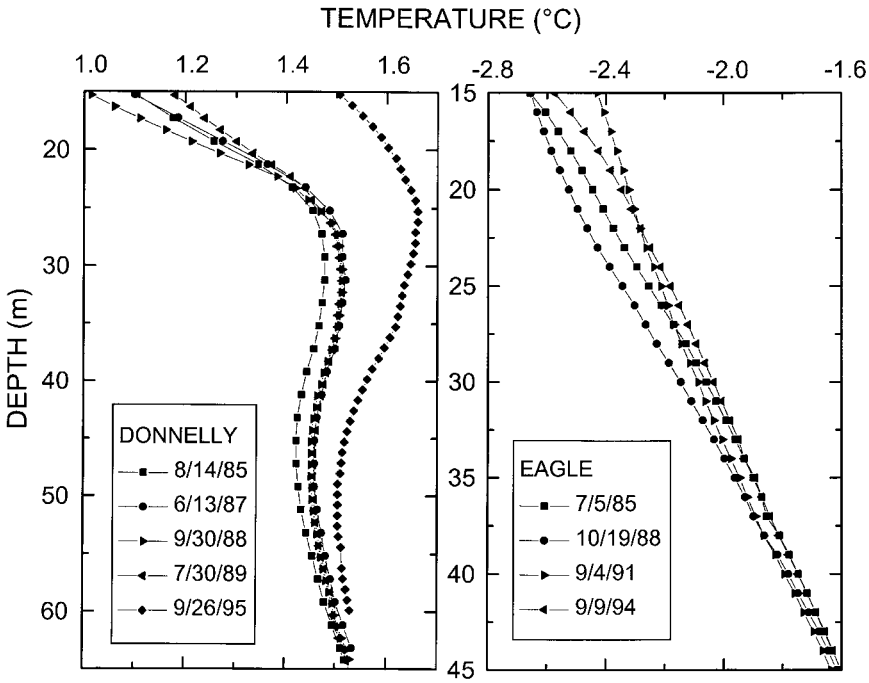

Figure 13 Temperature profiles at the Donnelly and Eagle sites.

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depth) and this warming has penetrated deeper than the depth of the hole.

Eagle. Figure 13 presents the four temperature profiles available for this site, which show that temperatures at depth were nearly constant for the decade from 1985 to 1994. While the 1991 profile shows a warming, the 1994 profile indicates a cooling. The profiles were nearly linear at depth indicating relatively constant surface temperatures (MAST $\approx -3.1\,^{\circ}$C) immediately prior to the time of drilling. There is no evidence in these profiles for the recent warming observed in the transect 330 km to the west.

Kotzebue, Nome and Bethel. Holes were drilled near Kotzebue (1982), Nome (1985) and Bethel (1988) but these holes have not been measured regularly. At Kotzebue (30 m hole, Figure 14) in the continuous permafrost zone (Figure 1), the MAST $\approx -4.5\,^{\circ}$C. The site cooled about 0.19 °C at the 20 m depth from 1983 to 1986, a trend consistent with permafrost temperatures at Prudhoe Bay (Osterkamp *et al.*, 1994). At Nome (63 m hole, Figure 14), the MAST $\approx -1.4\,^{\circ}$C in 1985 and 1986 and the profiles were linear with no curvature below the depth of seasonal variations

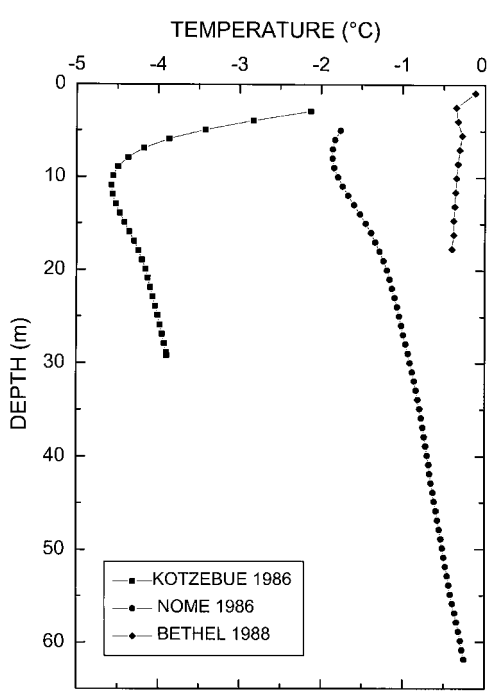

Figure 14 Selected temperature profiles at the Kotzebue, Nome and Bethel sites.

indicating no recent changes in MAST prior to drilling. At Bethel (18 m hole, Figure 14), all temperatures were warmer than $-0.4\,^{\circ}$C with a MAST $\approx -0.3\,^{\circ}$C in 1988. Curvature in the profile indicated a warming at the site prior to the time the hole was drilled.

Other sites. Since 1977, additional sites were established in discontinuous permafrost where temperatures and other data have been obtained. Warming of the permafrost temperatures was also observed at these sites, however; the presence of unfrozen water, nearby surface disturbances, and other factors make it difficult to draw unambiguous conclusions from the data regarding the source of the warming.

Timing, magnitude and rate of warming. The above data show that permafrost temperatures in boreholes along a transect from Old Man near the Arctic Circle to Gulkana and at Healy (160 km west of the transect) generally warmed in the late 1980s and 1990s. This trend was not followed at Eagle, about 330 km east of the transect. Ground temperatures also warmed at Donnelly where there is no permafrost.

Permafrost temperature profiles were measured once per year at about the same time each year. However, seasonal variations and the near-surface curvature in the warming temperatures profiles make it difficult to obtain an accurate estimate of the magnitude of the warming at the permafrost table. Our estimate for the magnitude of the warming at the permafrost table is 0.5 °C to 1.5 °C with typical values of 1 to 1.5 °C. This yields estimated warming rates near the permafrost table of about 0.05 to 0.2 °C a^{-1}.

Thickness and Basal Thawing

Lack of data on snow cover in the discontinuous permafrost of Alaska during the first half of the century makes any analysis of permafrost temperatures difficult. However, highly correlated air temperatures in permafrost areas of Alaska and warming of continuous permafrost temperatures in northern Alaska during the last century suggest that permafrost temperatures throughout Alaska may have warmed during the last century. Penetration depth of the warming depends on the thermal properties of the permafrost and typically exceeds 100 m in Arctic Alaska (Lachenbruch and Marshall, 1986). In discontinuous permafrost

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Table 2 Thermal data for sites penetrating permafrost and Birch Lake.

Site	Thawed gradient (°C km^{-1})	Frozen gradient (°C km^{-1})	Base of IBP (m)	Temperature at the base of IBP (°C)	Depth of the 0 °C isotherm (m)
Gulkana	72	76	37.28	−0.144	39.24
Birch Lake	–	40	–	–	63.0[1]
College	105	71	65.2	−0.11	66.14
UAF1	72	42	25.14	−0.106	26.53
UAF2	67	31	38.00	−0.105	39.61
UAF3	42	26	35.47	−0.06	36.74

[1] Obtained by extrapolation of the temperature profile downwards.

regions, permafrost thicknesses are commonly much less than 100 m so that the century-long warming should have penetrated to the base of the permafrost unless it contains significant amounts of unfrozen water, which would retard the thermal response. Consequently, basal thawing of the discontinuous permafrost should be occurring at present. Since linearity of the temperature profiles through the permafrost cannot be used to determine whether or not the permafrost is in equilibrium with present climate, attempts were made to measure the position of the base of the IBP and the 0 °C isotherm to determine if the permafrost was thawing at the base in response to climate change.

The temperature accuracy requirements for this procedure are severe. The error in position Δx for an error in temperature ΔT is

$$\Delta x = \Delta T / G \tag{1}$$

where G is the geothermal gradient. With $G = 0.04\,°\mathrm{C\ m^{-1}}$ and $\Delta T = 0.005\,°\mathrm{C}$, $\Delta x = 0.125$ m. For the gradients found in this study, calculations using (1) showed that Δx ranged from 0.05 to 0.19 m. Thawing at the base of the ice-bearing permafrost should be small, less than a centimetre per year (Osterkamp, 1983), since for present conditions some of the geothermal heat is conducted through the phase boundary into the IBP. The longest time series available for a hole penetrating permafrost is 18 years, so all of the results are still within the uncertainties of the measurements. No reliable trends in the position of the base of the IBP or the positions of the 0 °C isotherm could be detected. Since the warming of the last decade has now penetrated to the base of the IBP at the Gulkana site, basal thawing has just begun or this thawing is accelerating (because of the century-long warming). It appears that the temperature accuracy needs to be about 0.001 °C or better to detect thawing at the base of the IBP in a reasonable time. The results shown in Table 2 are the most precise determinations and are the average of the 1993 to 1996 temperature profiles measured with the same equipment for three holes (Table 1) and three other holes drilled on the University of Alaska campus (UAF1,2,3). Birch Lake was included in this group since the downward extrapolation to the 0 °C isotherm was only 2 m. However, this extrapolation may not be reliable because of freezing-point depression at the base of the IBP.

The standard deviations for these depth determinations range from 0.03 to 0.06 m for the four temperature profiles (1993 to 1996) except for Birch Lake. However, the position of the base of the IBP depends on the judgement of the person making the determination, so the systematic error could be greater.

In 1979, the UAF1 hole was heated through the depth of the permafrost in an attempt to determine the thickness of the IBP. The principle of this method is that ice in the formation constrains the temperature rise at the phase change temperature until the ice melts completely, compared with levels without ice where the temperatures continually increase as heat is added to the formation. This effect produces a smaller change in temperatures in the IBP compared with the change in the underlying unfrozen material (Figure 15) and indicates a depth of about 25.4 m for the IBP compared with 25.14 m found from consideration of the gradients (Table 2).

Effects of Thermal Offset in the Active Layer

Continuous daily time series of temperatures were obtained with automatic data loggers in the air and at closely spaced intervals in the active layer and

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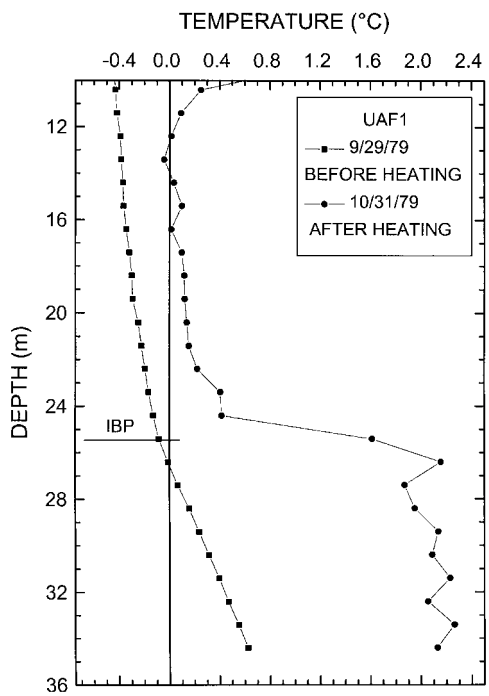

Figure 15 Two temperature profiles at the UAF1 site measured before and after heating the borehole to determine the depth of ice-bearing permafrost. In the later profile, temperatures in the ice-bearing permafrost are constrained by the latent heat while those below it are not.

permafrost down to the 1 m depth at four of the permafrost observatories using methods described previously (Osterkamp *et al.*, 1987; Romanovsky and Osterkamp, 1995). These measurements are useful for calculating mean annual temperatures in the air, in the active layer and near the permafrost table; for investigating heat and mass flow in the active layer; for calibrating numerical models which can be used to extend the time series into the past if nearby meteorological data are available; and to predict future active layer and permafrost conditions for hypothetical climate scenarios (Smith and Riseborough, 1996; 1998; Romanovsky and Osterkamp, 1996; 1997b; Osterkamp and Romanovsky, 1998).

The thermal offset

$$\Delta T = T_{ps} - T_{gs} \tag{2}$$

is the difference between the mean annual temperatures at the permafrost table T_{ps} and the ground surface T_{gs}. For a periodic steady state surface temperature and a homogeneous active layer with constant but different thermal properties in the thawed and frozen states, the thermal offset can be written (Kudryavtsev, 1981, p. 40; Romanovsky and Osterkamp, 1995)

$$\Delta T_k = I_t(K_t/K_f - 1)/P \quad \text{for } K_t I_t \leqslant K_f I_f \tag{3a}$$

$$\Delta T_k = I_f(1 - K_f/K_t)/P \quad \text{for } K_t I_t > K_f I_f \tag{3b}$$

where I_t and I_f are thawing and freezing indices at the ground surface, P is the period (1 year) and K_t and K_f are the thawed and frozen thermal conductivities of the active layer. Equations (3) show the explicit dependence of thermal offset on the ratio of the thawed to frozen thermal conductivities. Values of ΔT can be calculated from (2) and (3) (assuming that K_t and K_f are known) using the time series of temperature measurements. Reasonable agreement between values of ΔT obtained from the definition (2) and from the derived equation (3) and calculated with numerical models has been obtained in cold permafrost (Romanovsky and Osterkamp, 1995; 1997a; Osterkamp and Romanovsky, 1998). However, variations in the thermal properties of the active layer because of the presence of unfrozen water in the frozen active layer, variable water contents throughout the thaw season, and changing lithology with depth make application of (3) difficult in regions of warm permafrost.

Thermal offset enables the presence of equilibrium or aggrading permafrost at sites where mean annual ground surface temperatures are warmer than 0 °C (Burn and Smith, 1988). This is important in the context of climatic change because thermal offset allows permafrost to survive changes that produce positive ground surface temperatures. An illustration of this is shown by the mean annual temperature profiles in the active layer for the Hogan Hill site (Figure 16). Additional measurements show that for 8 years (1986–94), T_{gs} (0.03 m depth) remained above 0 °C, ranging from 0.9 to 2.5 °C. T_{gs} then became negative for late 1994 through late 1996. The depth of the permafrost table was typically about 1 m and the deepest ground temperature measurements were 0.88 m so that ΔT cannot be calculated. However, an extrapolation of the temperature profiles downward 0.1 to 0.2 m to the permafrost table would yield typical values of ΔT from 1 to 2 °C with a maximum of about 2.5 °C. Values for ΔT at Bonanza Creek (where permafrost survives with $T_{gs} > 0\,°C$), UAF4 and the University Farm (a cleared agricultural site) were typically about 1 °C.

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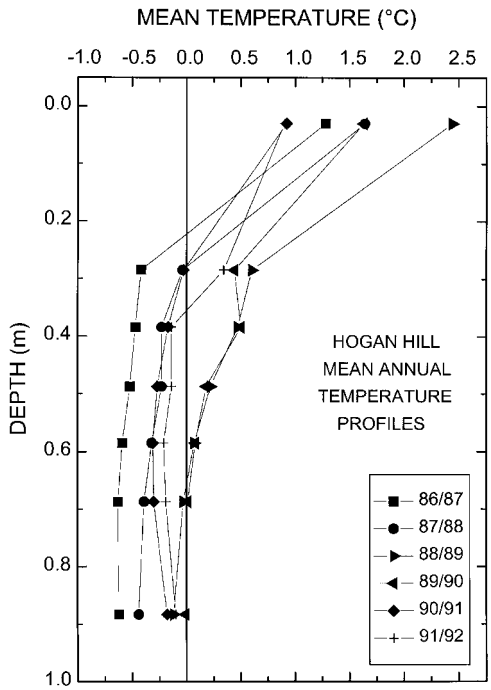

Figure 16 Mean annual temperature profiles in the active layer at Hogan Hill for 1986 to 1992.

Air Temperatures and Snow Cover

The cause of the above described warming of the permafrost is of considerable interest since it could potentially be interpreted as evidence for climatic warming. In the short term, two of the primary controls on permafrost temperatures are the air temperatures and the depth of the winter snow cover. An examination of Figure 2 shows that the MAAT at Fairbanks International Airport varied within 4 °C for the period from 1989 through 1995 with 1996 much colder than the average, but there is no evidence for a systematic increase in MAAT over this period when the permafrost was warming. Air temperatures for this period at Bettles, Gulkana, Eagle and at many stations throughout Alaska show a pattern similar to that at Fairbanks. It appears that the observed warming of the permafrost from 1989 to 1996 along the transect from Old Man to Glennallen and at Healy was not a result of changing air temperatures.

This result is not surprising in view of the thick snow accumulations during these years (Figure 2) and the strong impact of snow cover on permafrost temperatures. The timing, duration and accumulation dynamics (especially the maximum thickness) of the snow cover influence the permafrost temperatures in a non-linear way (Zhang *et al.*, 1996). These factors must be incorporated into a numerical model to determine their combined effect on permafrost temperatures.

Observed Thawing

Thawing has been observed at several sites. At the UAF1 site, the temperatures in the near-surface permafrost had similar values independent of the season, which indicated that the active layer was no longer refreezing to the permafrost each year and that a talik had formed. The presence of unfrozen water in the lower part of the active layer and upper permafrost could have produced a similar effect with distributed latent heat retarding cooling of partially frozen soil at that depth. However, probing showed that the permafrost table thawed down to the 2.4 m depth between 1979 and 1994 for an average rate of 0.1 m a^{-1}.

At the UAF4 site, mean annual temperatures at the 0.9 m depth were positive from 1990 through 1993 and probing to about 1.1 m did not reach the permafrost table during this period. Temperatures in the deeper permafrost did not show a seasonal dependence, also indicating the presence of a talik during this period.

The Healy site was established in 1985. At that time, there was no evidence of thermokarst in the area. By 1989, thermokarst had developed in undisturbed ground in the area of the drill hole (generally within a radius of 200 m). A survey in 1996 found that extensive thermokarst had developed in nearby undisturbed areas within 1 km of the site.

Evidence for thawing permafrost and observations of active thermokarst have also been made at Mentasta, Cantwell, in the Tanana River floodplain and at other areas in southern Alaska (Osterkamp, unpublished).

The UAF1 site has a MAST ≈ 0 °C (1995–96) and is located about 100 m from a permafrost boundary that exists near the bottom of a south-facing slope. Such areas are common in the discontinuous permafrost zone where permafrost is usually absent under south-facing slopes and present under north-facing slopes on valley floors where the surface is not disturbed. The warmest permafrost surface temperatures (warmer than -0.5 °C) are found near the boundaries between permafrost and unfrozen ground with the coldest temperatures occurring in low-lying areas of the

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valleys. Typical values for warming at the permafrost surface for the last 5 to 9 years exceed 1 °C as noted above. Consequently, it is likely that this warming has caused the permafrost in these marginal areas to begin thawing.

The majority of engineering and environmental problems are associated with the thawing of ice-rich permafrost in the top 10 m of the ground (Osterkamp, 1983; Osterkamp *et al.*, 1997). As a result, the time scales for thawing this layer of permafrost are of interest. The depth of thaw X at the UAF Farm site (cleared in 1940) reached 10 metres in 56 years. Thawing rates determined from temperature profiles (Figure 17) varied significantly over the last 20 years and accelerated beginning in 1989. For a step change in surface temperature, the thaw depth $X \approx b\sqrt{t}$, where b is a constant dependent on the thermal properties and surface temperature history and t is the time since thawing was initiated. This expression for X does not always hold in practice since thermal properties vary spatially and temporally, surface temperature varies with time, significant amounts of unfrozen water may be present in the permafrost (latent heat effects) and settling of the ground surface is not considered; however, it can give approximate values for estimating X. For this cleared site, $b \approx 1.3$ m a$^{-1/2}$. For the undisturbed and forested UAF1 site, $b \approx 0.7$m a$^{-1/2}$, indicating that time scales of the order of a century are required to thaw the top 10 metres of ice-rich permafrost.

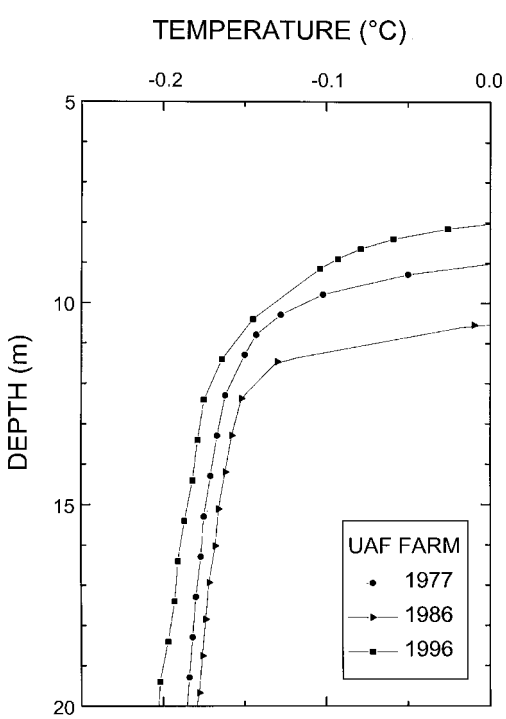

Figure 17 Temperature profiles at the UAF farm site showing the increased thawing rate since the late 1980s. The effects of unfrozen water (curvature in the upper portion of the profiles and retarded thermal response with time) are also shown.

For some environmental and engineering problems, it is necessary to estimate the time for thawing the full thickness of the permafrost. After an initial transient, the thawing rate at the base of discontinuous permafrost is approximately $q/L\phi$, where q is the geothermal heat flow and $L\phi$ is the volumetric latent heat of the permafrost (Osterkamp, 1983). This thawing rate is typically of the order of a centimetre per year, assuming that effects associated with variations in thermal properties, surface temperature, unfrozen water and surface subsidence are negligible. Comparison with the above data shows that thawing from the top of the permafrost is ten times faster than from the bottom. This was predicted by Romanovsky *et al.* (1992) and Lunardini (1996) while modelling the response of thin permafrost to climatic change. Clearly, permafrost will persist for a very long time after thawing begins at the surface, with time scales of centuries to millennia required to completely thaw even relatively thin discontinuous permafrost.

Numerical Modelling

Numerical modelling of the active layer and permafrost temperature regime at the Bonanza Creek LTER site near Fairbanks was used to improve our understanding of active layer and permafrost temperature dynamics and their relationships to climate change, and to investigate changes in active layer and permafrost conditions prior to the time that ground temperature data were available. The models used for these studies (Gosink and Osterkamp, 1990; Osterkamp and Gosink, 1991; Osterkamp and Romanovsky, 1996a; Romanovsky *et al.*, 1997) are based on the Goodrich (1976; 1978) and the Guymon–Hromadka (Guymon and Hromadka, 1977; Guymon *et al.*, 1984) models. Daily air temperatures and snow depth records from the Fairbanks International Airport meteorological station (Figure 2) were used for the upper boundary conditions. The lower boundary was placed at the approximate base of the permafrost at this site (54 m). A constant heat flux of 0.04 W/m^2 was used for the lower boundary condition. The models include the effects of latent heat and unfrozen water in the active layer and

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permafrost since it was found that the thermal response of the active layer and permafrost could not be successfully modelled without doing so. Time steps in these calculations were 15 minutes, while the space steps (200) were changed from 0.01 m within the upper 1 m of soils to 1 m at the lower boundary of the space domain (54 m). Site-specific calibration of the models was accomplished using annually measured temperature profiles (Figure 10) at this site and daily mean temperatures measured at the ground surface and at several depths in the first metre of soil. Drilling records were used to determine the lithology and the initial approximate thermal properties of the soils in the thawed and frozen states. The thermal properties (including unfrozen water content curves) were refined using a trial and error method (Osterkamp and Romanovsky, 1997). Final unfrozen water contents for the silts (Table 3) were similar to those of Tice *et al.* (1988).

A comparison between measured and calculated temperatures near the ground surface (0.02 m depth) using the calibrated model at the Bonanza Creek site is shown in Figure 18.

The calibrated models were used to calculate active layer and permafrost temperature dynamics for 1950–96 at the Bonanza Creek site (Figures 19 and 20) using meteorological data from the Fairbanks International Airport. The models predict that near-surface (0.12 m) active layer temperatures were above 0 °C in 1951, followed by 19 years of below 0 °C temperatures to 1971, and 16 years of temperatures varying about 0 °C. Since 1987, these temperatures have remained warmer than 0 °C with thermal offset ranging from 0.7 to 2.2 °C. The total ground surface warming was about 3 °C over 30 years for an average rate of 0.1 °C per year. 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. Near-surface permafrost temperatures followed a similar pattern. A warming trend began in the late 1960s and totalled about 2 °C over about 30 years for an average rate of

Table 3 Unfrozen water contents used in the numerical simulation.

Depth (m)	Soil	Volumetric unfrozen water
0–0.35	Moss (living and partially decomposed)	$W_u = 0.001\,\lvert T\rvert^{-0.100}$
0.35–1.2	Peat	$W_u = 0.032\,\lvert T\rvert^{-0.383}$
1.2–6.2	Silt	$W_u = 0.060\,\lvert T\rvert^{-0.350}$
6.2–22	Silty gravel	$W_u = 0.018\,\lvert T\rvert^{-0.100}$
22–54	Silty gravel	$W_u = 0.015\,\lvert T\rvert^{-0.170}$

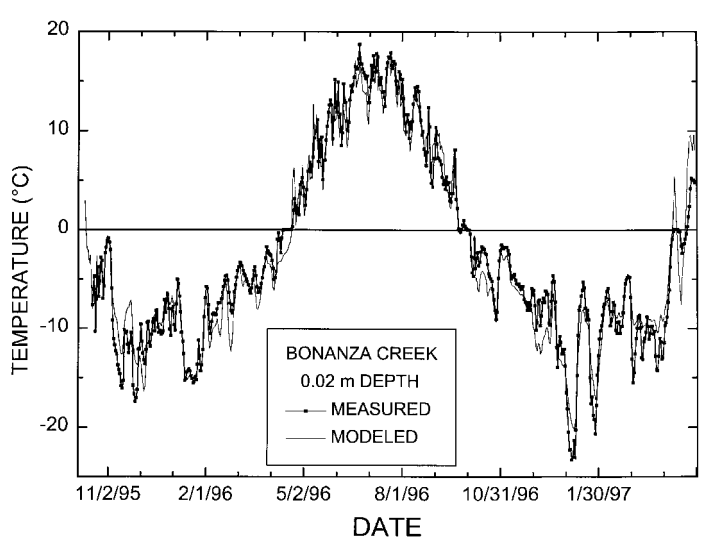

Figure 18 Comparison of measured mean daily temperatures at the Bonanza Creek site during 1995–97 for the 0.02 m depth with mean daily temperatures calculated using a calibrated numerical model.

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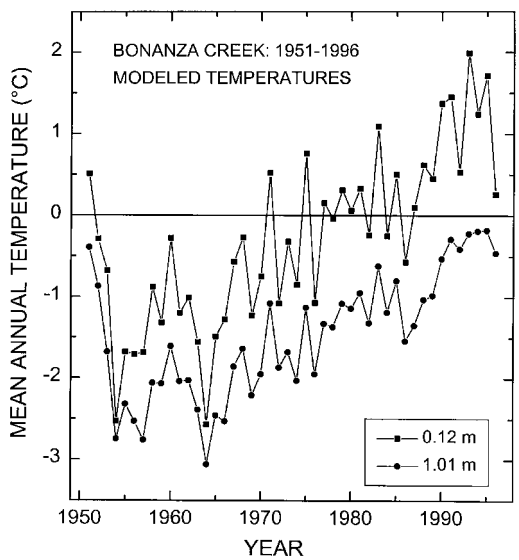

Figure 19 Calculated active layer (0.12 m depth) and near surface permafrost (1.01 m depth) mean annual temperatures using a model calibrated for the Bonanza Creek site and meteorological data from the Fairbanks International Airport station, about 25 km distant.

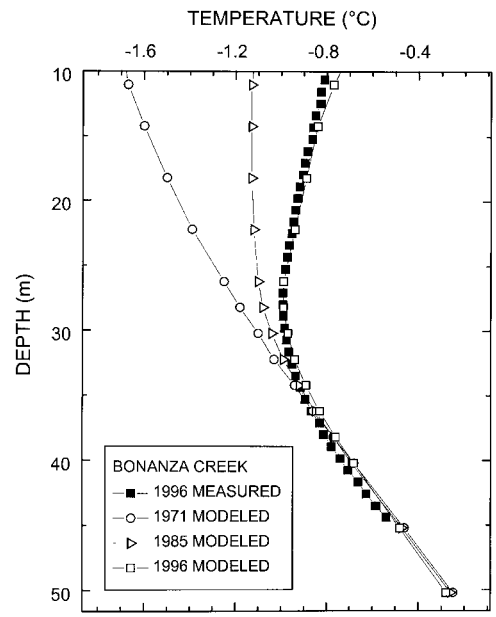

Figure 20 A measured temperature profile and calculated profiles using a calibrated numerical model at the Bonanza Creek site.

0.07 °C per year. An increased warming beginning in 1977 followed the initial warming of the late 1960s and early 1970s. Temperatures varied in a narrow range slightly colder than −1 °C in the late 1970s and 1980s coincident with warmer air temperatures and below average snow depths. They warmed abut 0.75 °C from 1989 to the mid 1990s while air temperatures remained similar to the earlier 1980s and snow depths were average to much more than average (except for 1994). Our interpretation of the above results is that the initial warming of permafrost in the late 1960s and early 1970s was a result of the combined effects of changes in air temperatures and snow covers. Warmer air temperatures caused the warming of permafrost in 1977 and in the late 1970s. Since the late 1980s through 1996, increased snow depths were responsible for the warming observed in measured permafrost temperatures and indicated by the modelling. While the modelling results are site specific, the measurements show similar trends at all the sites on the transect and at Healy. Patterns of air temperatures and snow depths at Bettles and Gulkana on the northern and southern ends of the transect are similar to those of Fairbanks. This suggests that the above interpretation may be valid for the region of the transect and at Healy.

Measured and modelled temperature profiles for 1996 and two other modelled mean annual temperature profiles for the Bonanza Creek site are shown in Figure 20. The curved form of the 1996 temperature profile is a result of the increase in the permafrost surface temperatures since the late 1960s. The unusually slow response of the permafrost temperature regime to the changing permafrost surface temperature is a result of unfrozen water in the frozen silt and silty gravel because of warm permafrost temperatures (typically between 0 °C and −1.2 °C). This effect was predicted by Riseborough (1990) and used by Burn (1992) to interpret temperatures in warm permafrost near Mayo, Yukon Territory, Canada.

SUMMARY

A continuous long-term programme for investigating the effects of climate and environmental conditions on the active layer and permafrost in Alaska was initiated in 1977. Permafrost observatories were placed in undisturbed terrain where active layer and permafrost temperatures and their response to climate were determined. The data consist of annually measured temperatures in boreholes ranging from 30 to 90 m in depth (typically 60 m). Since 1986, daily temperatures in the air, at the ground surface, and in the active layer and

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near-surface permafrost at 11 levels have been recorded by automatic data loggers at several sites. A few sites have supplementary information such as soil samples, vertical moisture (water and ice) profiles, soil thermal conductivities, active layer thicknesses, extent of taliks and thawed layers and water table levels.

The data show that discontinuous permafrost temperatures along a transect south from Old Man near the Arctic Circle to Gulkana and at Healy, 160 km west of the transect, generally warmed in the late 1980s and 1990s. This trend was not followed at Eagle, about 330 km east of the transect. Ground temperatures also warmed at Donnelly where there is no permafrost.

Estimates for the magnitude of the warming at the permafrost table ranged from 0.5 to 1.5 °C with typical values of 1 to 1.5 °C. Warming rates near the permafrost table were estimated to be about 0.05 to 0.2 °C a^{-1}.

The highly correlated air temperatures in the permafrost areas of Alaska and warming of deep permafrost temperatures in northern Alaska during the last century indicate that permafrost temperatures throughout Alaska may have warmed during the last century. In discontinuous permafrost regions, permafrost thicknesses are commonly less than 100 m, so the warming should have penetrated to the base of the permafrost causing the permafrost to begin thawing there. Attempts were made to measure the position of the base of the IBP and the 0 °C isotherm to determine if the permafrost was thawing at the base in response to climatic warming. Accuracy requirements to do this are severe and, with two decades of data, no reliable trends in the depth of the base of ice-bearing permafrost or in the depth of the 0 °C isotherm could be detected.

Thermal offset is important in the context of climatic change because it enables permafrost to form and survive even when mean annual ground surface temperatures are positive. Survival of such permafrost was observed at several sites. At Hogan Hill, permafrost survived for 8 years (1986 to 1994) when mean annual temperatures near the ground surface remained above 0 °C, ranging from 0.9 to 2.5 °C. Observed values for the thermal offset at four sites were typically 1 to 2 °C.

Mean discontinuous permafrost temperatures in marginal areas are typically warmer than −0.5 °C, indicating that the warming identified herein has probably caused permafrost in these areas to begin thawing. Thawing permafrost and thermokarst have been observed at several sites. Thawing rates at the permafrost table at two sites were about 0.1 m a^{-1}. Calculated thawing rates at the base of the permafrost are an order of magnitude slower. These data and calculations indicate that time scales of the order of a century are required to thaw the top 10 metres of ice-rich permafrost, which would be primarily responsible for environmental and engineering problems. Permafrost will persist at depth a long time after thawing begins, with time scales of centuries to millennia required to thaw even relatively thin discontinuous permafrost.

Measured air and ground temperatures were used to calibrate numerical thermal models for Bonanza Creek. It was necessary to include the effects of unfrozen water in the frozen silt and silty gravel because of warm permafrost temperatures (typically between 0 °C and −1.2 °C). The calibrated models were used to predict active layer and permafrost temperature dynamics beginning in 1950, beyond the period when ground temperatures were available. Ground temperatures began warming in the late 1960s. Near-surface (0.12 m depth) active layer temperatures warmed about 3 °C over 30 years (0.1 °C per year). Since 1987, these temperatures have remained warmer than 0 °C. 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. Near-surface permafrost temperatures followed a similar pattern. A warming trend began in the late 1960s and totalled about 2 °C over 30 years (average 0.07 °C per year). These temperatures warmed about 0.75 °C from 1989 to the mid 1990s while air temperatures remained similar to the 1980s and snow depths were average to much more than average (except for 1994). Our interpretation of the above results is that the combined effects of changes in air temperatures and snow covers caused the initial warming of permafrost in the late 1960s and early 1970s. Warmer air temperatures caused the warming of permafrost in 1977 and in the late 1970s. Since the late 1980s through 1996, increased snow depths were responsible for the warming observed in the permafrost temperatures and indicated by the modelling. While the modelling results are site specific, the measurements show similar trends at all the sites on the transect and at Healy. Patterns of air temperatures and snow depths at Bettles and Gulkana on the northern and southern ends of the transect are similar to those at Fairbanks. This suggests that the above interpretation may be valid for the region of the transect and at Healy.

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