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Shallow ground temperatures

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Abstract: The temperature in the ground changes according to daily or longer temperature cycles in the air. The amount of ground temperature change also diminishes rapidly with depth. Temperatures to a depth of 20 m, the approximate depth to which the yearly temperature cycle penetrates, are presented for various environments in the Mackenzie valley. As a rough guideline, average ground temperatures are about 4°C warmer than mean annual air temperatures. This difference depends mainly on the insulating affect of vegetation and snow and changes in the moisture content of the active layer. Smaller differences may result in peatlands where summer drying of organic soils enhances their insulating capacity. Even without a change in climate, disturbance at the ground surface will alter the ground thermal regime. Examples from the Norman Wells to Zama, Alberta oil pipeline show warming and ground subsidence associated with the clearing of the pipeline right-of-way.

Résumé : La température du sol dépend des cycles de la température de l'air, quotidiens ou à plus long terme. L'amplitude de la variation de la température du sol diminue rapidement avec la profondeur. Dans différents environnements de la vallée du Mackenzie, nous présentons les températures régnant à une profondeur de 20 m, la profondeur approximative à laquelle se font sentir les effets du cycle annuel de température. Grosso modo, les températures moyennes du sol sont plus élevées d'environ 4 °C que les températures annuelles moyennes de l'air. Cette différence est principalement attribuable à l'effet isolant de la végétation et de la neige et aux variations de la teneur en humidité du mollisol. On peut observer des écarts moins grands dans les tourbières où l'assèchement des sols organiques en été accroît leur capacité d'isolation. Même sans changement climatique, la perturbation de la surface du sol modifie le régime thermique du sol. À titre d'exemple, on observe un réchauffement du sol le long de l'oléoduc entre Norman Wells et Zama (Alberta), ainsi qu'une subsidence de la surface du sol causée par le dégagement du tracé.

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INTRODUCTION

An understanding of the current relationship between permafrost and climate is necessary before attempting to predict the impact of climate change on permafrost in the Mackenzie valley. The atmospheric climate is the main factor determining the existence of permafrost; however, the spatial distribution, thickness, and temperature of permafrost is highly dependent on the temperature at the ground surface. The temperature at the ground surface, although strongly related to climate, is influenced by several other environmental factors such as vegetation type and density, snow cover, drainage, and soil type. This paper characterizes ground temperatures within the depth range in which yearly changes take place, i.e. above 20 m.

Concepts and features of permafrost, and of the shallow ground thermal regime are first introduced. The broad relationship between climate and ground-surface temperatures in the Mackenzie valley is then outlined. Details on the great variability in the shallow ground thermal regime which exists due to differences in local environmental and site conditions are presented next, and illustrated with numerous examples from Geological Survey of Canada (GSC) study sites. Finally, some examples of the thermal response to surface disturbances are given. These examples may serve as an analogue for the effect of a sudden climate warming.

CHARACTERISTICS OF THE GROUND THERMAL REGIME

Temperature in the ground is directly related to the balance between incoming heat from the sun and the amount of heat re-radiated or reflected from the ground surface and consumed by evapo-transpiration. A small amount of heat also originates from the Earth's interior and, in conjunction with the thermal properties of subsurface materials, determines the maximum depth that permafrost can reach. Because this heat balance also controls air temperature, air temperature presents an accurate and easily measured quantity to relate to ground temperature. The relationship between the two is close, but not identical, because of the insulating effect of snow and vegetation.

Daily changes in air temperature penetrate only a few tens of centimetres below the ground surface. This tendency to dampen air-temperature change is a fundamental ground property. Snow, water, and vegetation between the ground and air add substantially to this damping. Only the annual change in air temperature from summer to winter is observed at depths of a few metres and even this is usually completely dampened out by a depth of approximately 10 m. This depth, where no annual cycle occurs, is known as the depth of zero annual amplitude. Below this depth, a systematic change in average annual temperature must take place, i.e. a change in climate, to cause a ground-temperature change. Systematic shifts in average annual ground temperature, whether observed within or below the depth of zero annual amplitude, can be used to infer past climate changes. An example of this is described in Dyke (2000a).

An example of the annual ground-temperature variation in a permafrost setting is shown in Figure 1. The maximum and minimum temperature experienced at each depth during the year define the annual ground-temperature envelope. The average temperatures at each depth define the mean annual ground-temperature profile. A year-long record for selected depths at another site is shown in Figure 2, along with the corresponding air-temperature record. Daily air-temperature

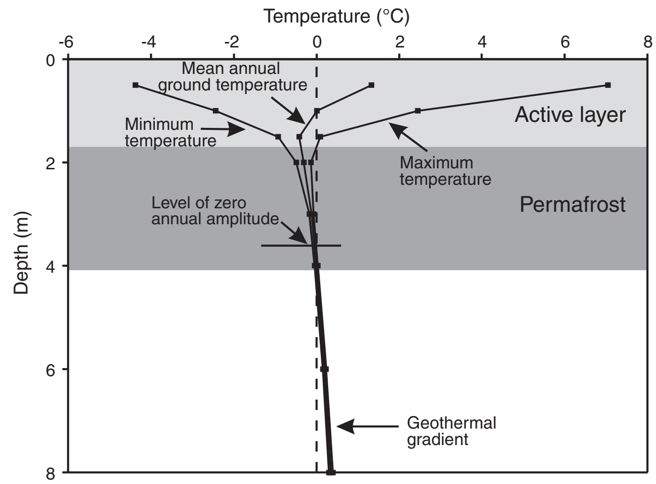


Figure 1. Features of the ground thermal regime in permafrost, illustrated with data from a borehole in mineral soil near Fort Simpson, with thin permafrost. Note: The slope of the temperature line below the depth of zero annual amplitude is the geothermal gradient (assuming climate is stable at the ground surface).

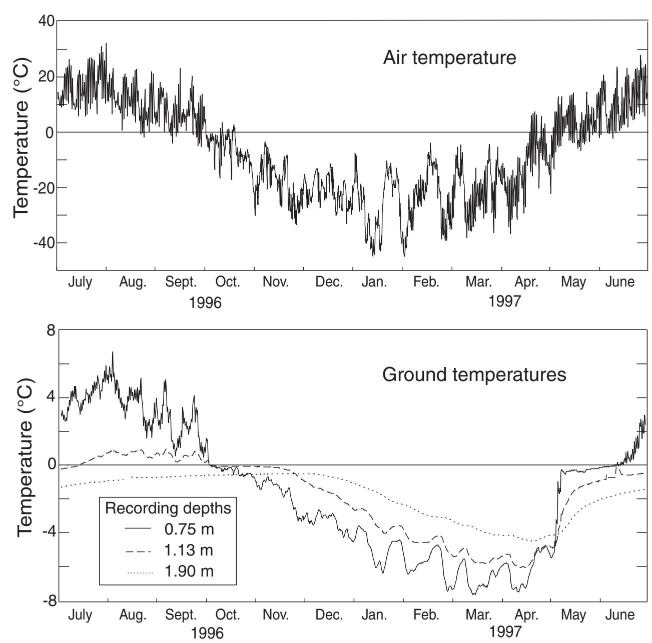


Figure 2. Air temperature and near-surface ground temperatures recorded from June 1996 to June 1997 at a forested site on a slope, near Saline River, north of Wrigley.

changes are completely removed by a depth of 1 m. As depth increases, the temperature changes become increasingly smooth, decreasing in amplitude and lagging progressively behind those of air temperature.

In permafrost environments, the layer of ground that freezes and thaws each year is known as the active layer, i.e. the zone where the maximum temperatures during the year exceed 0°C. (*see* Nixon (2000) for a discussion of active layers in the Mackenzie valley). The layer beneath the active layer that remains permanently below 0°C is permafrost. In permafrost environments, the mean annual temperature profile frequently exhibits a slight curvature towards higher temperatures within the active layer. This phenomena, known as the thermal offset, occurs due to differences in thermal properties of frozen and unfrozen ground. The upper part of the active layer may become particularly warm in summer, but this warmth will be restricted from penetrating deeply by the relatively low thermal conductivity of thawed ground. The thermal offset is also influenced by insulating snow cover (Goodrich, 1978, 1982; Burn and Smith, 1988). As a result of the offset, the mean annual ground temperatures at the surface and within the upper active layer are higher than those in the underlying permafrost (differences of over 1°C have been observed). In fact, the mean annual ground surface temperatures may be above 0°C, yet permafrost may exist. The temperature at the base of the active layer is thus more critical to the existence and dynamics of permafrost than the temperature at the ground surface (Smith and Riseborough, 1996).

Wet soils have quite different thermal properties than dry soils, and hence will respond differently to changes in surface temperature. A soil will have a higher heat capacity (the amount of heat required to raise the temperature of a unit volume by one degree) when wet than when dry, and thus the soil will cool or warm more slowly when wet. As well, there are differences between the thermal properties of frozen wet soils and those of unfrozen wet soils. Thermal conductivity (the quantity of heat that will flow through a unit area of a substance in unit time under a unit temperature gradient) is greater for wet soils when frozen than when unfrozen, since the thermal conductivity of ice is about four times that of water. In addition, in finer textured soils, the soil moisture will freeze or melt gradually over a range of temperatures below 0°C. Most soils thus have characteristic freezing curves (relationship between water content and temperature below 0°C), which depend on grain size, moisture content, pore-water salinity, and pressure. Unfrozen water contents may therefore be considerable in fine-grained soils at temperatures of 1 or 2° below 0°C. For example, a saturated silty clay with a porosity of 35% may contain 20% unfrozen water at a temperature of -0.5°C. The presence of unfrozen water will also lead to temperature-dependent mechanical properties, as well as to temperature-dependent thermal properties.

During freezing or thawing, ground temperatures are held at the freezing point as latent heat of fusion (the amount of heat required to melt the ice, or freeze the water) is absorbed or released. This phenomena is known as the zero curtain effect (*see* Fig. 2, where ground temperatures at a depth of 0.75 m drop rapidly below freezing in October, while those below at 1.13 m, where moisture contents are higher, remain at the freezing point for a considerably longer period of time). The gradual phase change is the result of an apparently increased heat capacity, an effect caused by the additional heat removal required to freeze the moisture in the soil.

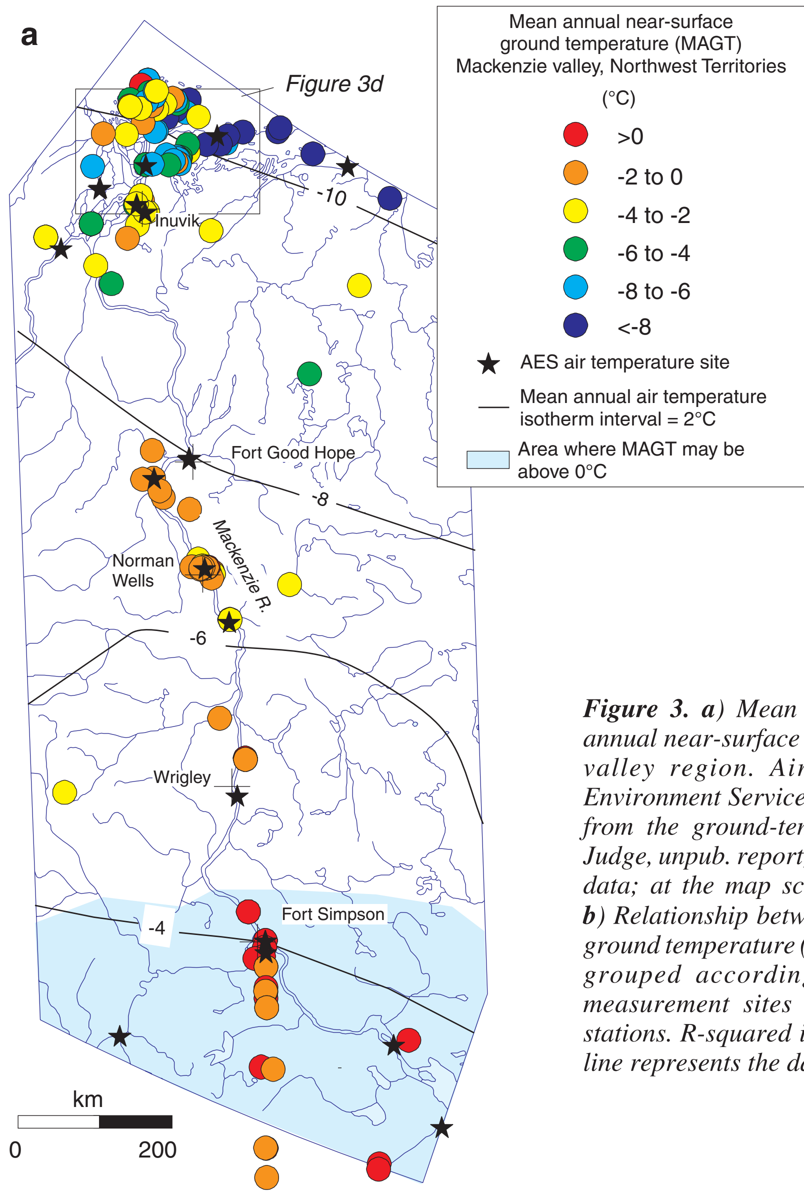
The actual relationship between the climate above the ground and the temperature below is a function of site-specific conditions which determine the amount of heat available at the ground surface (surface energy balance). Incoming solar energy is the dominant energy source, while a small portion arrives from geothermal heat from the Earth's interior (this is shown by the geothermal gradient in Fig. 1). The geothermal heat flux also varies depending on the geological environment and history. Factors such as slope aspect, surface vegetation (or roughness), soil moisture, snow cover, presence or absence of an insulating organic layer, drainage, and elevation greatly influence the local surface heat balance, and hence the amount of heat available for warming the ground.

NEAR-SURFACE GROUND TEMPERATURE

Air-temperature data from Atmospheric Environment Service weather stations (Atmospheric Environment Service, 1982) and near-surface ground-temperature data have been used to produce a map of mean annual air and ground-surface temperatures for the Mackenzie valley region (Fig. 3a). The mean annual air temperature is based on the 30 year climate normals for 1951–1980. The near-surface ground temperatures from 176 sites have been extracted from a ground-temperature database compiled for northern Canada (updated from Young and Judge, unpub. report, 1985). The near-surface ground temperature was either directly determined from observations in the top metre of the ground (the actual depth varies from site to site according to temperature sensor depth), or by extrapolation of the mean annual temperature profile at depth below the level of zero annual amplitude to intercept the ground surface (when only deeper temperatures were available).

The mean annual air temperature ranges from slightly greater than -4°C in the southern part of the region to less than -10°C in the north. Mean annual near-surface ground temperature ranges from about 3°C in the southern part of the valley to about -10°C in the north. Mean annual air and near-surface ground temperature are roughly correlated (Fig. 3b), but considerable variability exists due to all the ground-surface factors listed above. How both the air and ground temperature vary with latitude in the Mackenzie valley is shown in Figure 3c, which shows that although both air and ground temperature generally decrease with increasing latitude, ground temperatures are usually higher than air temperature, usually by 2 to 4°C.

The magnitude of the difference between air and ground temperature and the local variation in ground temperature are dependent, as stated above, on several factors such as snow cover, surficial materials, vegetation cover, moisture conditions, and exposure to wind. The ground temperature, therefore, may show considerable variation over a small area even a



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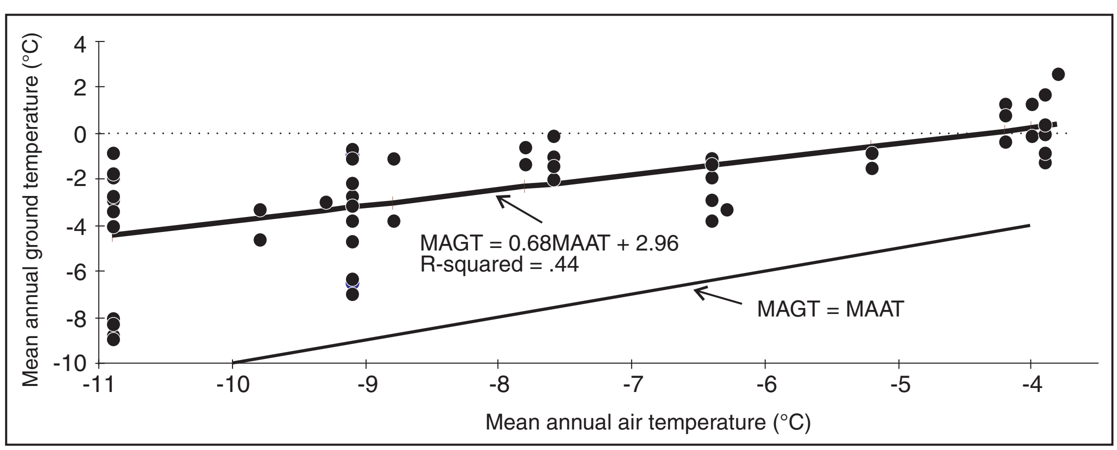

Figure 3. a*) Mean annual air temperature (isotherms) and mean annual near-surface ground temperatures (MAGT) for the Mackenzie valley region. Air temperature data are from Atmospheric Environment Service (1982). Ground-temperature data are extracted from the ground-temperature database (updated from Young and Judge, unpub. report, 1985). Note: there are over 175 sites with MAGT data; at the map scale one dot frequently represents several sites.* ***b****) Relationship between mean annual air (MAAT) and mean annual ground temperature (MAGT) for the Mackenzie valley. Data points are grouped according to the proximity of ground-temperature measurement sites to Atmospheric Environment Service climate stations. R-squared is a numerical measure of how well the equation line represents the data. A value of 1 would be a perfect fit.*

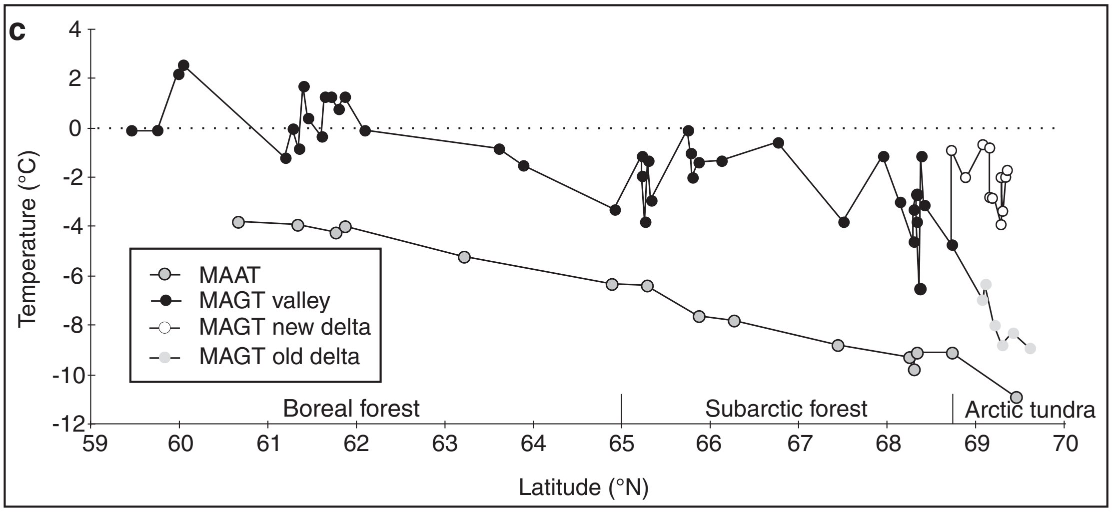

***Figure 3c**) The variation in mean annual air (MAAT) and ground temperature (MAGT) along the Mackenzie valley. Ecoclimatic regions (Ecoregions Working Group, 1989) are indicated along the latitude axis. In the Mackenzie Delta area, ground temperatures contrast markedly between the modern (new) delta and the adjacent tundra uplands (old delta). Note: points are joined with lines to highlight differences between each category; the lines are not necessarily representative of interpolated temperatures.*

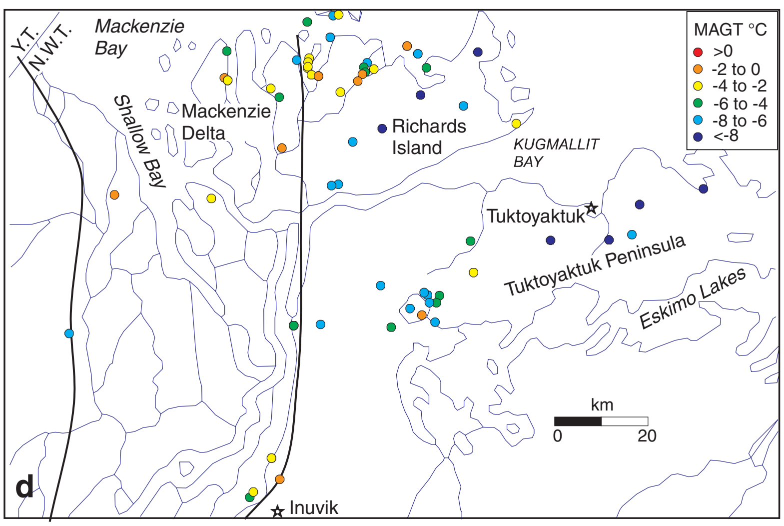

***Figure 3d**) Enlargement of part of the Mackenzie Delta area denoted on Figure 3a. Mean annual ground surface temperatures (MAGT) on the Mackenzie Delta are generally warmer than the adjacent tundra uplands of Richards Island and Tuktoyaktuk Peninsula.*

though air temperature may show little variation. In the area around Fort Simpson, for example, the mean annual air temperature is approximately -4°C, but near-surface ground temperatures are between 2 and -2°C. The influence of local factors can also be seen in the latitudinal profile of air and ground temperature in Figure 3c. There is a decrease in both mean annual air and ground temperature in the Mackenzie valley at higher latitude, but there is greater variation in ground temperature. There is an exception to this general trend in the western Mackenzie Delta region (*see* Fig. 3d). On the modern delta, ground temperatures are considerably warmer than adjacent tundra uplands. In fact, ground temperature here is generally warmer than -4°C, which is similar to that observed in the Mackenzie valley hundreds of kilometres to the south. Ground temperatures are about -8°C at a similar latitude on Richards Island. Vegetation (discussed later with specific examples) which leads to deeper snow cover, and the large amount of water cover maintained by lakes and river channels, are the main factors contributing towards maintaining the warmer ground temperatures in the Mackenzie Delta.

SHALLOW GROUND THERMAL REGIME

Over the past 30 years, many boreholes have been instrumented in the Mackenzie valley for measurements of the shallow ground thermal regime. These boreholes were generally drilled to obtain geotechnical and geothermal data on soils, and to determine permafrost distribution for engineering design or scientific research purposes. In the mid 1970s, analyses of both the shallow and deep thermal regime of the

Mackenzie valley were published by Judge (1973, 1975); these studies included discussion of heat flow, thermal properties, permafrost thickness and temperatures, and annual ground thermal regimes. Since 1980, many new boreholes and studies have contributed to the knowledge and baseline information on the shallow thermal regime in the Mackenzie valley, for example, those related to the Norman Wells pipeline (Pilon et al., 1989; MacInnes et al., 1989, 1990). Figure 4 shows ground-temperature envelopes from a selection of the boreholes throughout the Mackenzie valley and provides subsurface information to complement the near-surface data shown on Figure 3. These plots, which are with one exception from mineral soils, duplicate the general relationship, outlined in the preceding section, between ground temperatures and latitude along the Mackenzie valley.

The temperature profiles at the southern end of the Mackenzie valley (Fort Simpson region and south) show the variability which exists within the discontinuous permafrost zone. In Figure 4, ground-temperature profiles from this area show both an unfrozen mineral site (84-4A) and a frozen mineral site (85-8A), as well as a permafrost site in organic terrain (85-12B). Permafrost occurrence in this region is strongly linked to the presence and nature of peatlands (*see* Aylsworth and Kettles, 2000). Locally, throughout the Mackenzie valley, differences in several factors modify the ground thermal regime. Examples of many of the local influences and the resultant variability in the ground thermal regime are presented below.

Elevation

Increasing elevation can be expected to result in decreasing mean annual air temperatures. Thus, at the southern end of the Mackenzie valley, along the Norman Wells pipeline, permafrost occurrence increases in a southerly direction when terrain rises onto the Alberta Plateau (*see* Burgess and Lawrence, 2000). This relationship with altitude, however, does not always prevail. Figure 5 shows the temperature envelopes for two sites near Norman Wells. The Canyon Creek site is located on the floor of the Mackenzie valley, while the Kee Scarp site is located approximately 250 m higher in elevation and about 20 km to the north. The ground temperatures are warmer at the higher elevation, and permafrost is absent. By contrast, permafrost exists in the valley floor. Such a difference near Norman Wells may be related to the occurrence of pronounced winter air-temperature inversions in the region (*see* Dyke (2000a) for a discussion of inversions). The curvature in the profile at the Kee Scarp site also suggests that there has been recent ground-surface warming, whereas there is no evidence of this at the Canyon Creek site (*see* Dyke, 2000a). These differences emphasize the local variability in climate and ground thermal regime, and also suggest that the local response to any climate warming may be affected by the presence of inversions. There may also be differences in snow cover between the two locations which may contribute to their different response.

Bedrock versus mineral soil

The depth of penetration of the annual temperature wave (i.e. depth of zero annual amplitude) and the damping of the amplitude vary according to the nature of the subsurface materials. In bedrock, with little or no soil cover, there is less rapid attenuation of the annual wave. Thus, at the Kee Scarp site (Fig. 5), where a mere 20 cm of organic material and soil overlie bedrock, the depth of zero annual amplitude is about 20 m. At Canyon Creek, where bedrock is overlain by about 9 m of coarse till which is in turn covered by 40 cm of peat, the depth of zero annual amplitude is only about 10 m. For a given depth, the amplitude of the annual wave is greater in bedrock. For example, temperatures at 2.5 m depth have a range of 5°C at Kee Scarp, compared to 1°C at a similar depth at Canyon Creek. The active layer at the Canyon Creek site is about 1.5 m, whereas the frost penetration layer (the layer that freezes and thaws each year where there is no permafrost) at the bedrock site is around 3.5 m (based on 1987–1988 data).

Drainage

Another borehole at Canyon Creek and a borehole at Norman Wells (but this time in the valley floor) are used to show the influence of drainage on ground temperature and are compared in Figure 6. The soils at the Norman Wells borehole are lacustrine in origin and consist of 6 m of fine-grained silty clay overlying shale; the soils at Canyon Creek are from a coarse-textured ground moraine with 9 m of silty clay overlying shale. Both sites have a surface layer of around 40 cm of peat, and black spruce cover; however, the ground surface is hummocky and poorly drained at Norman Wells, whereas it is flat and well drained at Canyon Creek. Ground-ice contents are very low in the till and higher in the lacustrine clay. Ground temperatures are over 1°C warmer at Canyon Creek, and permafrost thickness there is 25 m. At the Norman Wells site, permafrost thickness is estimated (based on extrapolation of the geothermal gradient) to be about 55 m. The active layer at Norman Wells is about 50 cm, compared to 1.5–2 m at Canyon Creek.

Slope aspect

The orientation of a slope, or its aspect, is one factor determining the amount of incoming solar radiation received at the ground surface. The temperature envelopes plotted from two boreholes on the slopes on either side of Canyon Creek (Fig. 7) reveal that the west-facing slope, which receives greater solar radiation, experiences warmer conditions in the top 15 m than does the east-facing slope. Snow depths also differ on either side of the creek. Snow data from several years in the late 1980s (Burgess, 1993) revealed that snow depths are generally greater at the west-facing site than at the east-facing site. This may be related to differences in wind conditions, as well as to differences in site vegetation. The west-facing slope has a somewhat open cover of black spruce, whereas the east-facing slope has a denser cover of white spruce. More snow would thus be intercepted by the canopy at the latter site, and this could contribute to the colder winter minimum temperatures observed there. Colluvium is

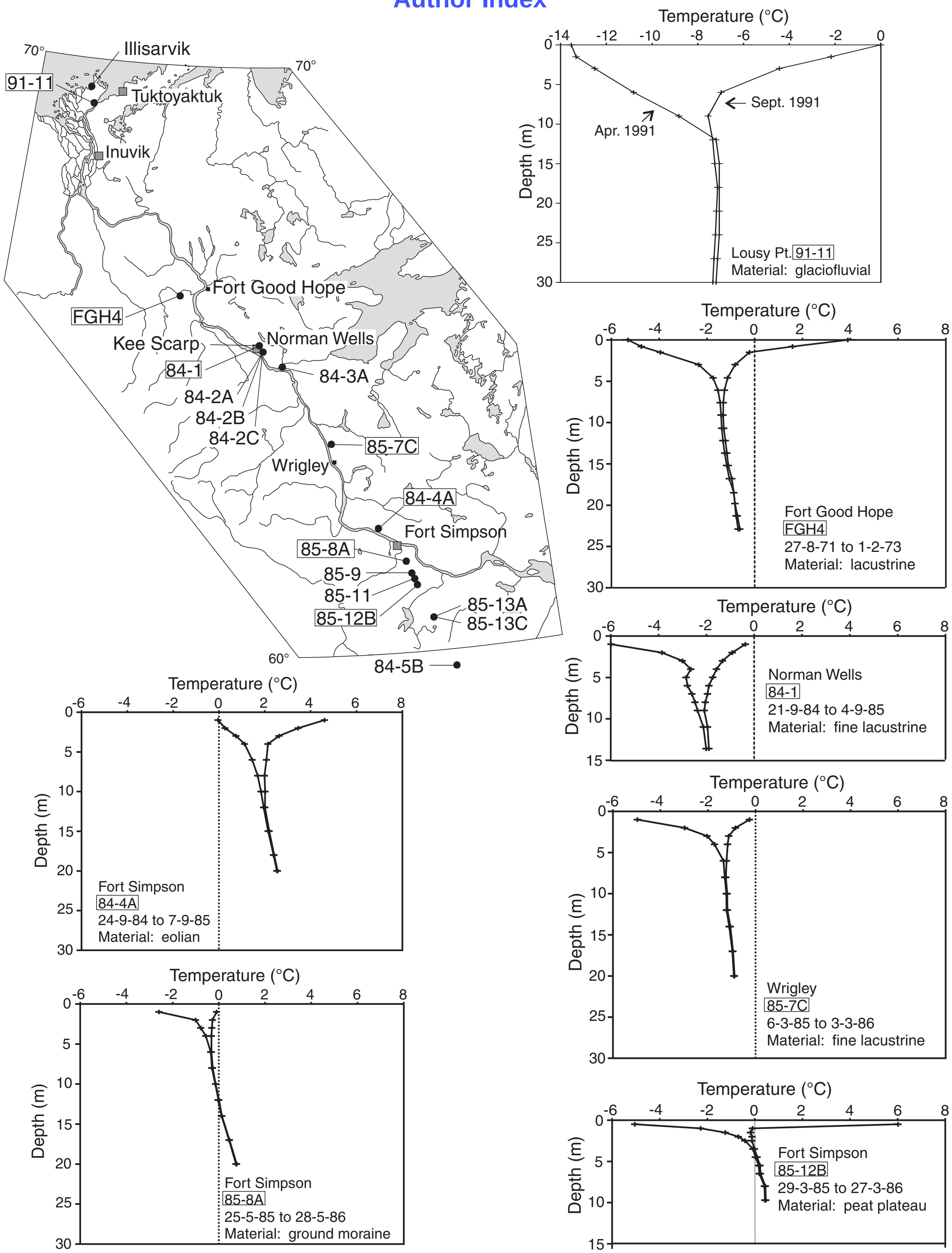

Figure 4. *Ground-temperature envelopes from boreholes in mineral terrain (with exception of site 85-12B which is in organic terrain). Borehole locations are labelled on the map. Other labelled sites are discussed elsewhere in the paper. Material and dates of data collection are indicated on each temperature-envelope plot. Temperature envelopes are based on a series of up to 12 temperature logs recorded over a period of approximately 1 year; with the exception of site 91-11, where the envelope is based on two logs, each of which is individually labelled.*

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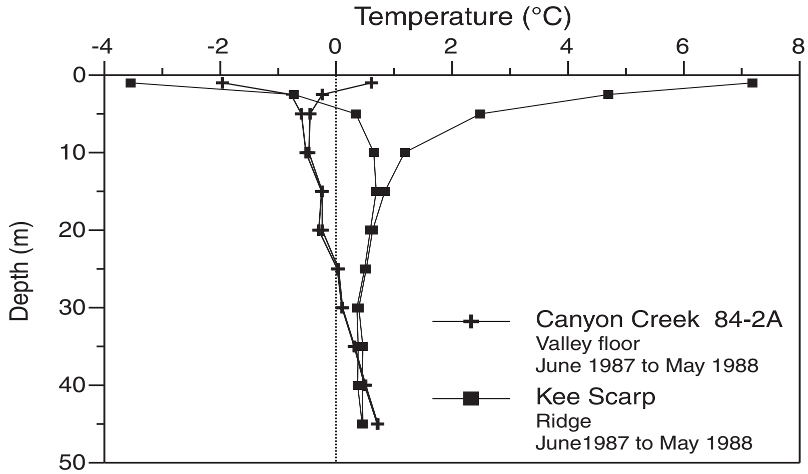
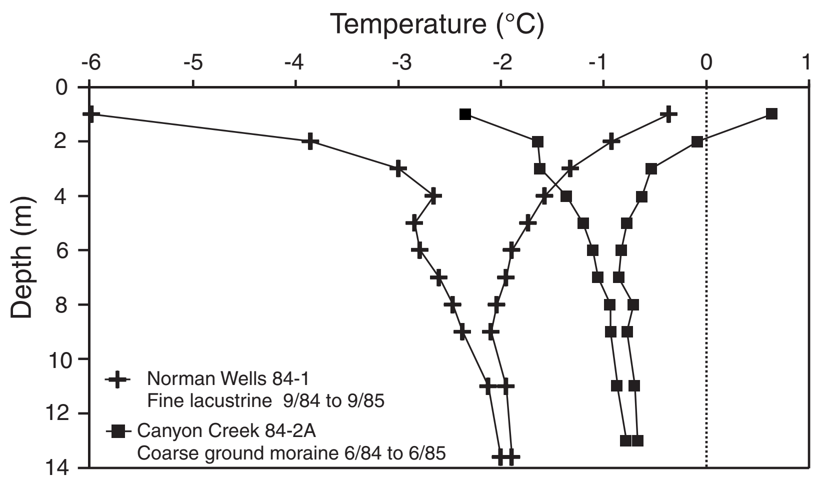


Figure 5.

Maximum and minimum ground temperatures recorded at two sites, located 20 km apart, near Norman Wells over the twelve-month period from June 1987 to May 1988. The Canyon Creek borehole is located on level terrain in the Mackenzie valley floor (site 84-2A), while Kee Scarp is located on a ridge some 250 m higher in elevation.

Figure 6.

Ground-temperature envelopes from two mineral soil sites on level terrain in the valley bottom: a fine lacustrine site at Norman Wells (84-1-T4) and a coarse ground moraine 20 km away at Canyon Creek (84-2A-T4). Data for the former site are from the twelve-month period from September 1984 to September 1985, while for the latter site the period is from June 1984 to June 1985.



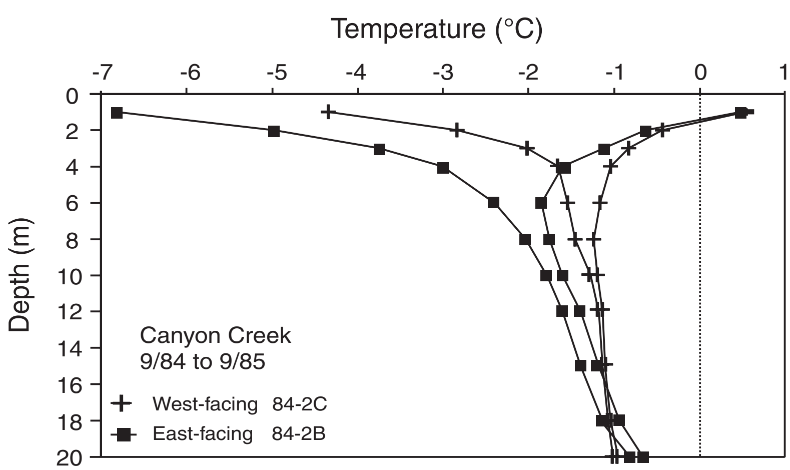


Figure 7.

Ground-temperature envelopes from adjacent opposite-facing slopes at Canyon Creek, for the twelve-month period from September 1984 to September 1985: site 84-2B-T4 is on the east-facing slope and site 84-2C-T4 is on the west-facing slope.

thinner at the east-facing site (with bedrock less than 3 m from the surface), whereas bedrock is at greater than 6 m depth at the west-facing site. These differences in lithology would explain the different geothermal gradients observed at the sites in Figure 7.

Borehole temperatures from the discontinuous permafrost zone

Mineral soil and insulating organic-layer variability

Figure 8 shows the variability in permafrost conditions in mineral soils in the vicinity of Fort Simpson, within the discontinuous permafrost zone. In this area, the presence of a surface organic layer is one of the key factors necessary for the existence of permafrost. Peat changes thermal conductivity during the year, becoming a particularly good insulator (low conductivity) in the summer when it is dry, and a good conductor in the fall and winter when it is wet. This characteristic enables permafrost to be preserved in an otherwise nonpermafrost environment. Site 84-4A is located in sandy soil at the base of a sand dune in eolian terrain east of the Mackenzie River and north of Fort Simpson. Soils at site 85-8A consist of 5 m of sand and silt overlying ice-rich clay and covered by 0.7 m of peat. At site 85-9, coarse granular soils have essentially no insulating surface organic layer, whereas at site 85-11, a 30 cm cover of peat overlies 1–2 m of gravel and sand which, in turn, rest on clay. Sites 84-4A and 85-9 with no surface peat have no permafrost and mean ground temperatures are around 1.5°C. Sites 85-8A and 85-11, both with a layer of peat at the surface, have warm permafrost with temperatures greater than -1°C at the former site, and warmer than -0.5°C at the latter. Permafrost thickness is also greater at 85-8A (11 m) than at 85-11 (2 m).

Peatland types: fen versus peat plateau

Peatlands, which are formed by the accumulation of plant materials, are organic wetlands that have 40 cm or more peat. In the southern parts of the Mackenzie valley, peatlands cover a large percentage of the terrain. The dominant forms of peatland are fens, which are unfrozen, and peat plateau bogs, which are frozen. A discussion of the characteristics and distribution of peatlands in the Mackenzie valley is given in Aylsworth and Kettles (2000). Peat plateaus may also contain internal collapse features which are unfrozen. Figure 9 illustrates the difference in fen and peat-plateau ground thermal regimes recorded at two peatland sites about 75 km north of the Alberta–Northwest Territories border. One site is located on a frozen peat plateau, with 1.6 m of peat and open black spruce forest, while the other is located 400 m to the south in an adjacent unfrozen patterned fen, with 5 m of peat and sedge with some dwarf birch and stunted black spruce. The active layer in the peat plateau bog is less than 1 m and permafrost (at temperatures less than -0.5°C) extends to a depth of about 4 m. Ground temperatures in the fen are about 2 degrees warmer, and seasonal frost penetration is about 1 m.

Unfrozen mineral versus frozen organic soil

The influence of a peat layer on ground temperatures is also shown in Figure 10. It compares frozen organic terrain of a 2 m high peat plateau some 70 km south of Fort Simpson (site 85-12B) to unfrozen mineral terrain some 25 km to the north (site 85-9) with no surface peat layer. Permafrost is only a few metres thick at the peat plateau site and at warm temperatures within 0.5° of 0°C. There is no permafrost, and ground temperatures are about 2°C warmer at the mineral soil site.

Influence of bodies of water

Ground temperatures are also strongly moderated by the presence of bodies of water. Under large and deep water bodies such as the Mackenzie River or large lakes, permafrost may be completely absent. The proximity to water bodies will also frequently produce a warming influence on ground temperatures of the surrounding shores or banks. Smaller bodies of shallow water, such as smaller lakes where bottom waters do not freeze in the winter, often are underlain by an unfrozen zone, or talik, which lies above the permafrost. Figure 11 shows a temperature cross-section beneath Illisarvik Lake on Richards Island in the Mackenzie Delta (*from* Burgess et al., 1982) and highlights the talik which existed to depths of almost 30 m beneath the centre of the lake prior its drainage in 1978. Illisarvik Lake was artificially drained as part an experiment to study permafrost aggradation in drained-lake

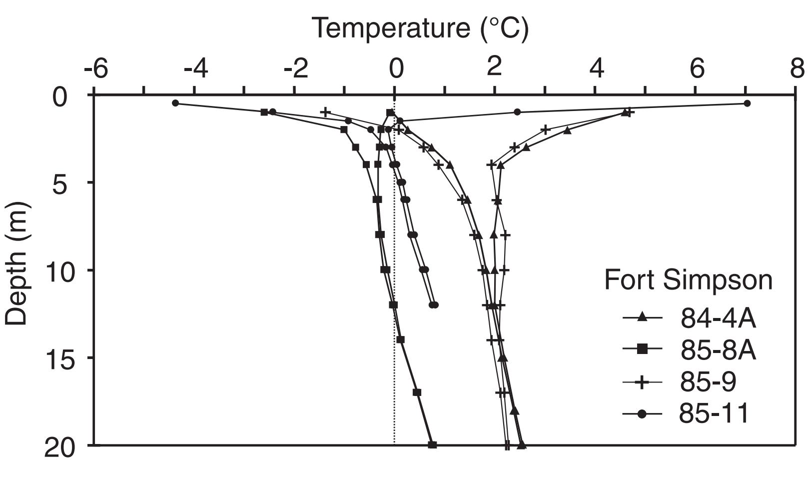


Figure 8.

The 1986 ground-temperature envelopes from several mineral soil sites in the Fort Simpson region. Soils at sites 85-9 and 85-11 are coarse granular gravels or sands, whereas at sites 84-4A and 85-8A soils are finer textured sands and silts. Permafrost exists at 85-8A and 85-11 due to the presence of a surface organic layer 30 cm or more in thickness. At sites 84-4A and 85-9 there is essentially no insulating surface organic layer.

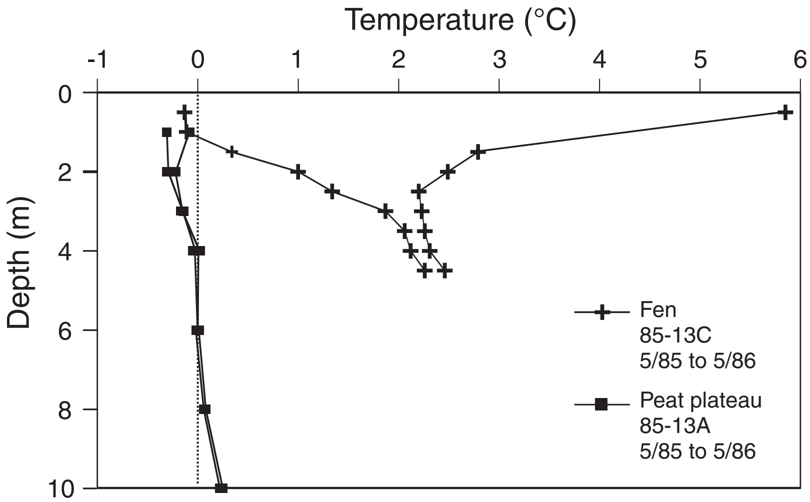


Figure 9.

Temperature envelopes from a peat plateau (site 85-13A) and a nearby fen (site 85-13C) along the Norman Wells pipeline; data from twelve-month period from May 1985 to May 1986.

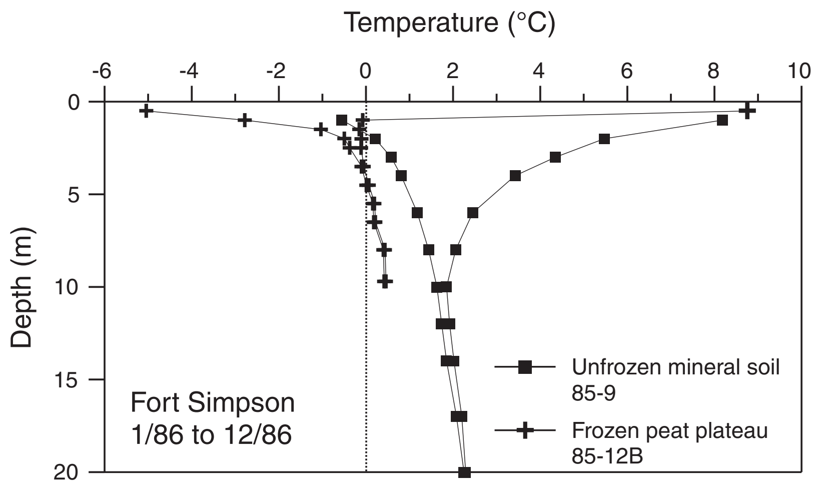


Figure 10.

Comparison of two sites south of Fort Simpson: a peat plateau with permafrost (site 85-12B) and unfrozen mineral soil (site 85-9): 1986 ground-temperature envelopes.

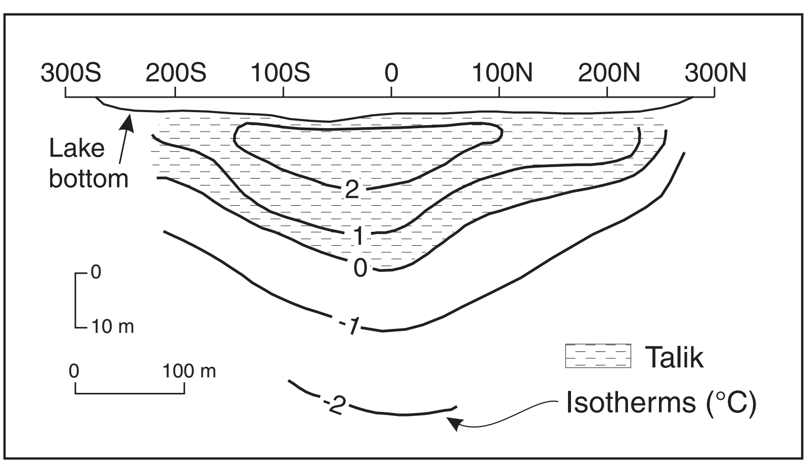


Figure 11.

Temperature cross-section beneath Illisarvik Lake, Richards Island, Mackenzie Delta, prior to its drainage in 1978.

bottoms (Mackay, 1981). Along the actively eroding coasts and shorelines of the Mackenzie valley, catastrophic lake drainage is a common geomorphic process, and has often resulted in the formation of pingos, as permafrost aggrades into the exposed unfrozen lake bottom sediments.

In addition to lake drainage, parts of the Mackenzie River channel, Mackenzie Delta front and offshore experience continual changes as river channels migrate and shorelines and bars shift. These dynamic processes lead to corresponding dynamic and diverse vegetation, snow cover, and ground thermal regimes, as discussed in Dyke (2000b; *see also* Smith and Hwang, 1975).

Snow cover

Snow acts as an insulator, and the difference between air and ground surface temperature tends to be greater in areas covered by a thick snow pack (Goodrich, 1982). Data from Canyon Creek, for example (Stuart et al., 1991), shows that as snow depth increases, changes in air temperature are accompanied by smaller changes in soil temperature. Once the snow cover is greater than 50 cm thick, soil temperature is only affected by large sudden changes in air temperature.

The dramatic influence of snow depth on shallow ground temperature is clearly illustrated in Figure 12 with four GSC sites on the modern Mackenzie Delta. Mean annual ground temperatures range from -9°C at a site with almost no snow cover to about -2.5°C at a site with a significant snow cover. Variations in snow cover are related to the different vegetation which exists at the sites. Vegetation is non-existent at the sand flat and snow is usually blown off the site resulting in little snow cover in winter. The shallow ground temperature on the sand bar is therefore lower than at the other sites which each have a vegetation cover and thicker snow packs. At the dwarf willow (tundra) site, the low vegetation cover accumulates about 10 cm of snow. Ground temperatures at this site are therefore lower than at the other vegetated sites. Snow depths at the sedge site increase to about 20 cm. The taller willows trap snow to a depth in excess of 60 cm. Where taller willows occur, snow depths can reach 1 m. Shallow ground temperatures are warmest at the willow-covered site.

RESPONSE TO SURFACE DISTURBANCE

Climate variability or climate change due either to natural or anthropogenic causes may lead to ground-surface temperature changes. In addition, other activities which directly disturb the ground surface, such as clearing of vegetation for roads, pipelines or other rights-of-way, or destruction of the vegetation and surface organic material due to forest fires also affect the ground-surface temperature. This section illustrates changes in the ground thermal regime that have occurred over a ten-year interval in response to the construction of the Norman Wells pipeline.

The Norman Wells pipeline, in operation in the Mackenzie valley since 1985, is 328 mm in diameter and runs from Norman Wells to Zama, Alberta. The pipeline is buried and traverses the discontinuous permafrost zone more or less parallel to the Mackenzie River. Clearing of trees on the right-of-way and construction took place from 1983 to 1985. A series of monitoring sites were established by the government along the route to study the impact of construction and operation on permafrost terrain (Pilon et al., 1989; MacInnes et al., 1989, 1990). The effect of suddenly removing the trees is akin to a sudden step increase in surface temperature; during construction, the surface organic layer was also frequently scraped to obtain a stable working platform. The rate and magnitude of ground-temperature changes have varied according to soil type, ice content, and initial ground thermal condition (Burgess and Riseborough, 1990; Burgess, 1992).

Examples of the variability in the terrain response are illustrated in the cross-sections of Figure 13. These show the depth of thaw (active layer) at the time of site establishment in the 1980s and ten years later in the mid-1990s. Note that thaw depths are greater in the vicinity of the buried pipe due to the warm pipe-operating temperatures (generally >0°C), the increased level of terrain disturbance in the pipeline trench, and the fact that the trench backfill is frequently subsided and wetter than the adjacent right-of-way (ROW). In general, away from the pipe, thaw depths on-right-of-way were initially around 1 m. Increase in thaw depth on the right-of-way due to clearing and construction at these particular sites has varied from 1–2 m at site 84-3A, to 4 m at site 85-7C

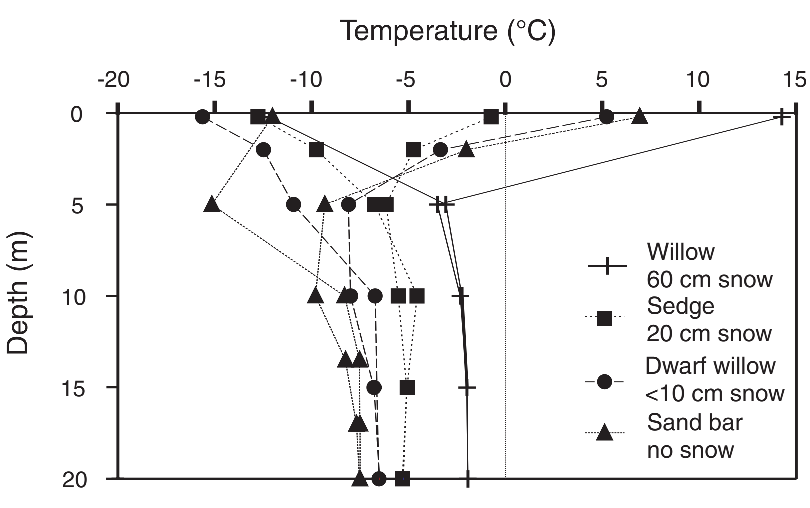


Figure 12.

Ground-temperature profiles at four sites with different vegetation on the outer Mackenzie Delta. The profiles show the effect of different snow depths caused by the height of the respective vegetation. They vary from willows, trapping 60 cm of snow, to an unvegetated sand flat kept clear of snow by the wind. The insulating effect of the snow also reduces the maximum depth of annual temperature variation. Dates of the temperature profiles at each site are March and July 1992.

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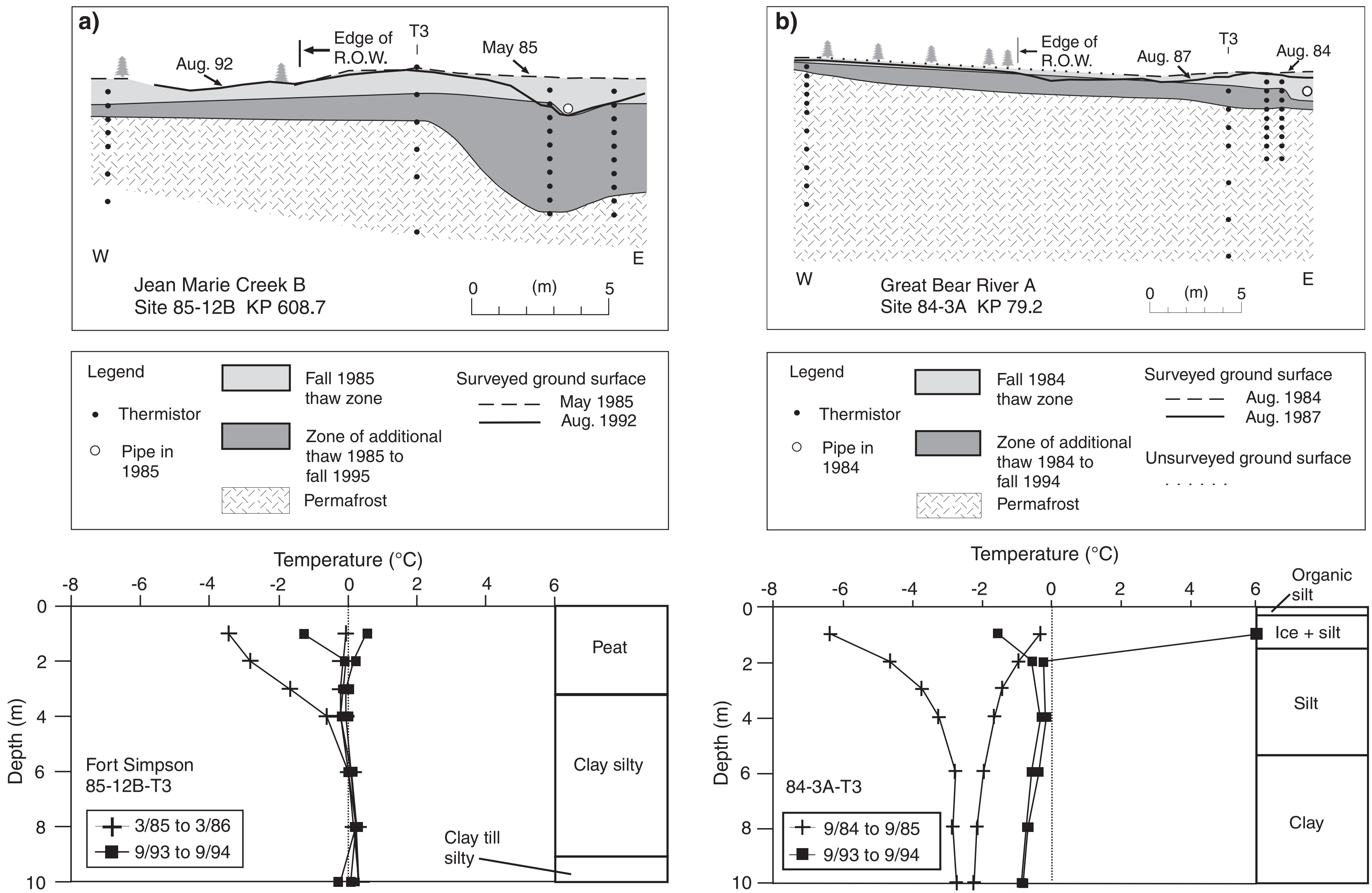

Figure 13. *Cross-sections showing change in thaw depth, permafrost thickness, and surface settlement related to the Norman Wells pipeline. Ground-temperature envelopes show the change in thermal regime on the pipeline right-of-way. Data from several sites illustrate the diversity in the response of different terrain units to surface disturbance.* ***a)*** *Site 85-12B is an ice-rich peat plateau south of Fort Simpson.* ***b)*** *Site 84-3A is on an ice-rich fine-grained alluvial terrace near Tulita (formerly Fort Norman).* ***c)*** *Site 84-5B is also an ice-rich peat plateau on the Alberta Plateau (thicker peat and thicker permafrost than 85-12B).* ***d)*** *Site 85-7C is in fine-grained lacustrine soils north of Wrigley. KP = kilometre post along Norman Wells pipeline.*

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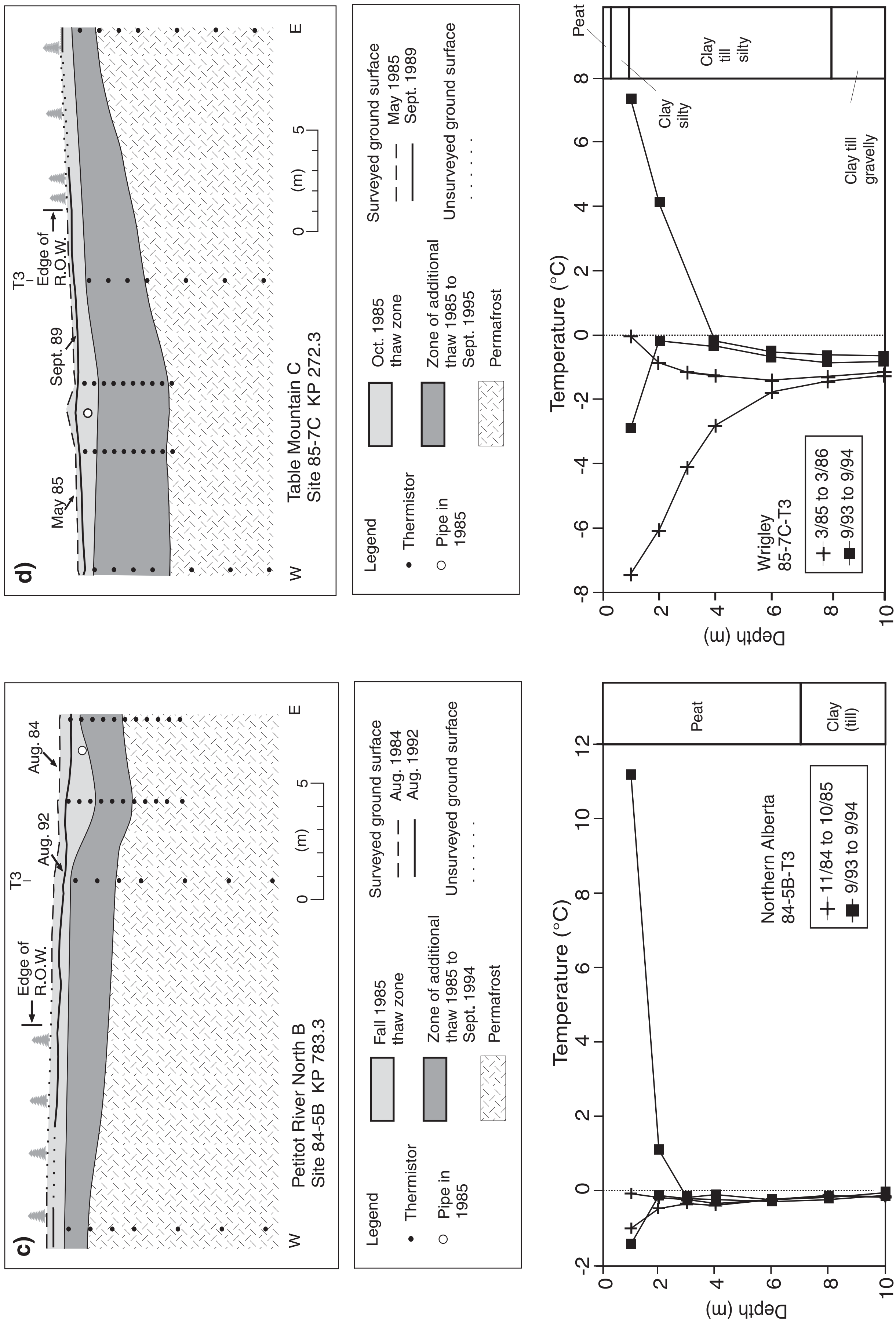

Figure 13 (cont.)

(fine-grained ice-rich lacustrine soils near Wrigley). The smaller increase in thaw depth at site 84-3A is due to a 1 m layer of massive ice near the surface.

The cross-sections are accompanied by annual temperature envelopes on the right-of-way for the first year after site establishment and about 10 years after. Data from the right-of-way cable furthest from the pipe have been selected so as to minimize the thermal effects of the pipe. The two envelopes illustrate the change in the ground thermal regime that has occurred over this time interval. The cross-sections also show the change in surface elevation, i.e. thaw settlement, that has occurred subsequent to site establishment (survey dates vary from site to site). Further discussion of thaw settlement potential for various terrain types can be found in Aylsworth et al. (2000a) and Burgess et al. (2000). Small changes in thaw depth are also observed at the off-right-of-way cable, and these are largely related to the surface disturbance caused by drill-rig movement to the off-right-of-way sites.

In the mid 1990s there have been several large and extensive forest fires in the Mackenzie valley, and these have traversed large sections of the pipeline right-of-way. The response of terrain to forest fires is also site specific and dependant on several factors. Mackay (1995) presented data from a burn area near Inuvik that showed the variability in changes in the active layer depth over time for sites with different initial permafrost and ground-ice conditions, vegetation changes, relief, and snow cover.

The off-right-of-way at pipeline site 84-3A was burnt in the spring of 1995. The existence of the monitoring site will provide both the base-line data and ongoing observations to allow an examination of the impact on the shallow thermal regime. New instrumentation has also been installed on a slope that burnt in the summer of 1994, to examine the thermal impact and recovery of terrain at several elevations along the slope, and to compare these to the conditions at an unburnt location on the slope. The creek valley at this location experienced numerous active-layer detachment slides within weeks of the fire. Slope stability under a warming climate, with or without increased forest fire activity, is a concern in the Mackenzie valley, and is further discussed in Aylsworth et al. (2000b) and Dyke (2000c).

SUMMARY

This paper has presented data that show the broad general relationship, and great local variability, between climate and near-surface ground temperature in the Mackenzie valley. Local variability arises due to differences in environmental and site conditions, such as vegetation, snow cover, elevation, surface organic layer, soil type, moisture content, and thermal properties. Prediction of the response of the shallow ground thermal regime to climate change must thus take into account this variability and the complexity of the interactions between climate above the ground, climate at the ground surface, and climate in the ground.

Geothermal models are frequently employed to assess the ground thermal response to climate change. Many existing models simulate the complete surface energy-balance equation, but frequently there are insufficient data available to characterize all the necessary input parameters. Recently, the use of n-factors (a transfer function between air temperature and temperature at the ground surface which takes into account the influence of vegetation and snow cover) has become more prevalent in geothermal simulations. The characterization and measurement of n-factors for natural surfaces is therefore becoming increasingly important (*see* Taylor, 2000). Smith and Riseborough (1996) presented a new formulation of the permafrost-climate system which links ground temperature to the annual cycle of atmospheric temperature, with the modulating effects of local surface and lithological conditions (n-factors also appear in their formulation).

Assessing the impact of climate warming on the ground thermal regime requires not only a knowledge of the current ground thermal regime, but also a prediction of how air temperatures will change and the availability of a geothermal simulation model which can transfer atmospheric changes in climate to the ground surface. Determination of changes in precipitation and vegetation are also critical. For example, if an air temperature increase is accompanied by a decrease in snow cover, ground temperatures may not increase at all since the latter change can offset the former. Burgess et al. (2000) present one modelling approach that was used to examine various warming scenarios and the possible associated transient changes in permafrost and the shallow ground thermal regime at three locations in the Mackenzie valley.

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We would like to acknowledge our colleagues in the Terrain Sciences Division of the GSC for their contribution of data on the ground thermal regime. The collection of the data presented here has in many cases also been the result of collaborative field efforts or funding with other agencies and individuals, notably the Department of Indian and Northern Affairs (Northern Affairs Program) for study sites along the Norman Wells pipeline and in the Mackenzie Delta.

REFERENCES

Atmospheric Environment Service

1982: Canadian Climate Normals; Temperature, v. 2; Environment Canada, 306 p.

Aylsworth, J.M. and Kettles, I.M.

2000: Distribution of peatlands; *in* The Physical Environment of the Mackenzie Valley, Northwest Territories: a Base Line for the Assessment of Environmental Change, (ed.) L.D. Dyke and G.R. Brooks; Geological Survey of Canada, Bulletin 547.

Aylsworth, J.M., Burgess, M.M., Desrochers, D.T., Duk-Rodkin, A., Robertson, T., and Traynor, J.A.

2000a: Surficial geology, subsurface materials, and thaw sensitivity of sediments; *in* The Physical Environment of the Mackenzie Valley, Northwest Territories: a Base Line for the Assessment of Environmental Change, (ed.) L.D. Dyke and G.R. Brooks; Geological Survey of Canada, Bulletin 547.

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Aylsworth, J.M., Duk-Rodkin, A., Robertson, T., and Traynor, J.A.
2000b: Landslides of the Mackenzie valley and adjacent mountainous and coastal regions; *in* The Physical Environment of the Mackenzie Valley, Northwest Territories: a Base Line for the Assessment of Environmental Change, (ed.) L.D. Dyke and G.R. Brooks; Geological Survey of Canada, Bulletin 547.

Burgess, M.M.
1992: Analysis of the pipe and ditch thermal regime, Norman Wells pipeline; *in* Proceedings of the 11th International Conference on Offshore Mechanics and Arctic Engineering, Calgary, Book no. H0744B, v. V, pt. A, p. 575–584.
1993: Snow depth and density measurements, Norman Wells pipeline study sites, Mackenzie Valley, 1985 to 1991; Geological Survey of Canada, Open File 2626, 13 p.

Burgess, M.M. and Lawrence, D.E.
2000: Permafrost and surficial materials along a north-south transect: observations from the Norman Wells pipeline; *in* The Physical Environment of the Mackenzie Valley, Northwest Territories: a Base Line for the Assessment of Environmental Change, (ed.) L.D. Dyke and G.R. Brooks; Geological Survey of Canada, Bulletin 547.

Burgess, M.M. and Riseborough, D.W.
1990: Observations on the thermal response of discontinuous permafrost terrain to development and climate change — an 800 km transect along the Norman Wells pipeline; *in* Proceedings of the Fifth Canadian Permafrost Conference, Collection Nordicana No. 54, Laval University, p. 291–297.

Burgess, M.M., Desrochers, D.T., and Saunders, R.
2000: Potential changes in thaw depth and thaw settlement for three locations in the Mackenzie valley; *in* The Physical Environment of the Mackenzie Valley, Northwest Territories: a Base Line for the Assessment of Environmental Change, (ed.) L.D. Dyke and G.R. Brooks; Geological Survey of Canada, Bulletin 547.

Burgess, M.M., Judge, A., Taylor, A., and Allen, V.
1982: Ground temperature studies of permafrost growth at a drained lake site, Mackenzie Delta; *in* Proceedings of the 4th Canadian Permafrost Conference, (ed.) H.M. French; Associate Committee on Geotechnical Research, National Research Council of Canada, Ottawa, p. 3–11.

Burn, C.R. and Smith, C.A.S.
1988: Observations of the "Thermal Offset" in near-surface mean annual ground temperatures at several sites near Mayo, Yukon Territory, Canada; Arctic, v. 41, no. 2, p. 99–104.

Dyke, L.D.
2000a: Climate of the Mackenzie River valley; *in* The Physical Environment of the Mackenzie Valley, Northwest Territories: a Base Line for the Assessment of Environmental Change, (ed.) L.D. Dyke and G.R. Brooks; Geological Survey of Canada, Bulletin 547.
2000b: Shoreline permafrost along the Mackenzie River; *in* The Physical Environment of the Mackenzie Valley, Northwest Territories: a Base Line for the Assessment of Environmental Change, (ed.) L.D. Dyke and G.R. Brooks; Geological Survey of Canada, Bulletin 547.
2000c: Stability of permafrost slopes; *in* The Physical Environment of the Mackenzie Valley, Northwest Territories: a Base Line for the Assessment of Environmental Change, (ed.) L.D. Dyke and G.R. Brooks; Geological Survey of Canada, Bulletin 547.

Ecoregions Working Group
1989: Ecoclimatic regions of Canada; Canada Committee on Ecological Land Classification, Environment Canada, Ecological Land Classification Series, no. 23, 118 p.

Goodrich, L.E.
1978: Some results of a numerical study of ground thermal regimes; *in* Proceedings, Third International Conference on Permafrost; National Research Council, v. 1, p. 29–34.
1982: The influence of snow cover on the ground thermal regime; Canadian Geotechnical Journal, v. 19, no. 4, p. 421–432.

Judge, A.S.
1973: The thermal regime of the Mackenzie Valley: Observations of the natural state; Environmental–Social Committee, Northern Pipelines Task Force on Northern Oil Development Report No. 73–38, 177 p.
1975: Geothermal Studies in the Mackenzie Valley by the Earth Physics Branch; Geothermal Series Number 2, Geothermal Service of Canada, Earth Physics Branch, Energy Mines and Resources Canada, 12 p.

MacInnes, K.L., Burgess, M.M., Harry, D.G., and Baker, T.H.W.
1989: Permafrost and terrain research and monitoring: Norman Wells pipeline: environmental and engineering considerations; Department of Indian and Northern Affairs Canada, Northern Affairs Program, Environmental Studies Report No. 64, v. 1, 132 p.
1990: Permafrost and terrain research and monitoring: Norman Wells pipeline: research and monitoring Results: 1983–1988; Department of Indian and Northern Affairs Canada, Northern Affairs Program, Environmental Studies Report No. 64, v. 2, 204 p.

Mackay, J.R.
1981: An experiment in lake drainage, Richards Island, Northwest Territories: a progress report; *in* Current Research, Part A; Geological Survey of Canada, Paper 81-1A, p. 63–68.
1995: Active layer changes (1968 to 1993) following the forest tundra fire near Inuvik, N.W.T., Canada; Arctic and Alpine Research, v. 27, no. 4, p. 323–336.

Nixon, F.M.
2000: Thaw-depth monitoring; *in* The Physical Environment of the Mackenzie Valley, Northwest Territories: a Base Line for the Assessment of Environmental Change, (ed.) L.D. Dyke and G.R. Brooks; Geological Survey of Canada, Bulletin 547.

Pilon, J.A., Burgess, M.M., Judge, A.S., Allen, V.S., MacInnes, K.L., Harry, D.G., Tarnocai, C., and Baker, H.
1989: Norman Wells to Zama pipeline permafrost and terrain research and monitoring program: site establishment report; Geological Survey of Canada, Open File 2044, 332 p.

Smith, M.W. and Hwang, C.T.
1975: Thermal disturbance due to channel shifting, Mackenzie Delta, N.W.T., Canada; *in* Permafrost: North American Contribution to the 2nd International Conference on Permafrost; National Academy of Sciences, Washington, D.C., p. 51–60.

Smith, M.W. and Riseborough, D.R.
1996: Permafrost monitoring and detection of climate change; Permafrost and Periglacial Processes, v. 7, p. 301–309.

Stuart, R.A., Etkin, D.A., and Judge, A.S.
1991: Recent observations of air temperature and snow depth in the Mackenzie valley area and their implications on the stability of permafrost layers; Environment Canada, Atmospheric Environment Service, Canadian Climate Centre Report No 91–2, 178 p.

Taylor, A.
2000: Relationship of ground temperatures to air temperatures in forests; *in* The Physical Environment of the Mackenzie Valley, Northwest Territories: a Base Line for the Assessment of Environmental Change, (ed.) L.D. Dyke and G.R. Brooks; Geological Survey of Canada, Bulletin 547.