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Abstract: A major field program was undertaken in March 2007 by the Geological Survey of Canada in order to address gaps in baseline environmental information in the Mackenzie Valley between Fort Good Hope and Norman Wells, Northwest Territories. Sites were selected to represent a range of ground-thermal, terrain, and vegetation conditions. Eleven boreholes were preserved and instrumented with temperature cables to provide information on the ground-thermal regime. Data collected from ten of these boreholes in September 2007 allow a preliminary characterization of the ground-thermal regime in an area where little recent data are available. Key baseline ground-thermal information was generated for a suite of representative terrain types that may be utilized in planning northern development and environmental impact assessment. Ongoing collection of data from the thermal-monitoring sites will continue to facilitate improved characterization of current permafrost conditions and change detection.

Résume : En mars 2007, la Commission géologique du Canada a entrepris un important programme de travaux sur le terrain afin de combler des lacunes dans l'information environnementale de base dans la vallée du Mackenzie, entre Fort Good Hope et Norman Wells, dans les Territoires du Nord-Ouest. Le choix des sites visait à représenter une gamme de conditions ayant trait au régime thermique du sol, à la nature du terrain et à l'état de la végétation. Onze sondages ont été maintenus en état et instrumentés à l'aide de câbles indicateurs de la température, afin d'obtenir de l'information sur le régime thermique du sol. Les données recueillies en septembre 2007 dans dix de ces sondages permettent d'effectuer une caractérisation préliminaire du régime thermique du sol dans une région pour laquelle il y avait peu de données récentes. L'information de base essentielle ainsi obtenue pour une série de types de terrains représentatifs pourra être utilisée aux fins de la planification de la mise en valeur du Nord et de l'évaluation des incidences environnementales. La collecte continue de données aux sites de surveillance du régime thermique permettra d'améliorer la caractérisation de l'état actuel du pergélisol et la détection des changements.

INTRODUCTION

Permafrost is an important feature of the Mackenzie Valley landscape that has impacts on both the natural and socio-economic environment of the region. Permafrost and its associated ground ice can affect entire ecosystems through its influence on drainage patterns and ground stability, and also present challenges to northern development. Since permafrost is a thermal condition, its distribution and temperature are sensitive to changes in the surface energy balance that may result from changes in climate or alterations of the ground surface such as that due to clearance of vegetation or removal of the organic layer associated with development. Any warming and subsequent thawing of permafrost can lead to changes in the landscape such as slope movements, thermokarst development, and ground subsidence, which can have important implications for the integrity of northern infrastructure as well as surface and subsurface hydrology, ecosystems, and northern lifestyles.

Knowledge of permafrost conditions (temperature, active-layer thickness, and ground-ice conditions) and their spatial and temporal variation is critical for rational planning of development in northern Canada and for understanding the impact of environmental disturbance and climate change on the permafrost environment. Increased activity is anticipated in the Mackenzie Valley associated with proposed hydrocarbon development, which includes construction of a pipeline to carry natural gas from the Mackenzie Delta to northern Alberta. Knowledge of ground-thermal conditions is essential for both engineering design and assessment of environmental impacts associated with these developments. In addition, ongoing monitoring of permafrost conditions is essential to understand how these conditions may change over time, to assess impacts on northern development, and to develop mitigation strategies.

Since the mid 1980s, the Geological Survey of Canada (GSC) has been developing and maintaining a permafrost-monitoring network in the Mackenzie Valley, including a suite of sites along the Norman Wells to Zama pipeline corridor (*see* e.g. Smith et al., 2004, 2005b). One of the significant gaps in this network was the region between Norman Wells and Inuvik. Gaps in baseline geotechnical and permafrost information were identified in an analysis led by the Department of Indian and Northern Affairs (Gartner Lee Limited, 2003). In 2004, the GSC undertook to address some of these gaps with funding obtained through a Northern Energy Development Memorandum to Cabinet. Fieldwork conducted between 2005 and 2007 was directed toward the drilling of several boreholes, collection of samples to determine geotechnical properties, preservation of boreholes, and installation of instrumentation for long-term ground-temperature monitoring. In March 2007, an important gap between Norman Wells and Fort Good Hope was addressed through the drilling of boreholes at nine locations. Eleven boreholes were preserved for temperature measurement. An earlier paper (Smith et al., 2007) summarized the fieldwork conducted between Norman Wells and Fort Good Hope and presented preliminary information on surficial materials and thermal conditions. This paper summarizes the ground-temperature data collected between March and September 2007 and provides a preliminary description of the ground-thermal regime between Norman Wells and Fort Good Hope.

REGIONAL SETTING

The physical landscape of the study area is primarily a result of the last continental glaciation that covered most of the region about thirty thousand years ago, hence most areas are underlain by unconsolidated glacial and postglacial deposits. Extensive deposits (up to 30 m thick) of glaciolacustrine and lacustrine silt and clay, which are commonly ice-rich, are found in the region that are associated with the large temporary lake basins that formed during deglaciation (Aylsworth et al., 2000; Duk-Rodkin and Lemmen, 2000). The postglacial landscape comprises morainic and fluvial landforms of the northern Interior Plains. Boreal forest dominates the area and is characterized by spruce, shrub undergrowth, and a moss-lichen floor. Where drainage is impeded, accumulations of peat (Aylsworth and Kettles, 2000) cover the mineral soils.

The regional climate is characterized by long winters with normal mean January air temperature (based on 1971–2000 normals) of −26.5°C and normal mean July temperature of 17°C at Environment Canada's Norman Wells weather station (Fig. 1). Normal annual total precipitation is about 290 mm at Norman Wells, of which about half falls as snow that stays on the ground from October to April.

The study area lies within the zones of intermediate and extensive discontinuous permafrost defined by Heginbottom (2000) with permafrost underlying 35–90% of the land surface (Fig. 2). An analysis of the geotechnical borehole

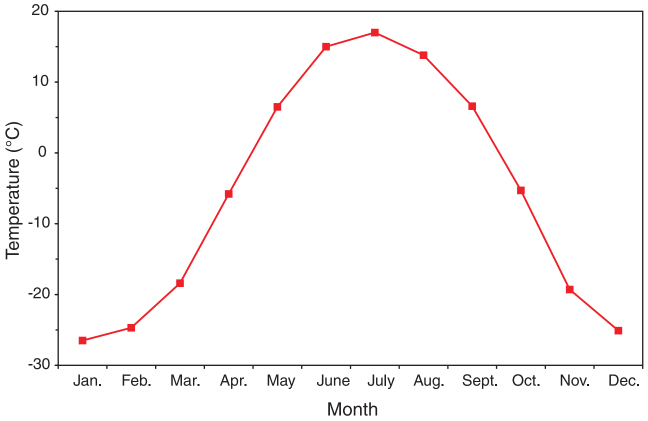

Figure 1. Normal (1971–2000) mean monthly air temperature at Norman Wells, Northwest Territories (Environment Canada website, http://www.climate.weatheroffice.ec.gc.ca/climate_normals/index_e.html).

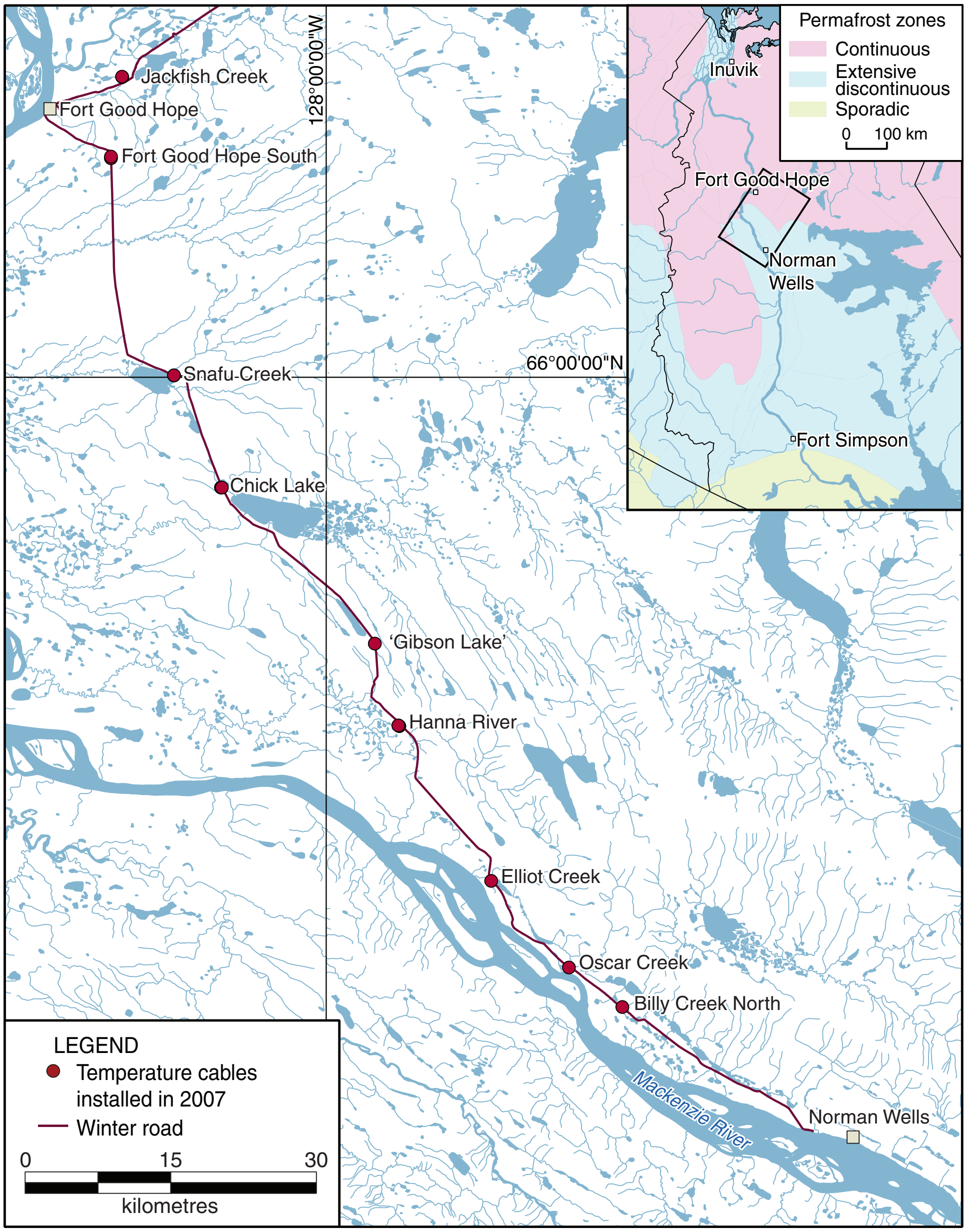

Figure 2. Permafrost distribution in the Mackenzie Valley and location of thermal-monitoring sites established in 2007 between Fort Good Hope and Norman Wells (note 'Gibson Lake' is an informal name).

database of Smith et al. (2005a) provides preliminary information on the distribution of frozen ground within the Mackenzie corridor and indicates that unfrozen ground may underlie up to 30% of the ground surface between Fort Good Hope and Norman Wells (Smith et al., 2007). Permafrost, where present, is generally less than 50 m thick and mean annual near-surface ground temperatures are generally –2°C or higher (Smith and Burgess, 2000, 2002).

Information on the shallow ground-thermal regime between Norman Wells and Fort Good Hope is largely based on measurements made in the early 1970s (*see* Judge, 1973). More recent data were collected between 1989 and 2000 from a GSC monitoring site at 'Gibson Gap' (informal name: 65°46′N, 127°55′W), about 70 km north of Norman Wells. The cable at 'Gibson Gap' was partially damaged during a 1998 or 1999 fire. Data have not been collected from this site since 2000. The establishment of ground-thermal–monitoring sites within this region therefore addresses a major gap in our knowledge of recent conditions.

STUDY SITES AND INSTRUMENTATION

Sites were chosen along the winter road (Fig. 2), allowing access during the winter drilling program as well as helicopter access during summer visits to retrieve data. Sites were selected to be representative of the range of terrain and vegetation conditions in the region. At some sites two boreholes were established tens of metres to 500 m apart to capture the spatial variability and transitions in surficial materials, permafrost, and ground-ice conditions that may occur over short distances and may be important for design of transportation and transmission infrastructure. Further details on site selection are given in Smith et al. (2007).

Geotechnical drilling and borehole preservation were conducted in March 2007. A rubber track-mounted M5T drill rig operated by Geotech Drilling Services Ltd. was engaged by EBA Engineering Consultants to conduct this work. Attempts were made to drill 16 boreholes between Norman Wells and Fort Good Hope to depths of 15 m to 20 m. All sites were accessed from the winter road and were located at distances of 20 m to 30 m from the road. Prior to drilling, each site was cleared of snow and brush to provide access to the site and also to provide a stable and safe platform for the drill rig. Care was taken to not cause excessive disturbance or damage to ground surface material (mineral and organic) and vegetation. Complete recovery of vegetation is expected within a year with minimal impacts of site disturbance on the ground-thermal regime. An environmental monitor from the appropriate community (Norman Wells or Fort Good Hope) accompanied the field crew to ensure that all work was carried out in a respectful manner.

Due to limitations of the drill rig and the difficult subsurface conditions encountered at some sites, it was not possible to complete all boreholes to the desired depth of 15–20 m. In some cases, borehole collapse or refusal at shallow depths (less than 4–5 m) made it impractical to preserve the boreholes for temperature measurement. Smith et al. (2007) provided details of the March 2007 field program and a description of all boreholes drilled including details on surficial materials. A total of 11 boreholes (Table 1; Fig. 2) were preserved through the installation of polyvinyl chloride (PVC) casing of 50 mm diameter. Silicone oil was placed in the PVC casing to reduce convection within the hole. Table 1 provides a brief description of the study sites and the instrumentation installed.

Multisensor temperature cables were installed in all but one of the boreholes in March 2007. A temperature cable was subsequently installed in one of the shallower boreholes (FGHS-02) in September 2007. Thermistors on the cables are YSI 46004, which have an accuracy of ±0.1°C. Eight-channel data loggers manufactured by RBR Ltd. were attached to all cables to collect data at 8-hour intervals. The measurement system allows for a resolution of ±0.01°C.

GROUND-THERMAL REGIME

Data collection and analysis

Sites were visited in late September 2007 to acquire data from data loggers connected to temperature cables in ten boreholes. At some sites the data logger malfunctioned, resulting in limited data collection. Temperature measurements were also made manually utilizing a portable multimeter. The late September ground-temperature profile is fairly representative of the period of maximum thaw penetration; however, cooling in the upper portion of the ground can occur in late summer and/or early fall and the September profile may fail to capture the maximum thaw penetration, whereas the ground at depth may continue to warm into the fall. Profiles of maximum and minimum ground temperatures for the March to September 2007 period were also determined from the continuous data-logger records. These profiles do not represent the ground-temperature envelope

Table 1. Landform and vegetation cover of sites between Fort Good Hope and Norman Wells (Smith et al., 2007). Sites are ordered with increasing distance from Fort Good Hope. Maximum depth of ground-temperature measurement (cable depth) and active-layer thickness (ALT) determined through probing (range shown in parentheses) or interpolation of ground-temperature profiles is also provided.

Site name	Borehole	UTM co-ordinates (zone 9W)	Landform	Vegetation cover	Cable depth	Sept. average ALT and range determined by probing (cm)	ALT determined by ground temperature (cm)
Jackfish Creek	JF-02	7351772N, 523779W	Eolian dune on moraine plain, well drained, high spot	Black spruce forest and moss cover	20 m	Too coarse to probe	190
Fort Good Hope South	FGHS-01	7343386N, 522694E	Hummocky peatland	Dense shrub and open black spruce	8 m	>120	200
	FGHS-02	7343323N, 522694E	Hummocky peatland	Peat plateau, lichen, open black spruce	5 m	84 (70–98)	NA
Snafu Creek	SC-01	7320273N, 529474E	Moraine plain	Peat bog, open black spruce forest, and lichen cover	16.8	57 (55–60)	70
Chick Lake	CL-01	7308478N, 534634E	Moraine plain	Peat and organic soil with open black spruce forest and shrubs	20 m	100 (95–105)	120
'Gibson Lake'	GL-01	7292195N, 550960E	Hummocky moraine plain	Recovering burnt area with peat and shrubs	20 m	59 (58–60)	90
Hanna River	HR-01	7283597N, 553624E	Lacustrine plain	Boggy burnt area	20 m	55 (50–60)	74
Elliot Creek	EC-01	7267146N, 563736E	Lacustrine undulating plain, well drained elevated area	Peat cover on edge of open, mature black spruce forest	20 m	75 (70–80)	NA
	EC-02	7267404N, 563714E	Lacustrine plain overlain by alluvial sediments	Peat cover on edge of dense, mature black spruce forest	9.7 m	71 (70–72)	80
Oscar Creek	OC-01	7258009N, 572437E	Undulating glaciolacustrine terrain overlain by alluvial sediments	Peat cover with dense-forested birch and black spruce	16 m	60 (50–70)	50
Billy Creek North	BCN-01	7254396N, 578107E	Alluvial and eolian sediments overlying low-lying lacustrine plain	Peat cover with dense-forested black spruce and mixed shrubs	15 m	Too coarse to probe	190

NA = not available

(especially at shallower depths) since a full year of data has not been collected; however, preliminary information is provided on the variation in temperatures that may occur at each depth.

Maximum thaw penetration (defined as the depth of the 0°C isotherm) was determined through interpolation of the ground temperature from either the late September (manual reading) or maximum logged temperature profile (whichever was available). In addition, manual probing, through insertion of a metal probe into the ground to the point of refusal, was conducted around each borehole to determine whether frozen ground was present in the upper 1.2 m (Table 1). For sites where granular material was present in the upper 1 m of the ground, it was not possible to probe to the base of the active layer. Other information extracted from the ground-temperature data was an estimate of the depth of the zero annual amplitude or the maximum depth to which seasonal temperature variations penetrate.

Thermal data

Figure 3 summarizes ground temperature at approximately 8 m depth (the greatest depth with data available for all sites considered), zero-amplitude depth, and average active-layer thickness determined from the September or maximum temperature profile for the ten boreholes located between Fort Good Hope and Norman Wells. For the Hanna River site (HR-01), only the September ground-temperature data were available due to problems with the data logger. Therefore, for comparison purposes, only the September ground temperatures at 8 m are shown in Figure 3. The cable at site BCN-01 was damaged during the summer and data from August 11, 2007 is presented. Difficulties were also encountered with the instrumentation at site EC-01 and data from July 5, 2007 are presented. Although the temperature profiles are not directly comparable between these two sites and the others, the change in temperature at a depth of 8 m (based on data collected) between July and September is probably minimal. Insufficient ground-temperature data were available to determine the maximum thaw depth at site EC-01 and the active-layer thickness could only be determined through manual probing. Thaw depths determined through probing and interpolation of ground-temperature profiles are also summarized in Table 1. Active-layer thicknesses determined by the two methods were comparable.

September ground-temperature profiles are provided in Figure 4 for all sites except BCN-01 (August profile presented) and EC-01 (July profile presented). The maximum and minimum temperatures recorded for each depth are shown for nine boreholes in Figure 5.

Although ground temperatures are generally lower at the more northerly sites (Fig. 3) a strong relationship between latitude and temperature is not indicated. The thermal condition of the ground is affected more by vegetation and soil

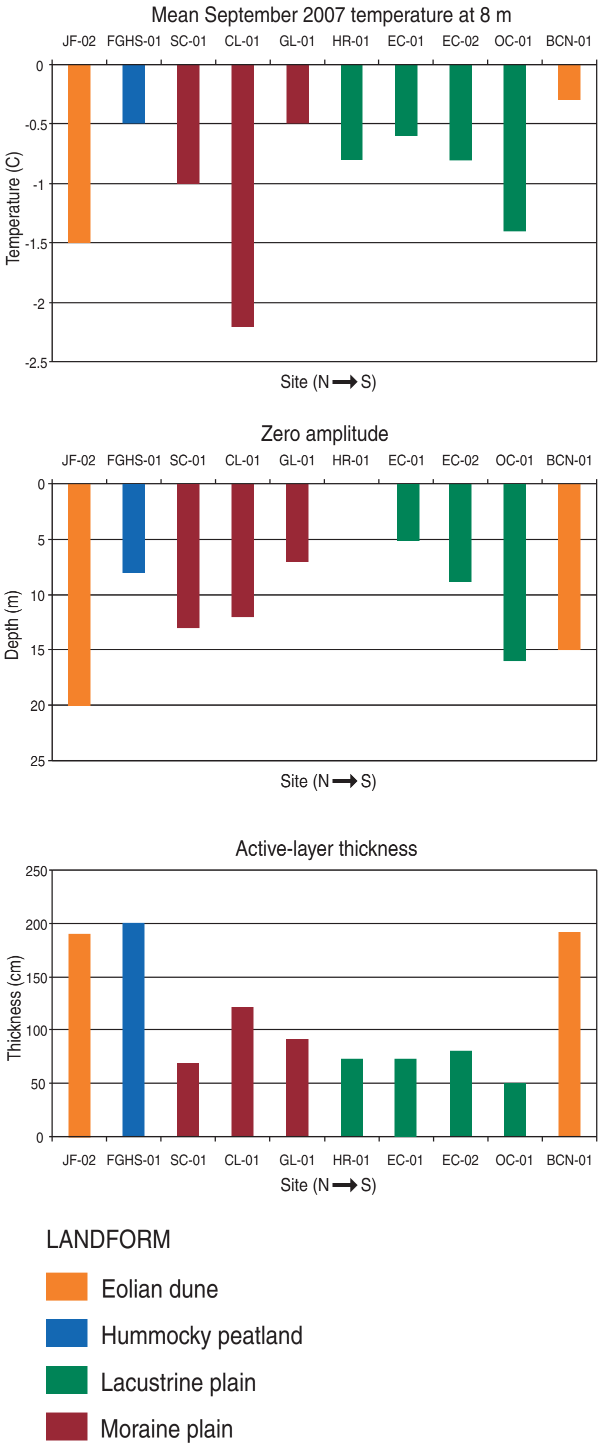

Figure 3. September ground temperature at 8 m, zero-amplitude depth, and active-layer thickness determined from interpolation of ground temperature for sites ordered north to south and classified according to landform type. Site EC-01 active-layer thickness was determined through probing and active-layer thickness for site BCN-01 is based on the maximum ground temperature between July and August. Temperature data for sites BCN-01 and EC-01 are from August and July, respectively as data were not available for September. Insufficient data were available for site HR-01 to determine the depth of zero amplitude.

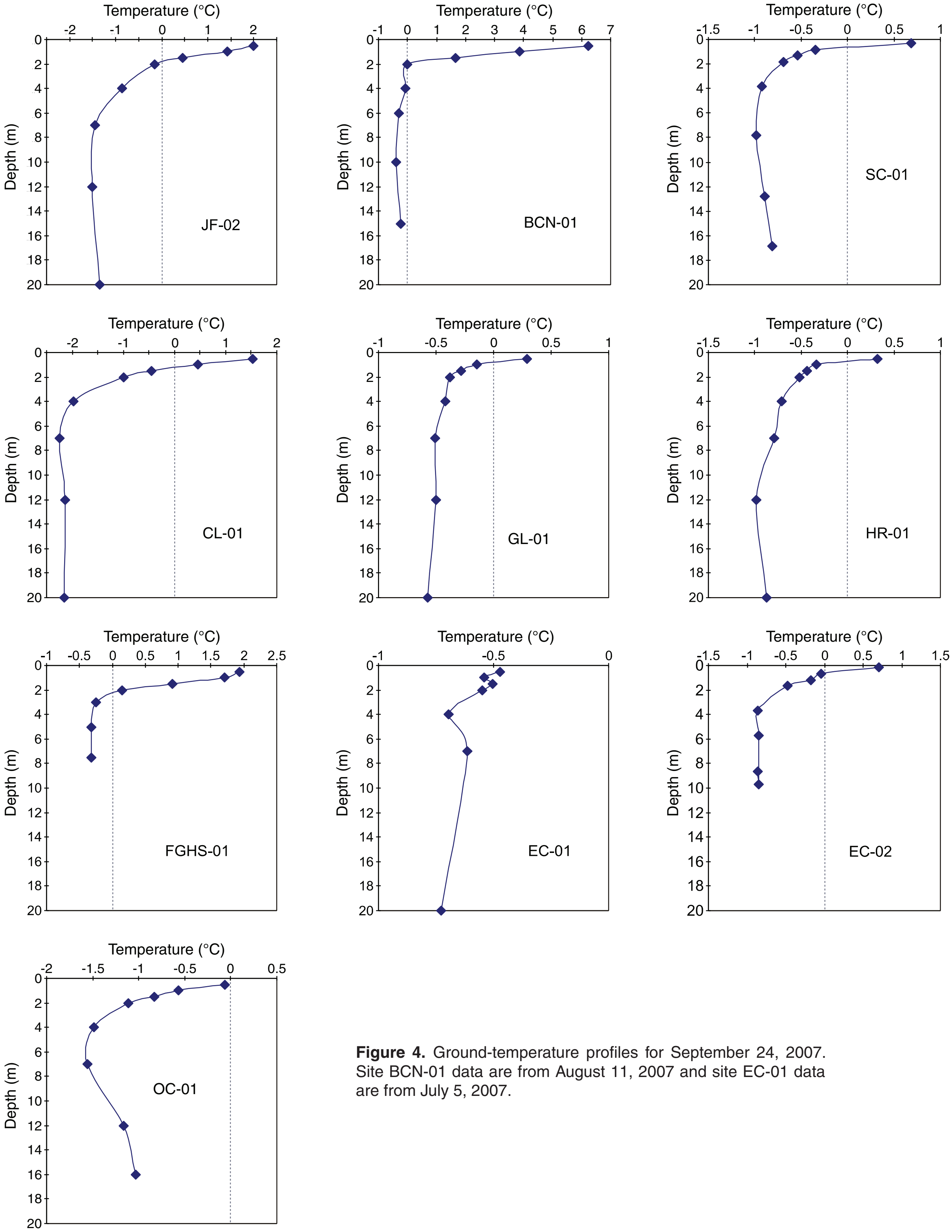

Figure 4. Ground-temperature profiles for September 24, 2007. Site BCN-01 data are from August 11, 2007 and site EC-01 data are from July 5, 2007.

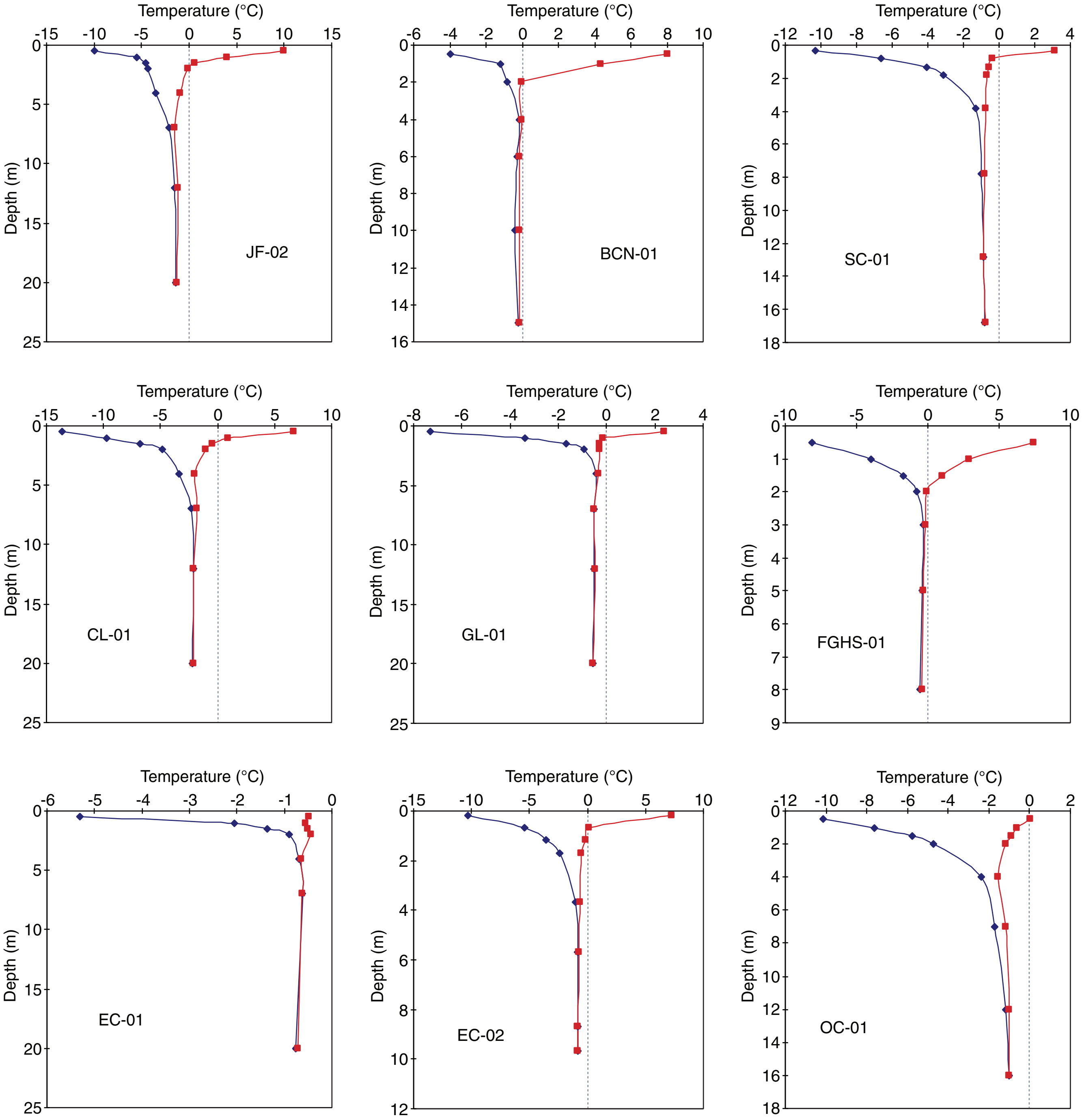

Figure 5. Maximum (red) and minimum (blue) ground temperature for the period March to September 2007. Site BCN-01 data were only available until August 11, 2007 and site EC-01 data were only available until July 5, 2007.

conditions than latitude. The lowest September ground temperatures were observed for sites JF-02, CL-01, and OC-01 (Fig. 3, 4). These three sites have a depth of zero amplitude greater than 10 m and a large range in temperature at shallow depths (Fig. 5) compared to other sites. Sites JF-02 and BCN-01 were both underlain by eolian sediments, but were located on the opposite ends of the north-south Fort Good Hope-Norman Wells transect (Table 1; Fig. 2). Also, site JF-02 was located in a well drained elevated area whereas site BCN-01 was located in a flatter location and closer to the floodplain with alluvial sediments. In addition, site BCN-01 had a much higher ice and moisture content compared to site JF-02 (Smith et al., 2007). At site BCN-01, ground temperatures were about –0.1°C at depths of 2 m to 15 m whereas at site JF-02, ground temperatures were −1.5°C at depths of 7 m to 20 m (Fig. 4, 5). Ground-temperature data from site BCN-01 appears to confirm the presence of permafrost at the site. Unfrozen zones within the permafrost at site BCN-01 were recorded on the drilling logs (Smith et al., 2007) and these were probably due to the thawing of the warm permafrost with drilling disturbance since no talik is indicated by the ground-temperature profile.

Sites SC-01, CL-01, and GL-01 were all on moraine plains with peat and organic soil. Site GL-01 had the additional characteristic of being in a recovering burnt area (Table 1). Site CL-01 had the thickest active layer (Fig. 4) among these three sites and also had the highest ice content (Smith et al., 2007). Lower ground temperatures of −2°C from 7 m to 20 m depth were also observed for site CL-01, whereas data indicate that site GL-01 had the shallowest zero amplitude at 7 m (Fig. 5). In contrast, site SC-01 with a coarser soil of lower ice content and a thicker organic layer, had the deepest zero amplitude at 13 m. Although site GL-01 was located at an elevation of more than 100 m higher than surrounding monitoring sites, ground temperatures were not found to be lower than the sites located at lower elevation. Warming of the ground following burning of vegetation and organic material at site GL-01 may be a factor. Also, Taylor et al. (1998) found that frequent air-temperature inversions in the Mackenzie Valley may result in higher ground temperatures at higher elevations.

Field observations during drilling noted unfrozen ground between approximately 4 m and 8 m depth at site SC-01 (Smith et al., 2007). The ground-temperature data, however, indicates the presence of permafrost at this depth (Fig. 5). The sediments at this depth consisted of clay and gravel and were likely poorly ice-bonded. In addition, some thawing may have occurred due to the drilling disturbance. These circumstances likely led to this soil being misclassified as unfrozen in the field.

The hummocky peatland at site FGHS-01 is underlain by permafrost at temperatures warmer than –0.5°C (Fig. 4, 5). Although the active-layer thickness is about 2 m, ground temperatures below this depth exhibit little variation (Fig. 5). Field observations during drilling indicated that permafrost was not present at this site (Smith et al., 2007). The ground-temperature data, however, indicate that permafrost is present (Fig. 4), although it is at temperatures close to 0°C. Thermal disturbance during drilling may have caused some thawing. In addition, the fine-grained material would have a high unfrozen water content at temperatures that are only a few tenths of a degree below 0°C.

Sites HR-01, EC-01, EC-02, and OC-01 were all located in lacustrine plains and had comparable active-layer thicknesses (Fig. 3, 5); however, sites EC-02 and OC-01 were established in flatter terrain underlain by alluvial sediments, whereas site EC-01 was situated in a well drained elevated area with a more open vegetation cover and site HR-01 was in a boggy burnt area (Table 1). Site EC-01, with a thicker peat cover and higher ice content at shallow depths, had a shallower zero-amplitude depth than site EC-02 or OC-01 (Fig. 3, 5), illustrating that latent heat effects associated with freezing and thawing of the shallow ground buffer the downward propagation of surface temperature. The denser forest cover at site OC-01 was probably a factor in the colder September ground temperature (Fig. 4) experienced at that site by reducing the amount of solar radiation received.

SUMMARY

To address gaps in baseline permafrost conditions, the GSC undertook a major field program to establish new thermal-monitoring sites. During March 2007, a key gap in the discontinuous permafrost zone between Fort Good Hope and Norman Wells was addressed through the establishment of 11 thermal monitoring sites in representative terrain units. These monitoring sites cover the range of conditions found within the region, including thermal regime, terrain type, vegetation cover, and peat thickness.

Ground-temperature data collected during the first six to seven months following site establishment allows a preliminary characterization of the ground-thermal regime. The results show that mean ground temperatures can be quite variable, ranging from lower than −2°C to higher than –0.5°C. Although there is a general decrease in ground temperature northward, local factors such as vegetation and soil conditions have a significant influence. These results show that permafrost temperatures can be quite close to the thawing point and that vegetation removal and surface disturbance that may accompany construction of pipelines or other infrastructure in the region may lead to degradation of permafrost. Some of this warmer permafrost (temperature >-1°C) occurs in ice-rich fine-grained sediment that may exhibit significant settlement and ponding upon thawing, having implications for infrastructure integrity, drainage, and ecosystems. In addition, thin marginal permafrost may thaw in response to vegetation clearing and surface disturbance associated with pipeline construction, but the ground may freeze again around chilled pipelines, resulting in frost heave or drainage disruption.

Key baseline information on the ground-thermal regime has been generated through this project that is essential for infrastructure design, the assessment of environmental impacts, and land-use planning. In particular, ground-thermal data are now available for a region for which no recent data were available. The data presented here provides a preliminary characterization of the ground-thermal regime, which will be refined as more data becomes available. The ongoing operation of the monitoring network and collection of thermal data will also facilitate improved characterization of permafrost-climate interaction and predictions of climate-change impacts. The monitoring network can also be an important component of future monitoring programs associated with hydrocarbon and other development in the Mackenzie corridor.

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