Contents

Author Index

Climate of the Mackenzie River valley

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Abstract : The Mackenzie River valley is dominated by cold, dry air moving south from the high arctic in winter but receives a warm if brief summer as the arctic high pressure area retreats northward. Dry conditions are periodically modified by low-pressure cells moving from the Pacific Ocean or Beaufort Sea. Mean monthly temperatures in winter and summer tend to be uniform throughout the Mackenzie valley south of Inuvik. In winter, this is due to the parallelism between the arctic front and the Mackenzie valley as it traverses the region. In summer, longer daylight hours compensate for lower sun angles with increasing latitude to favour even heating. Snow and rainfall are low by North American standards but occasional heavy rains do occur. Throughout the 20th century, mean annual temperatures for most recording stations have on average risen between 1 and 2°C and snowdepth at the end of February has decreased.

Résumé : En hiver, la vallée du Mackenzie est envahie surtout par de l'air sec et froid en provenance de l'Arctique, alors qu'en été la migration vers le nord de la zone de haute pression de l'Arctique produit un climat chaud sur une courte période. Les conditions d'aridité sont périodiquement modifiées par des cellules de basse pression provenant de l'océan Pacifique ou de la mer de Beaufort. Les températures mensuelles moyennes en hiver et en été sont à peu près uniformes dans toute la vallée, au sud d'Inuvik. En hiver, l'uniformité des températures est attribuable au parallélisme de la vallée du Mackenzie et du front arctique au moment où celui-ci traverse la région. En été, les périodes d'ensoleillement plus longues compensent pour l'angle du soleil peu élevé sous cette latitude, ce qui favorise le réchauffement. Les précipitations nivales et pluviales sont faibles comparativement aux autres régions de l'Amérique du Nord, mais, à l'occasion, il y tombe des pluies abondantes. Tout au long du 20^{e} siècle, les températures annuelles moyennes à la plupart des stations d'enregistrement ont augmenté de 1 à 2 °C, et l'épaisseur du manteau nival de la fin de février a diminué.

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INTRODUCTION

The climate of the Mackenzie River valley, like the climate of any region, is fundamentally determined by the absorption of solar radiation by the Earth's surface and atmosphere. The strength of this radiation is determined by latitude, but snow cover, clouds, and the large change in hours of daylight (Fig. 1) and sun elevation during the year modify this input. Furthermore, the solar input is constantly redistributed between regions by atmospheric circulation. Thus, circulation causes air that has reached a thermal and moisture state elsewhere to arrive and influence the climate of the Mackenzie valley.

In winter, the Mackenzie valley is dominated by air originating in the polar region. The Cordillera protects this air from modification by easterly movement of mild, moist Pacific air and the very low sun angles throughout the Mackenzie valley in winter ensure an almost uniformly low solar input. In summer, the general circulation pattern changes markedly. Arctic air recedes, allowing low-pressure cells access from the west. Accompanying this change, air flow from the south and the long hours of sunlight act to make the area the warmest in all of Canada for its latitude (Stuart and Judge, 1991).

Climate is the primary factor determining the occurrence of permafrost and the intensity of landscape-forming processes. This paper describes the present-day climate of the Mackenzie valley, based mainly on climate normals for the interval 1961–1990 (Environment Canada, 1993). In this sense, this description is somewhat updated from the only thorough treatment of Mackenzie valley climate in existence, the two-volume monograph by Burns (1973). The almost complete limitation of climate recording stations to communities along the generally linear transect formed by the Mackenzie River and Delta restrict the accuracy with which parameters such as temperature or snowfall can be depicted by conventional contour maps. Although this paper makes use of maps for describing the behaviour of the atmosphere in this region, it otherwise adopts a corridor approach to depicting climate parameters along the Mackenzie valley.

The mean annual solar radiation reaching the area is shown in Figure 2 (Hare and Thomas, 1979). This is the amount of heat potentially available for warming the ground and the air near the ground. It is dependent on latitude and the amount of radiation returned to space by reflection from cloud cover. Much of the radiation received at the ground surface is also returned to space due to reflection from the ground surface, and later by re-radiation from the ground. This returned amount is roughly equal over the region. When the re-radiated amount is subtracted from the incoming amount, net radiation, or the amount left to warm the ground, remains. Net radiation has a proportionately much larger decrease from south to north than mean annual radiation. This indicates the gradation of net solar heat input present along the Mackenzie valley.

TEMPERATURE

The mean monthly temperature for the Mackenzie valley is shown in Figure 3. This figure (and other similar ones) treat the meteorological stations located along the Mackenzie River out to the Beaufort Sea at Tuktoyaktuk as a north-south transect. This way of depicting a climatic parameter makes variation along the axis of the valley readily apparent; however, it must also be realized that all stations are in valley-bottom locations and no information on the relationship of temperature to elevation is contained. An interesting feature of the mid-summer and mid-winter temperature distribution in the Mackenzie valley is its general uniformity south of Inuvik. The highest and lowest mean monthly temperatures vary by no more than 5°C throughout this section.

Atmospheric temperature inversions, whereby the expected decrease in air temperature with altitude is reversed, are common throughout the Mackenzie valley, especially in winter (Stuart et al., 1991). Although detailed records of temperature changes with altitude are available for Fort Smith, Norman Wells, and Inuvik, there is no corresponding information for temperature change with increasing elevation. Inversions in winter at Norman Wells typically result in air temperatures at an altitude of 1000 m which are 10°C warmer than at ground level. This is approximately the elevation of the top of the mountain ridge immediately east of Norman Wells (Norman Range of the Franklin Mountains). Measurements to determine the correspondence of temperature with elevation on this ridge are underway by the Geological Survey of Canada (Taylor et al., 1998).

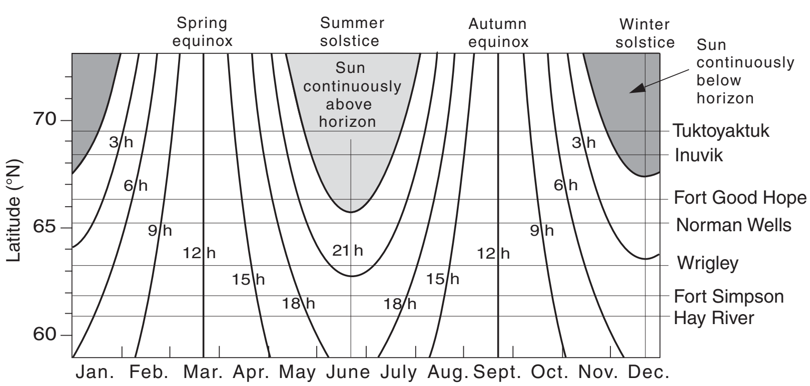

Figure 1.

Hours during which the top of the sun is above the horizon for any latitude in the Mackenzie River valley at any time during the year. The sun never sets in summer for at least a short time north of latitude 65°43′N, increasing to almost two months for the latitude of Tuktoyaktuk. Similarly, the sun never rises in the winter for at least a short time north of latitude 67°23′ and Tuktoyaktuk is continuously without direct sunlight for almost two months. The long hours of sunlight in summer and long darkness in winter contribute to the uniformity of high and low temperatures throughout the region.

Differences in the overall amount of freezing or thawing air temperature throughout the Mackenzie valley show more contrast than the maximum and minimum monthly temperatures, as shown by the transect of freezing and thawing indices in Figure 4. Although the information shown in Figures 3 and 4 is essentially the same, freezing and thawing indices express, in one number, the combined effect of duration and magnitude of freezing and thawing temperatures. They are a commonly available, useful alternative to radiative heat-flux measurements for estimating ground temperature. The considerable increase in proportion of freezing degree days northward along the valley reflects the increasing dominance of winter high-pressure systems which travel from the high Arctic generally southeasterly (Fig. 5). By January, an extensive ridge of high pressure is established over the Mackenzie valley, forming an effective block to the westward movement of warm, low-pressure areas which tend to reside in the Gulf of Alaska (Fig. 6). This dominance continues from December through March (Environment Canada, 1988). The uniform cold temperatures pointed out in Figure 4 result, in part, from the almost simultaneous incursion of the arctic air mass over all parts of the Mackenzie valley in the winter, as indicated by the residence times of arctic air in Figure 7. Warm intervals during the winter are caused by warm air masses that are part of low-pressure cells that displace the Mackenzie valley high-pressure ridge.

PRECIPITATION

Precipitation is restricted in the Mackenzie valley because of the rain-shadow effect of the Cordillera. The valley is typified by a precipitation of 300 to 400 mm, tapering off along the Mackenzie Delta to 250 mm at Inuvik and 125 mm at Tuktoyaktuk. Low-pressure systems enter the Mackenzie valley from several sources, but the channelling effect of the valley results in two major routes (Fig. 8). The first involves air which originates in the northern Pacific Ocean and moves through Alaskan valleys into Yukon Territory and then into the Mackenzie valley, often moving south from there. Air that moves directly south from the Beaufort Sea combines

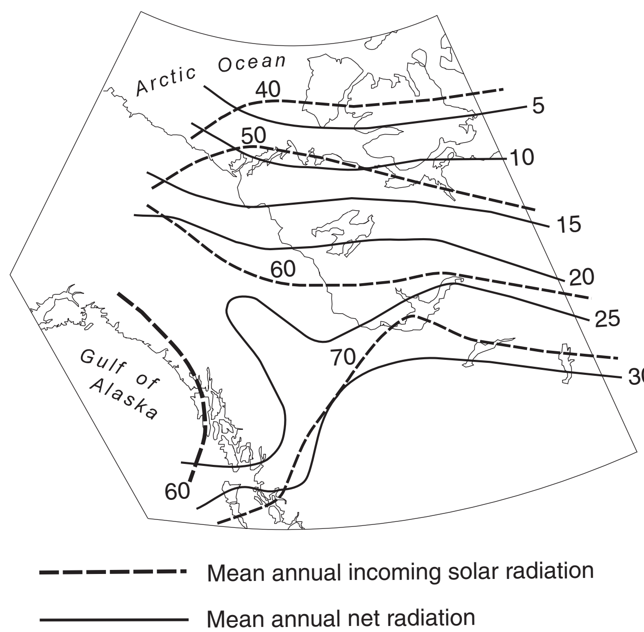

Figure 2.

Annual incoming solar radiation (kilolangleys = kilocalories/cm^2) is the basis for the Mackenzie valley's thermal character (dashed lines). Radiation input decreases with latitude, but is also reduced by cloud cover. Annual net radiation (solid lines) is the amount of energy that reaches the ground and remains to warm it. Although net radiation is ultimately responsible for determining air temperature, heat is redistributed by the movement of air masses to give a climate different from that determined by radiation at a particular location. In the case of the Mackenzie valley, heat is removed by cold air from the north, but brought in by warm air from the west or south (map adapted from *Hare and Thomas, 1979).*

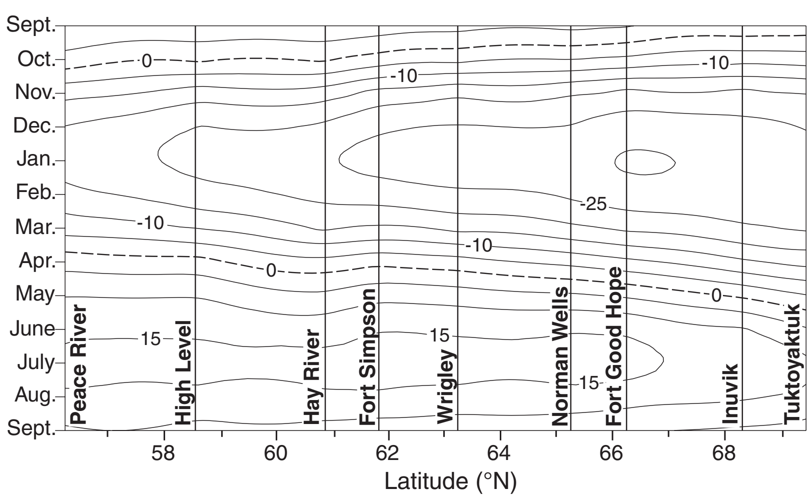

Figure 3.

Mean monthly temperature (°C) throughout the year, based on the 1961–1990 climate normals (Environment Canada, 1993) for settlements along the Mackenzie valley. The observations have been contoured to show the general trend of temperatures spatially. Note the generally similar mid-summer and mid-winter mean monthly temperatures for the valley south of Inuvik.

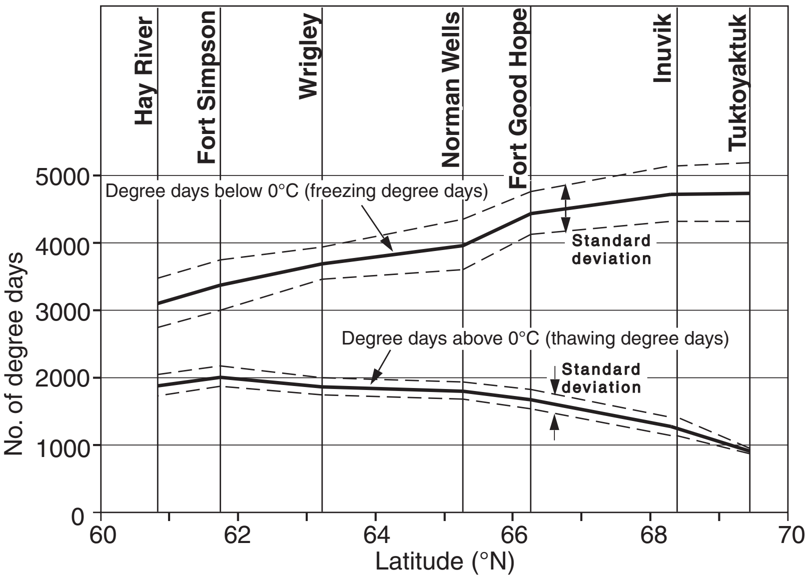

Figure 4.

A transect of freezing and thawing indexes (degree days above and below 0°C) along the Mackenzie valley. The freezing index must usually be greater than the thawing index for permafrost to persist. This is due mainly to the insulating effect of snow cover and the consequent reduction in the freezing index at the ground surface; however, in peatlands, this effect can be offset by the insulating effect of dry peat in summer. Under this condition, permafrost can persist when the indices are roughly equal. The wider standard-deviation band for the freezing index is due to the greater winter temperature variability associated with influxes of warm air from the Pacific Ocean.

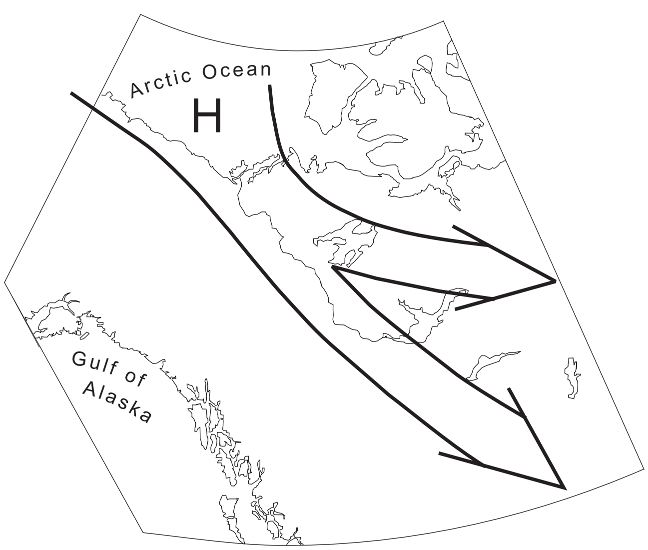

Figure 5. *Prevailing routes for the movement of arctic air into the Mackenzie valley during November to March. This air proceeds down the valley and continues to the east or southeast to act as the source for cold air masses that reach southern Canada and the United States (*adapted from *Burns, 1973).*

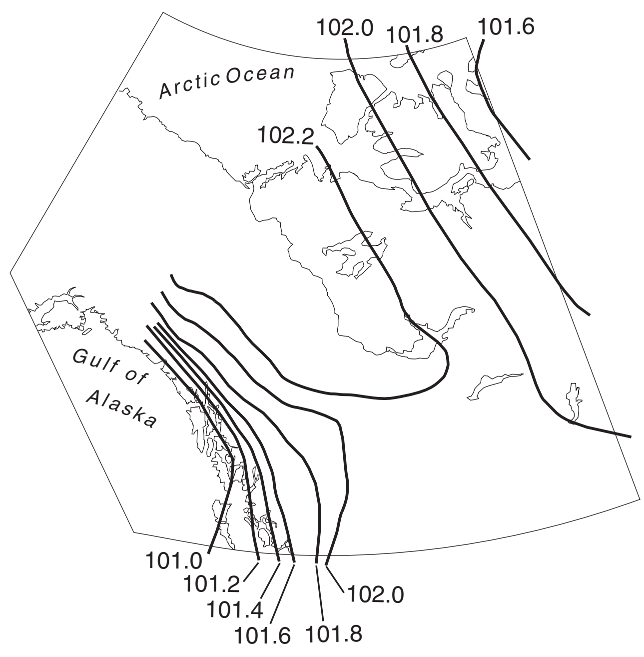

Figure 6. *Mean sea-level atmospheric pressure (kPa) for January, based on the 1951–1980 climate normals. This pattern is typical of the winter, and features the dominating ridge of high pressure centred over the Mackenzie valley. The steep gradient to low pressure in the Gulf of Alaska results from low-pressure cells that typically reside in this area. Occasionally, they displace the high-pressure ridge and move eastward across the Mackenzie valley (*adapted from *Environment Canada, 1988).*

Contents

Author Index

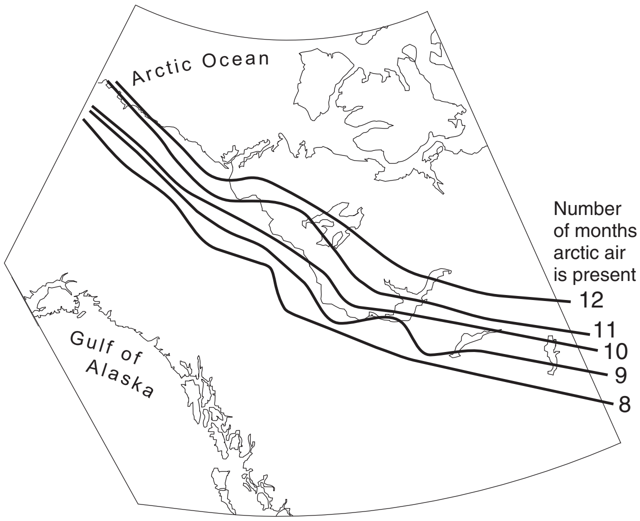

Figure 7. *Dominance of arctic air in the Mackenzie valley region. The contours represent the number of months per year arctic air is present over any location. The front shifts position during the year, remaining north of the Mackenzie valley during the summer, then moving south of it in late fall. The parallelism between this moving boundary and the valley contributes to the uniform cold temperatures in winter (diagram* adapted from *Bryson and Hare, 1974).*

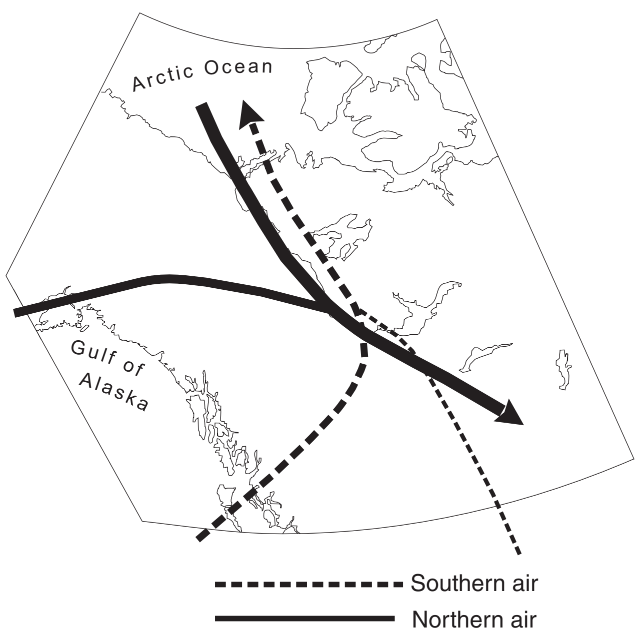

Figure 8. *Major routes of low-pressure systems entering the Mackenzie River valley. Decreasing line prominence indicates decreasing frequency with which paths are followed. Routes from the Beaufort Sea and Gulf of Alaska are the primary paths for low-pressure systems in summer and fall. Systems moving from the south (dashed lines) are infrequent, but are most likely to bring the heaviest precipitation, as was the case with the 1988 record heavy rains in the southern valley (*adapted from *Burns, 1973).*

with this flow to form the primary air pathway. The second pathway draws air from further south in the Pacific Ocean along routes that break through the Cordillera from central British Columbia to as far south as the Columbia River. This air then moves north into the Mackenzie valley by way of the Liard River valley or the plains to the east of the Cordillera.

Individual daily rainfalls are typically light with few exceeding 5 mm (Fig. 9); however, heavy rains can happen, as indicated by the summer occurrence of daily rainfalls occasionally exceeding 50 mm for sites south of Inuvik. Most of these heavy rains result from local convective storms and are inadequately represented by records from climate stations. Observations of local flooding, such as the 1970 flood of the Keele River (Burns, 1973), are evidence of otherwise unrecorded heavy rains. Also, severe frontal storms occasionally reach the region. For example, two storms moving into the Mackenzie valley from late June to mid-July, 1988, along the least-frequently traversed route shown in Figure 8, resulted in the highest recorded rainfalls for the entire region (Jasper and Kerr, 1992). Between June 29 and July 3, 260 mm of rain fell at Nahanni Butte. These storms produced a maximum discharge of 33 700 m^3/s for the Mackenzie River at Norman Wells, the highest discharge ever measured there.

By November, most precipitation falls as snow. Mean monthly snowfall rises sharply in the fall and then diminishes (Fig. 10) as the high-pressure area develops in the Mackenzie valley and prevents humid air moving in from the west. Snow accumulation proceeds more steadily throughout the fall and winter (Fig. 11), as the decrease in snowfall is compensated for by a decrease in the likelihood of thaws. The snowpack reaches its maximum depth by some time in March and then begins a more rapid ablation as the high-pressure area breaks up. As with rainfall, snowfall at Tuktoyaktuk is low compared with stations further up the Mackenzie valley, although it is typical of arctic coastal values. This is due to the dominance of arctic air, and relative remoteness from moisture-carrying storm tracks further south.

WIND

Wind patterns in the Mackenzie valley are complex due to the mountainous nature of the region. Local influences include chinook winds from the Cordillera, channelled flows through major valleys such as the Liard valley, and diurnal winds resulting from surface-temperature differences. Through the bulk of the Mackenzie valley, there is a general northwest-southeast trend to the wind direction due to the channelling effect of the valley. Of the record sites available, this trend is seen most markedly at Norman Wells and Fort Simpson (Fig. 12). Winds at Inuvik and Tuktoyaktuk show a prominent component from the east, reflecting circulation in the arctic high-pressure area, unhindered by the low surroundings. Differences in temperature between water and land offset other influences at Hay River, resulting in no strongly preferred direction.

Contents

Author Index

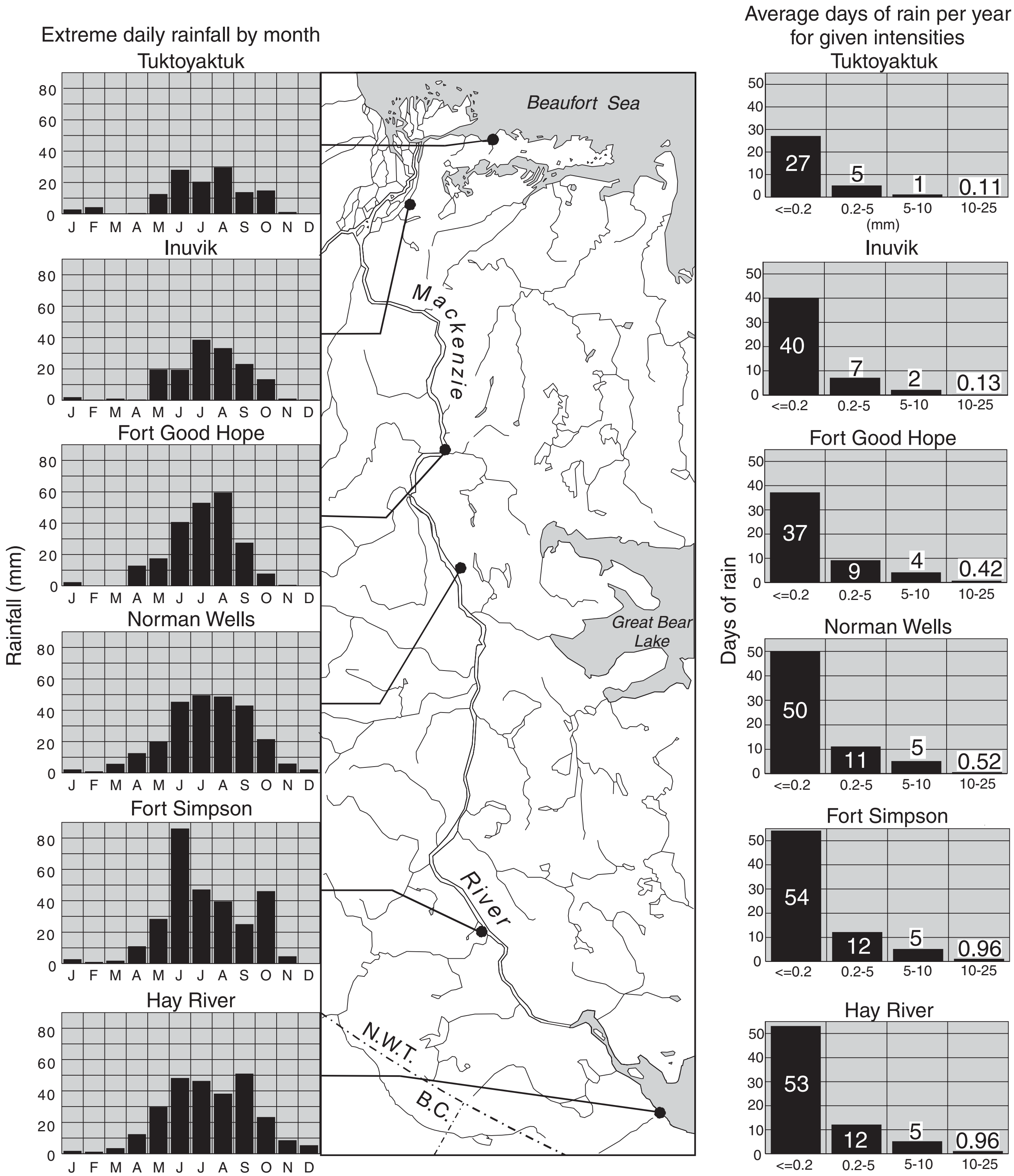

Figure 9. *Rainfall intensity along the Mackenzie valley. The bar graphs on the right show the average number of days per year having rainfall of given amounts. The graphs on the left show the single most extreme rainfall for each month during the interval 1961–1990. Rainfalls tend to be most frequent and heaviest in the southern half of the Mackenzie valley because of the incursion of moisture-laden North Pacific air masses. Furthermore, Pacific air is most likely to be unstable and produce the convective storms that are usually associated with heavy rains (diagram compiled from 1961–1990 climate normals (Environment Canada, 1993)).*

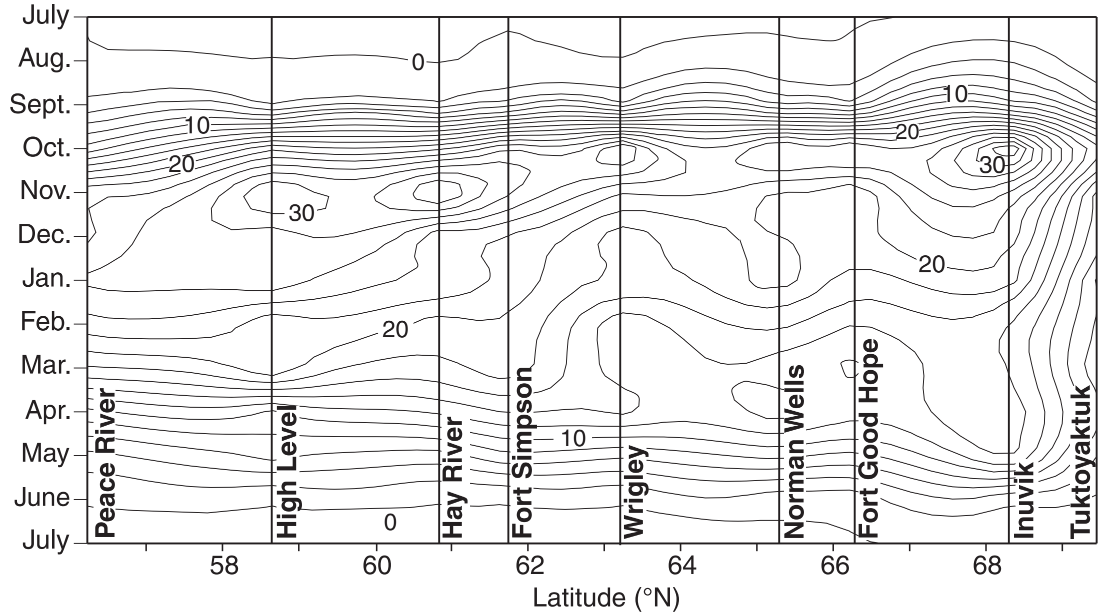

Figure 10. Mean monthly snowfall (in centimetres) generalized along the Mackenzie valley with a continuation into northern Alberta. Snowfall is heaviest in the fall, before the arctic high-pressure ridge, pictured in Figure 6, has established itself and formed a barrier to the eastward movement of low-pressure cells. By the time this high dissipates in the spring, warming reduces the chance of precipitation as snow (diagram compiled from 1961–1990 climate normals (Environment Canada, 1993)).

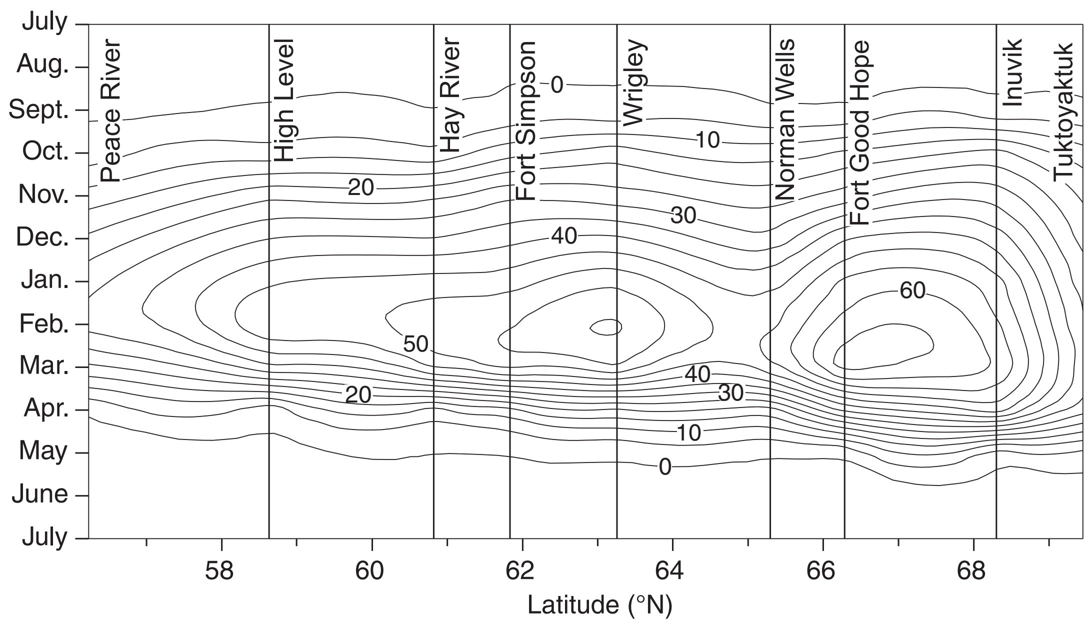

Figure 11. Snow depth at month's end (in centimetres) generalized for a transect following the Mackenzie valley. Heavier snowfalls in fall are still subject to thawing episodes, whereas lighter falls in winter seldom thaw, resulting in an overall steady accumulation. Decreasing snowfalls in warming temperatures in spring lead to a rapid decrease in snow depth.

RECORDED CHANGES

This summary is based on averages of measurements over a fixed interval of time, and so gives no indication of change. For some stations, climatic records exist prior to the 30 year interval on which much of this summary is based. Measurement records are thus available that can be used to discern change over intervals occasionally longer than 50 years. For several Mackenzie valley stations, plots of average annual temperature and snow depth at the end of February are presented in Figure 13. For both these parameters, linearregression lines have been included in the histories. The regression lines show the overall average trend for the period of record. Although short-term variability is greater than the regression trends for both parameters, all locations show an overall increasing temperature and decreasing snow depth for roughly the last 50 years, except Fort Good Hope, where a slight decrease in temperature has occurred. Although ground temperatures would be expected to respond to the overall warming observed in Figure 13, Stuart et al. (1991) have noted that the corresponding decrease in snow depths may offset this

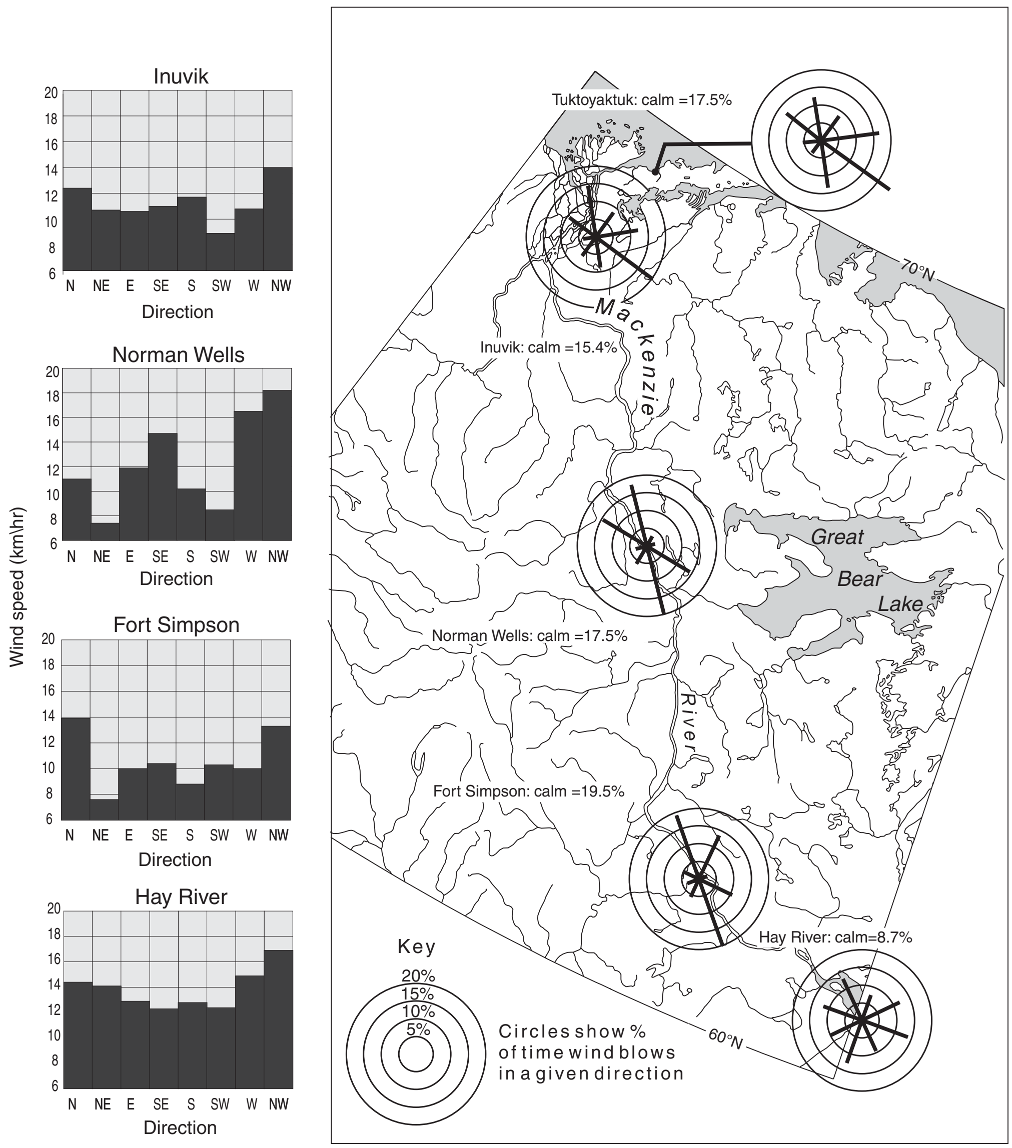

__Figure 12.__ Wind direction and speed for settlements in the Mackenzie valley. Winds tend to be channelled by the Mackenzie valley, being northwesterly for outbreaks of the arctic high and southeasterly when this air is replaced by warmer air from the south. Dominant easterlies on or near the arctic coast result from the clockwise circulation about the arctic high. Winds at Hay River suggest the influence of onshore-offshore temperature differences beside Great Slave Lake competing with more regional patterns of flow. Average wind speeds are highly variable, but show a slight tendency to be strongest from the north or northwest and the southeast, again reflecting the channelling effect of the valley.

Contents

Author Index

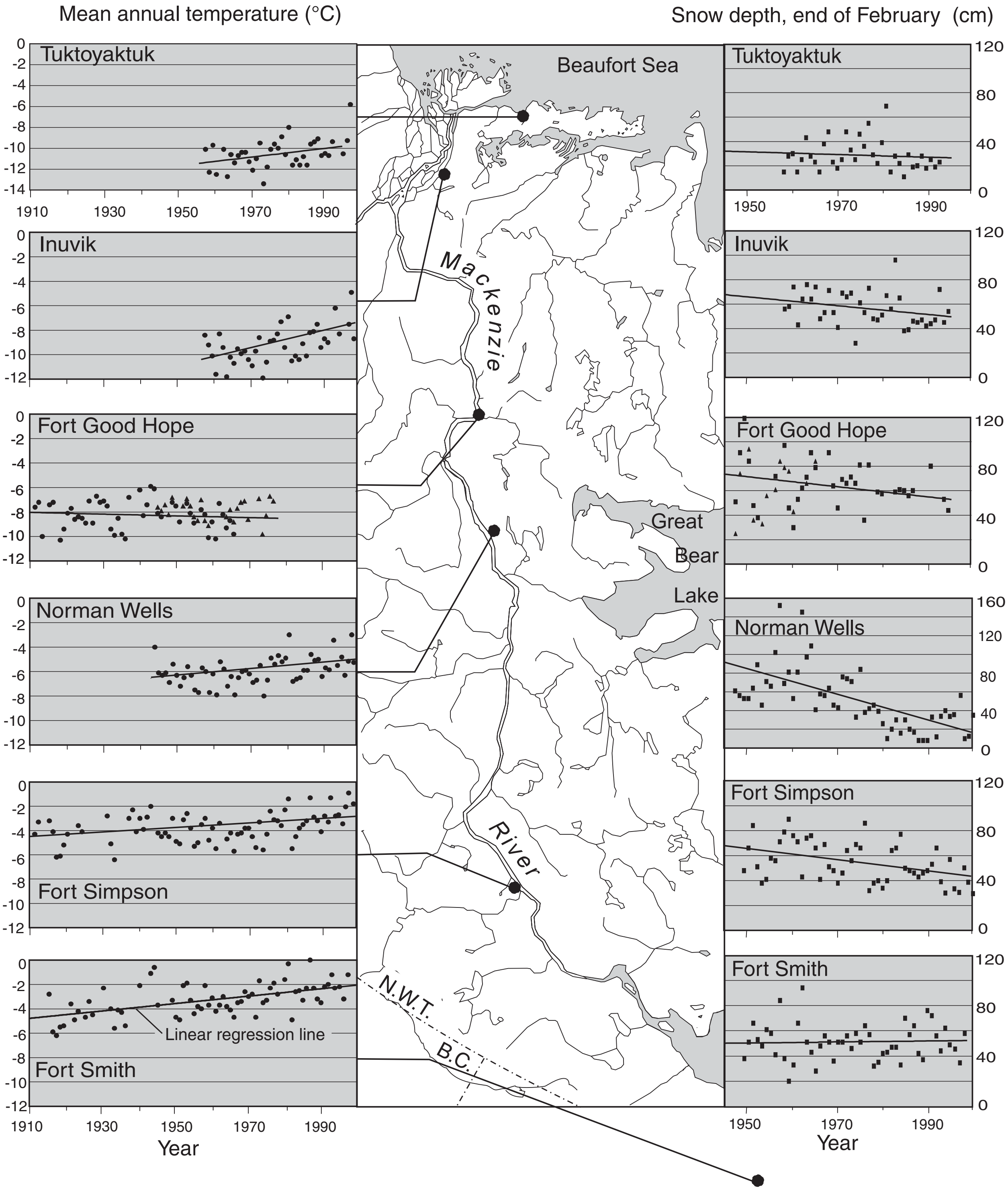

Figure 13. The six longest Environment Canada climate records available for mean annual temperature and snow depth at the end of February for stations in the Mackenzie valley. Linear regression lines suggest an overall warming and decrease in snow depth for the intervals of record. These trends are consistent with other indications of climate change during the emergence from the Little Ice Age, such as retreat of glaciers, ground temperature warming, and degradation of permafrost near its southern limit.

Contents

Author Index

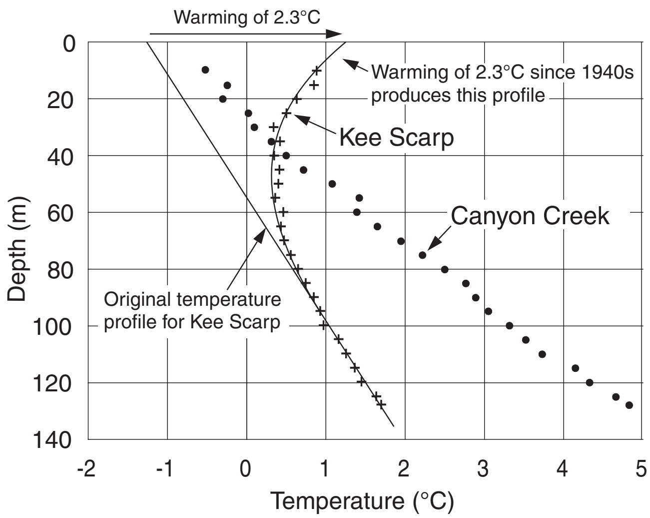

Figure 14. *Ground temperatures measured in the Kee Scarp borehole (crosses) and Canyon Creek borehole (dots) near Norman Wells. The deepest values for the Kee Scarp borehole are used to define the initial linear temperature gradient that is assumed to have existed before a warming in air temperature produced the curvature in the observations. The difference in temperature given by the two trends at the surface is the inferred warming. The Canyon Creek borehole shows no curvature, but projects to the same surface temperature as probably originally existed at Kee Scarp. Atmospheric temperature inversions in winter may be delaying the response to an overall warming that is apparent in the higher elevation Kee Scarp borehole.*

change by providing less insulation against cold penetration in winter. Therefore, ground warming may be delayed by decreasing snow depths.

USE OF GROUND TEMPERATURES FOR INFERRING PAST AIR TEMPERATURES

Independent evidence indicating an air temperature rise at Norman Wells is available from ground-temperature measurements in a 128 m borehole on Kee Scarp, a limestone ridge lying about 300 m higher than, and a few kilometres from, the Norman Wells climate station (Burgess et al., 1990). The temperature change with depth exhibits strong curvature that can be attributed to climate warming during the last few decades (Fig. 14). A change in temperature at the ground surface has been propagated downwards, displacing temperatures from the original linear gradient. The time since the beginning of the change can be determined by matching predicted temperature profiles with the borehole data. The analysis of the Kee Scarp borehole shows that the curvature in the temperature profile is consistent with a gradual ground-surface temperature increase of 2.3°C starting in the mid-1940s or a sudden increase in the mid-1960s (A.E. Taylor, pers. comm., 1996).

The inferred temperature increase at the Kee Scarp site is greater than the average annual air-temperature warming of 1°C over the same time interval indicated for Norman Wells (Fig. 13). A forest fire which burned the area around the Kee Scarp borehole, and probably destroyed insulating surface vegetation in 1954, may account for part of the warming. In contrast, a temperature profile to the same depth at Canyon Creek, another location near Norman Wells, but at the same elevation as the climate station, shows no suggestion of a temperature change (Fig. 14). The equilibrium temperature profiles for both boreholes give the same temperature when projected to the ground surface, differing in slope because of different ground thermal conductivities at the two sites. The higher elevation of the Kee Scarp site may be associated with a more pronounced air-temperature warming because of the tendency for the coldest air to pool at the lowest elevations during inversions. The lack of a temperature change at the Canyon Creek site may be due to a compensating effect of decreasing snow depth if the trend of decreasing snowfall at Norman Wells indicated in Figure 13 is representative of the area. Although these explanations for the ground temperatures at the two sites cannot be verified, the difference in temperature between the two boreholes is a suggestion of how important local climate may be in controlling ground temperature and the distribution of permafrost.

ACKNOWLEDGMENTS

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