uOttawa

L'Université canadienne
Canada's university

FACULTÉ DES ÉTUDES SUPÉRIEURES ET POSTOCTORALES

uOttawa

L'Université canadienne
Canada's university

FACULTY OF GRADUATE AND POSDOCTORAL STUDIES

Megan Ann James
AUTEUR DE LA THÈSE / AUTHOR OF THESIS

M.Sc. (Geography)
GRADE / DEGREE

Department of Geography
FACULTÉ, ÉCOLE, DÉPARTEMENT / FACULTY, SCHOOL, DEPARTMENT

Historic Change in Permafrost Distribution in Northern British Columbia and Southern Yukon Territory, Canada

TITRE DE LA THÈSE / TITLE OF THESIS

A. Lewkowicz
DIRECTEUR (DIRECTRICE) DE LA THÈSE / THESIS SUPERVISOR

S. Smith
CO-DIRECTEUR (CO-DIRECTRICE) DE LA THÈSE / THESIS CO-SUPERVISOR

B. Lauriol

C. Burn

Gary W. Slater
Le Doyen de la Faculté des études supérieures et postdoctorales / Dean of the Faculty of Graduate and Postdoctoral Studies

Historic Change in Permafrost Distribution in Northern British Columbia and Southern Yukon Territory, Canada

Megan James

Thesis submitted to the
Faculty of Graduate and Postdoctoral Studies
In partial fulfillment of the requirements
For the MSc Geography

Department of Geography
Faculty of Arts
University of Ottawa

© Megan James, Ottawa, Canada, 2010

Library and Archives
Canada

Published Heritage
Branch

395 Wellington Street
Ottawa ON K1A 0N4
Canada

Bibliothèque et
Archives Canada

Direction du
Patrimoine de l'édition

395, rue Wellington
Ottawa ON K1A 0N4
Canada

Your file Votre référence
ISBN: 978-0-494-69096-3
Our file Notre référence
ISBN: 978-0-494-69096-3

NOTICE:

The author has granted a non-exclusive license allowing Library and Archives Canada to reproduce, publish, archive, preserve, conserve, communicate to the public by telecommunication or on the Internet, loan, distribute and sell theses worldwide, for commercial or non-commercial purposes, in microform, paper, electronic and/or any other formats.

The author retains copyright ownership and moral rights in this thesis. Neither the thesis nor substantial extracts from it may be printed or otherwise reproduced without the author's permission.

AVIS:

L'auteur a accordé une licence non exclusive permettant à la Bibliothèque et Archives Canada de reproduire, publier, archiver, sauvegarder, conserver, transmettre au public par télécommunication ou par l'Internet, prêter, distribuer et vendre des thèses partout dans le monde, à des fins commerciales ou autres, sur support microforme, papier, électronique et/ou autres formats.

L'auteur conserve la propriété du droit d'auteur et des droits moraux qui protège cette thèse. Ni la thèse ni des extraits substantiels de celle-ci ne doivent être imprimés ou autrement reproduits sans son autorisation.

In compliance with the Canadian Privacy Act some supporting forms may have been removed from this thesis.

While these forms may be included in the document page count, their removal does not represent any loss of content from the thesis.

Conformément à la loi canadienne sur la protection de la vie privée, quelques formulaires secondaires ont été enlevés de cette thèse.

Bien que ces formulaires aient inclus dans la pagination, il n'y aura aucun contenu manquant.

Canada

Abstract

The impact of recent climate change on permafrost distribution was evaluated by repeating the 1964 survey of Roger Brown along the Alaska Highway from Whitehorse, YT to Fort St. John, BC in August 2007 and 2008. Results demonstrate that: (1) significant degradation of permafrost has occurred over the past four decades, especially in the southernmost part of the route where 67% of the permafrost sites in 1964 no longer exhibit perennially frozen conditions; (2) the mapped southern limit of discontinuous permafrost appears to have shifted roughly 75 km northward; (3) most of the permafrost still present in the study area is in peat or under thick organic mats, which probably relates to a large thermal offset or to the latent heat requirements of thawing permafrost; and (4) that where permafrost has persisted, it is very thin, discontinuous, at temperatures just below 0°C, and its location may relate in part to the existence of atmospheric temperature inversions in the region. Changes in permafrost are attributed to significant climatic warming, primarily in winter, at rates of 0.4°C to 0.5°C per decade from 1965-2008. The results augment the very limited number of field studies of long-term change to permafrost in Canada, and are relevant to northern residents who must adapt to changing permafrost conditions.

Acknowledgements

Support for this project has been provided by the Federal Government of Canada's International Polar Year Program (Thermal State of Permafrost in Canada Project), the NSERC Northern Internship Program, the NSERC Postgraduate Scholarship program, the W. Garfield Weston Foundation, the Northern Scientific Training Program, DIAND, and the Yukon Geological Survey. This thesis benefited from the assistance of numerous individuals. Antoni Lewkowicz and Sharon Smith, thesis supervisor and co-supervisor, respectively, showed admirable patience and gave valuable direction and expert advice. Catherine Henry and Samantha Darling provided exceptional field assistance. Panya Lipovsky gave excellent guidance, while Jean Bjornson, Phillip Bonnaventure and Marian Kremer provided highly appreciated advice and technical assistance. Gratitude is also owed to Mike Sawada, who allowed the use of his research facilities. Also, thank you to Roger Yen, who gave so much support and help, and to my family, who always gives me so much love and encouragement.

Table of contents

List of Tables

List of Figures

1.0 Introduction and Objectives

1.1 Introduction

The distribution and characteristics of permafrost are broadly climatically controlled, especially by air temperature and precipitation, although surface and subsurface factors have impacts at the local scale (Smith and Riseborough, 1996, 2002). Numerous studies have shown that permafrost should warm and diminish in extent with rising air and ground temperatures (ACIA, 2005; Anisimov and Nelson, 1997; Camill, 2005; Camill and Clark, 2005; IPCC, 2007; Jorgenson *et al.*, 2001; Lachenbruch and Marshall, 1986, Osterkamp and Romanovsky, 1999). However, most of these predictions are based on inferences through modeling, and there are very few field-based studies of long-term permafrost distribution change in Canada (an exception being Kwong and Gan, 1994). In contrast, these exist in Russia (e.g. Frauenfeld *et al.*, 2004; Pavlov, 1994).

In 1964, Roger J.E. Brown conducted a study of permafrost conditions along the Alaska Highway in the Yukon and Northern British Columbia (Brown, 1967). These baseline data come from a region where permafrost is scattered and thin, so that site revisits are likely to reveal changes in permafrost conditions. This thesis is based on revisits to Brown's sites in 2007 and 2008 as a means to compare current permafrost conditions with baseline data and uncover changes that may have occurred.

1.2 A Changing Climate

The international scientific community has agreed that the Earth's climate is changing at a rapid pace and, as a whole, is getting warmer (IPCC, 2007). These changes in climate, including changes in temperature, precipitation and oceanic and atmospheric circulation have been partially attributed to increased atmospheric concentrations of greenhouse gases, largely caused by human activities (ACIA, 2005; Anisimov and Nelson, 1997; Serreze *et al.*, 2000). The Intergovernmental Panel on Climate Change (IPCC) has projected a global temperature increase of 1.1°C to 6.4°C by 2099 (IPCC, 2007). Arctic regions are particularly vulnerable to climate change, and are expected to warm by 4°C to 7°C over the next 100 years (ACIA, 2005). Changes have already begun, with arctic temperatures having risen at nearly twice the rate of the rest of the world from 1966 to 2003 (ACIA, 2005).

1.3 Permafrost

Permafrost is perennially cryotic ground, earth materials that have remained below 0°C for at least two consecutive years (but up to thousands of years) (Brown and Péwé, 1973). Permafrost can vary greatly in thickness, from mere centimetres to hundreds of metres, depending on current and historical climate and mitigating environmental factors (Brown and Péwé, 1973; Shur and Jorgenson, 2007). Permafrost underlies most terrestrial surfaces in the Arctic, and also exists in sub-arctic and alpine regions (ACIA, 2005). In total, 23% of the northern hemisphere and roughly 50% of Canada are encompassed by permafrost zones (ACIA, 2005; Smith and Burgess, 1999). Since permafrost is not present beneath all terrain in these zones, it underlies somewhere between 13% and 18% of the northern hemisphere land area (Anisimov and Nelson, 1997.

Permafrost distribution is commonly classified into zones, based on the proportion of land underlain by permafrost. In the continuous zone, more than 90% of the land is underlain by permafrost, with the latter being absent beneath large lakes and rivers. In the widespread discontinuous zone, less than 90% of land is underlain by permafrost (ACIA, 2005; Heginbottom *et al.*, 1995). The sporadic discontinuous zone has less permafrost than the widespread discontinuous zone, but the proportion of permafrost used to delineate the two zones has not been fully agreed upon. ACIA (2005) defines the sporadic discontinuous zone as being 10% to 30% underlain by permafrost, while Heginbottom *et al.* (1995) define the sporadic discontinuous zone as being 10% to 50% underlain by permafrost. Zoltai (1971) and French and Egorov (1998) suggest that there be an additional zone classification for 'localized' permafrost, where permafrost only exists in very specific peat landforms in the boreal forest. However, due to a scarcity of weather stations with long data records in the Canadian north, permafrost zones can be located only very approximately, and it is currently not feasible to map permafrost at a high enough resolution to be able to delineate such a localized zone (French and Egorov, 1998; Zoltai, 1971). Heginbottom and Radburn (1992) delineate a zone called 'isolated patches' for regions where permafrost is thought to underlie less than 10% of terrain. The fact that, especially in warm permafrost, microclimate and microtopography can result in the presence or absence of permafrost makes high-resolution mapping over large areas particularly difficult. It is for this reason that in discontinuous areas, the exact distribution of permafrost is unknown unless the ground has been locally tested.

Permafrost conditions and climatic patterns are closely correlated, as permafrost is dependent upon climate (Romanovky and Osterkamp, 1995; Smith and Riseborough, 1996, 2002). The temperature at the top of permafrost (TTOP) can be linked to the atmospheric climate via seasonal surface heat transfer processes and ground thermal properties (Romanovky and Osterkamp, 1995; Smith and Riseborough, 1996, 2002).

Knowledge of this relationship allows determination of the limits and continuity of permafrost occurrence and is highly relevant to the understanding of potential impacts of climate warming and precipitation change on permafrost. According to the TTOP model (an equilibrium model), in order to represent the climate-permafrost relation, it is necessary to know three thermal indices. These are the mean annual air temperature (MAAT), which is measured above seasonal snow cover, the mean annual ground surface temperature (MAGST), and the temperature at the top of permafrost (TTOP) (Smith and Riseborough, 1996, 2002). Lunardini (1978), described a set of scaling factors called *n-factors* that can be used to take into account the effects of vegetation and snow cover on ground temperature (Karunaratne and Burn, 2004; Smith and Riseborough, 1996, 2002). Kudryavstev *et al.* (1974), developed equations to estimate annual depth of thaw of the active layer and temperature at maximum thaw depth (Kudryavstev *et al.*, 1974, Riseborough *et al.*, 2008). Figure 1 shows the relation between air temperature and permafrost temperature, defined by the surface and thermal offsets.

Smith and Riseborough (2002) indicate that the southern limit of discontinuous permafrost is where MAAT is roughly -1°C. This is due to the temperature gradients that exist between the MAAT and TTOP. The value of the surface offset, which is MAGST minus MAAT, is instrumental in determining what MAAT is needed in order for permafrost to exist at that location. This offset, or increase in temperature between the air and the ground surface, is primarily due to the multiple effects of snow and vegetation. Snow cover insulates the ground surface due to its low thermal conductivity, keeping the ground surface warmer than the air above it. The surface offset caused by snow is termed the nival offset. The length of snow duration and the snow depth are both

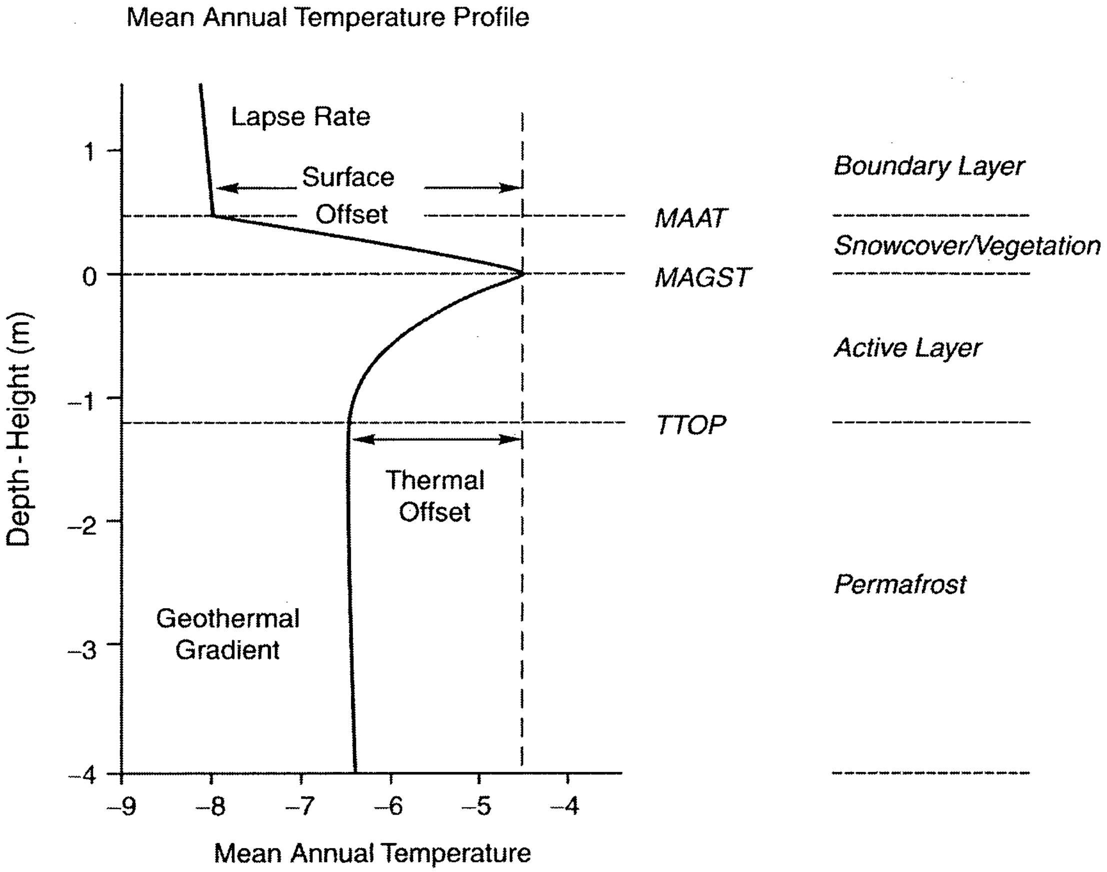


Figure 1. Schematic mean annual temperature profile through the surface boundary layer, showing the relation between air temperature and permafrost temperature (*after* Smith and Riseborough, 2002).

key factors in determining the MAAT needed to develop or maintain permafrost conditions. A site with deep snowcover throughout most of the winter will need a lower MAAT in order to have permafrost temperatures similar to those at a site with little snowcover. The nival offset is considered a critical factor in determining the northern limit of discontinuous permafrost (Smith and Riseborough, 2002).

Vegetation also contributes to the surface offset. Vegetation reduces the amount of solar radiation reaching, and therefore heating, the ground in summer, and can affect snow accumulation in winter, as blowing snow becomes trapped by stems and branches (Beilman *et al.*, 2001; Smith and Riseborough, 2002). However, since most permafrost regions have long winters and short growing seasons, vegetation is typically a less important factor than snow in determining the surface offset.

The other local factor that determines the temperature of permafrost, and its presence or absence, is the ground surface conductivity ratio, via the thermal offset. The thermal offset, which is equal to TTOP-MAGST, describes the decrease in temperature from the ground surface, through the active layer, to TTOP (Romanovky and Osterkamp, 1995). This temperature decrease occurs due to differences in thermal conductivity of the ground in different seasons. Conductive heat transfer in ice can be four times that of water (Smith and Riseborough, 2002). The thermal offset highlights the fact that soil or surficial materials, for example peat versus mineral soils, play a large role in determining the existence of permafrost and indeed are critical in determining the southernmost limit of discontinuous permafrost under equilibrium permafrost conditions (Camill, 2005; Smith and Riseborough, 2002).

Peatlands frequently host the southernmost extent of permafrost, because a very large thermal offset is created by the dry, insulating near-surface organic soil in summer (Beilman *et *al.*, 2001; Camill, 2005). According to calculations based on Canadian climate station MAAT data and thermal conductivity ratios representing a variety of soil conditions, peatlands in areas where regional MAAT is 1°C or slightly higher can still maintain permafrost, due to their exceptional insulating abilities (Smith and Riseborough, 2002). The insulating properties of peat can preserve permafrost that formed under colder conditions, during warmer time periods. In contrast, a MAAT of approximately -2°C represents the southern limit of permafrost in mineral soils (Camill, 2005; Smith and Riseborough, 2002).

Shur and Jorgenson (2007) have developed a conceptual model to classify types of permafrost in order to explain the complex interactions between climate and ecology that impact permafrost distribution. The five categories are: (1) climate-driven; (2) climate-driven, ecosystem-modified; (3) climate-driven, ecosystem-protected; (4) ecosystem-driven; and (5) ecosystem-protected (Figure 2). Climate-driven permafrost forms in the continuous zone as soon as the ground surface is exposed to the atmosphere. Climate-driven, ecosystem-modified permafrost occurs in the continuous permafrost zone where vegetation and surficial conditions promote the development of an ice-rich layer at the top of permafrost. If climate warming occurs, climate-driven permafrost can persist in the discontinuous permafrost zone as climate-driven, ecosystem-protected permafrost. This type of permafrost may not re-establish once degraded. Ecosystem-driven permafrost, which forms in poorly drained, low-lying areas and north-facing slopes in the discontinuous permafrost zone, is heavily influenced by ecosystem conditions such as a thick surficial organic layer. Ecosystem-protected permafrost exists in sporadic patches and cannot recover after a disturbance that impacts its protective organic mat. The fact that much permafrost in the discontinuous zone is so heavily dependent on its organic mat for its existence is relevant due to the importance of the fire regime in the boreal

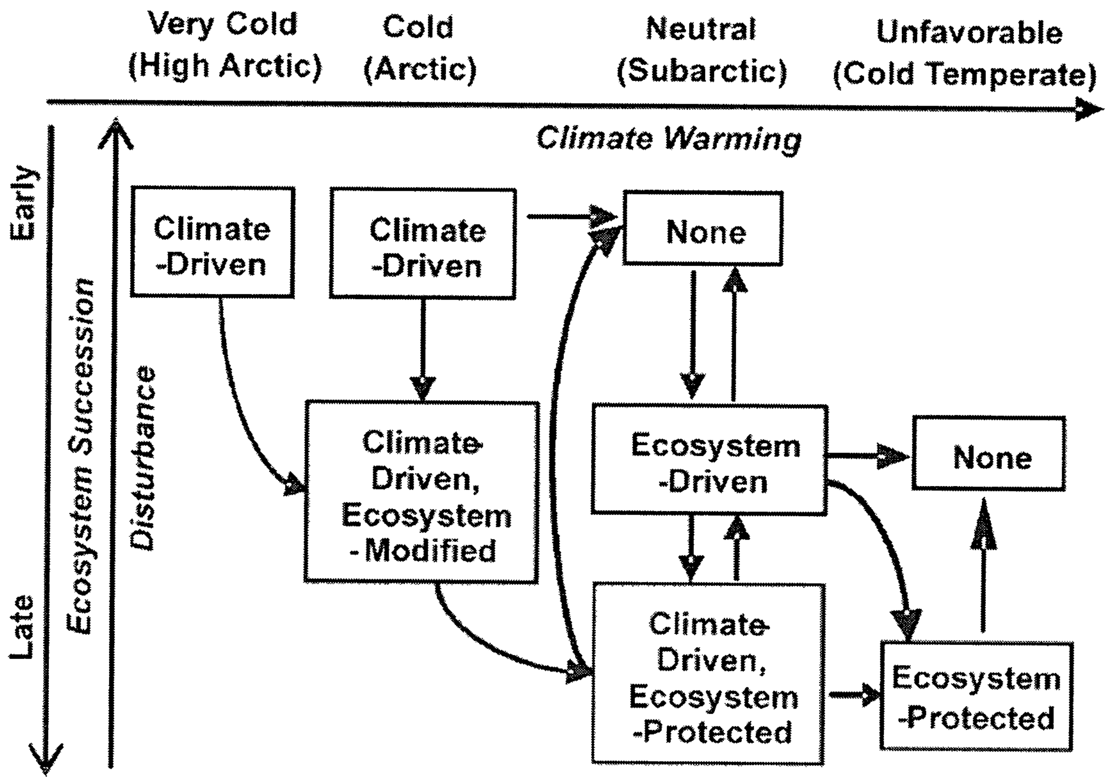


Figure 2. Permafrost conditions in relation to climate, ecological succession and disturbance (*after* Shur and Jorgenson, 2007)

forest (Stock *et al.*, 2002; Yoshikawa *et al.*, 2003). Fires can remove or alter the organic mat that protects near-surface permafrost, resulting in warming of the ground, thickening of the active layer and permafrost thaw (Burn, 1998; Yoshikawa *et al.*, 2003).

In terms of climate change impacts, warm permafrost, which is anywhere from a tenth of a degree below 0°C to roughly -5°C at the depth of zero annual amplitude, causes the most concern among permafrost scientists (ACIA, 2005; Brown and Péwé, 1973). This permafrost is most susceptible to thaw under a warming climate with or without changes in precipitation. The thaw of permafrost, especially ice-rich permafrost, can impact humans and the natural environment in a number of ways. Permafrost degradation can lead to ground subsidence (thermokarst) which can destabilize man-made infrastructure such as buildings, pipelines and roads, often causing high repair or design and construction costs (ACIA, 2005). It can also endanger people living in mountainous areas through mass movements such as landslides, which can occur when melting ground ice destabilizes earth materials. The natural environment can also be impacted by permafrost degradation through collapse of the ground surface, lake drainage, formation of wetlands, and toppling of trees (ACIA, 2005; Camill and Clark, 2000). In addition, feedback from changes in permafrost, such as an increase (or decrease) in carbon dioxide or methane emissions from wetlands, and changes in vegetation, could further affect the earth's climate (Anisimov *et al.*, 1997; Camill and Clark, 2000).

There is evidence suggesting that anthropogenic climate change has already begun to effect changes in permafrost conditions, but determination of this is difficult due to lag times between changes in climate and related changes in permafrost temperatures (Camill, 2005; Kwong and Gan, 1994; Lachenbruch and Marshall, 1986; Smith *et al.*, 2005). While deep permafrost provides useful archives of past air temperatures, only near-surface permafrost (within several tens of metres of the ground surface) has a short enough lag time (years to decades) to make it useful in determining recent climate changes, such as those occurring in the last half-century (Burn, 1998; Kwong and Gan, 1994; Smith *et al.*, 2005). While numerous studies have noted changes such as permafrost warming and increased active layer thicknesses over the last half-century (Frauenfeld, 2004; Kershaw, 2003) many of these have been undertaken in deep, cold permafrost where long lag times make attribution of the change to anthropogenic causes difficult (ACIA, 2005; Burn and Kokelj, 2009; Burn and Zhang, 2009; Lachenbruch and Marshall, 1986; Osterkamp, 2007; Osterkamp and Romanovsky; 1999; Serreze *et al.*, 2000).

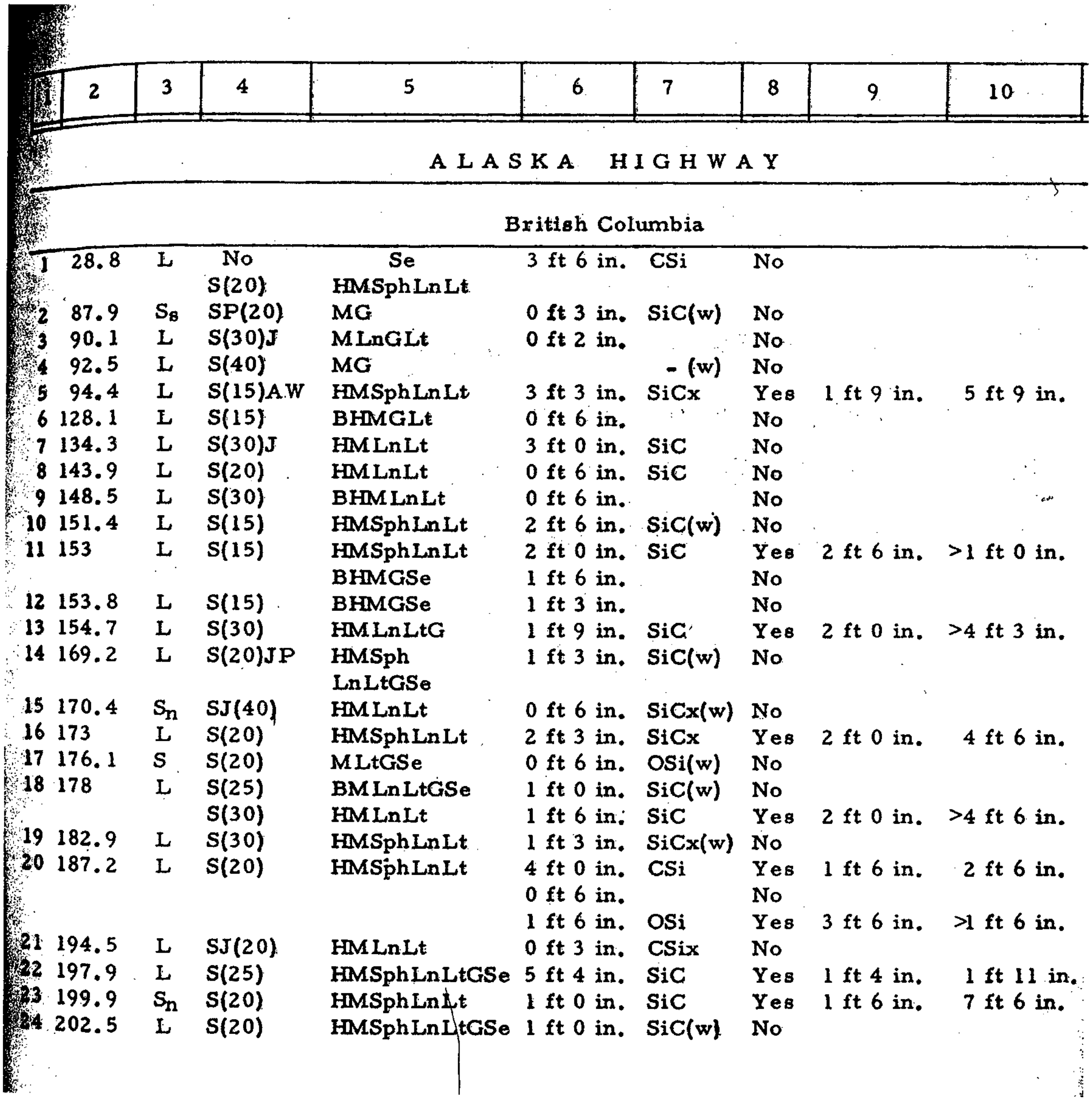
Near-surface permafrost responds more quickly to climate warming than deeper permafrost, but there are still lag-times involved (Burn, 1998b; Smith *et al.*, 2005; Stendel and Christiansen, 2002). Permafrost in the sporadic discontinuous zone is often able to persist because it is in peaty material, which acts as a buffer against atmospheric changes (Camill and Clark, 2000; Halsey et al., 1995; Shur and Jorgenson, 2007). Also, for permafrost very near 0°C, the absorption of latent heat required for phase change reduces permafrost warming trends that may be visible in colder permafrost (Smith *et al.*, 2005). The presence of large amounts of unfrozen water, causing a slowing of the thermal response, has also been implicated in warm permafrost lag times (Romanovsky and Osterkamp, 2000).

One of the few Canadian field studies to show changing permafrost conditions using baseline data for comparison was a repeat of a Roger J.E. Brown permafrost survey along the Mackenzie Highway, Northwest Territories (Kwong and Gan, 1994). The authors set out to discover whether there had been a northward migration of the southern limit of permafrost associated with climate change between 1962 and 1988. They tested for the occurrence of permafrost in 1988 and 1989 by revisiting sites used in a previous study of permafrost distribution by Roger J.E. Brown (1964). The researchers hand-augured at sites close to Brown's with similar vegetation and terrain characteristics and took instantaneous soil temperature measurements. Statistical analysis was then performed to establish a relationship between the disappearance of permafrost and climate warming. Kwong and Gan (1994) found that the southern boundary of the sporadic discontinuous permafrost zone had migrated roughly 120 km north over the 25 years since Brown's observations, and that there was a general warming trend in the region's climate from 1949 to 1989. These results must be viewed with a degree of skepticism, however, due to the absence in the paper of a detailed description of the methods used.

French and Egorov also concluded that 20th century climate warming caused the degradation of permafrost at its southern limit (1998). The authors used air temperature records from a number of weather stations, covering varying periods from 1910 to 1993, and ground temperatures collected at four sites near Thompson, Manitoba from 1969 to 1976 to infer the formation and degradation of marginal permafrost in response to short-term climatic fluctuations (French and Egorov, 1998).

1.4 Brown's 1964 Alaska Highway Study

Brown's study of the Alaska Highway, which this research attempted to repeat, took place in September 1964, when the active layer would have been close to its maximum thaw thickness. Brown investigated the entire Canadian section of the Alaska Highway, but this study is focused on the area between Fort St. John, BC and Whitehorse, YT, the 1330 km stretch where more than 90% of his sample sites were located (Brown, 1967). Figure 3 shows some of his field data. Brown pre-selected sites he believed were likely to have permafrost based on aerial



	2	3	4	5	6	7	8	9	10
ALASKA HIGHWAY									
British Columbia									
1	28.8	L	No	Se	3 ft 6 in.	CSi	No		
			S(20)	HMSphLnLt					
2	87.9	S_s	SP(20)	MG	0 ft 3 in.	SiC(w)	No		
3	90.1	L	S(30)J	MLnGLt	0 ft 2 in.		No		
4	92.5	L	S(40)	MG		- (w)	No		
5	94.4	L	S(15)AW	HMSphLnLt	3 ft 3 in.	SiCx	Yes	1 ft 9 in.	5 ft 9 in.
6	128.1	L	S(15)	BHMGLt	0 ft 6 in.		No		
7	134.3	L	S(30)J	HMLnLt	3 ft 0 in.	SiC	No		
8	143.9	L	S(20)	HMLnLt	0 ft 6 in.	SiC	No		
9	148.5	L	S(30)	BHMLnLt	0 ft 6 in.		No		
10	151.4	L	S(15)	HMSphLnLt	2 ft 6 in.	SiC(w)	No		
11	153	L	S(15)	HMSphLnLt	2 ft 0 in.	SiC	Yes	2 ft 6 in.	>1 ft 0 in.
				BHMGSe	1 ft 6 in.		No		
12	153.8	L	S(15)	BHMGSe	1 ft 3 in.		No		
13	154.7	L	S(30)	HMLnLtG	1 ft 9 in.	SiC	Yes	2 ft 0 in.	>4 ft 3 in.
14	169.2	L	S(20)JP	HMSph	1 ft 3 in.	SiC(w)	No		
				LnLtGSe					
15	170.4	S_n	SJ(40)	HMLnLt	0 ft 6 in.	SiCx(w)	No		
16	173	L	S(20)	HMSphLnLt	2 ft 3 in.	SiCx	Yes	2 ft 0 in.	4 ft 6 in.
17	176.1	S	S(20)	MLtGSe	0 ft 6 in.	OSi(w)	No		
18	178	L	S(25)	BMLnLtGSe	1 ft 0 in.	SiC(w)	No		
			S(30)	HMLnLt	1 ft 6 in.	SiC	Yes	2 ft 0 in.	>4 ft 6 in.
19	182.9	L	S(30)	HMSphLnLt	1 ft 3 in.	SiCx(w)	No		
20	187.2	L	S(20)	HMSphLnLt	4 ft 0 in.	CSi	Yes	1 ft 6 in.	2 ft 6 in.
					0 ft 6 in.		No		
					1 ft 6 in.	OSi	Yes	3 ft 6 in.	>1 ft 6 in.
21	194.5	L	SJ(20)	HMLnLt	0 ft 3 in.	CSix	No		
22	197.9	L	S(25)	HMSphLnLtGSe	5 ft 4 in.	SiC	Yes	1 ft 4 in.	1 ft 11 in.
23	199.9	S_n	S(20)	HMSphLnLt	1 ft 0 in.	SiC	Yes	1 ft 6 in.	7 ft 6 in.
24	202.5	L	S(20)	HMSphLnLtGSe	1 ft 0 in.	SiC(w)	No		

Figure 3. Example of Brown's field data, in this case from MP 28.8 to MP 202.5 of the Alaska Highway (Brown, 1967). Column 1 is Brown's observation point reference number, while the second column is the location of the site based on Alaska Highway mileage. Columns 3, 4 and 5, which contain site relief, tree species and surface terrain features, respectively, are symbolized in the same way as described in Appendix A. Column 6 is the thickness of living ground vegetation and peat observed, while column 7 is soil type. Soil types are symbolized by 'G' for gravel, 'Sa' for sand, 'Si' for silt, 'C' for clay, 'x' for scattered stones, 'O' for organic, and '(w)' for standing water or wet. Column 8 describes permafrost presence (yes) or absence (no). Column 9 shows the depth to permafrost, while column 10 shows the permafrost thickness or minimum known thickness, both in imperial units.

photographs and large-scale topographic maps (Brown, 1967). He tested 110 sites in the study area, of which 60 had permafrost, and made detailed observations such as depth to permafrost table if present, permafrost thickness (where possible), vegetation characteristics, peat thickness, underlying mineral soil and the character of ground ice (Brown, 1967). The investigations were performed with a 6-foot Hoffer probe and a 1.5 inch diameter screw-type soil auger, with extensions that could be added in order to penetrate up to 6 metres, although not in frozen stony and gravely soils (Brown, 1967). All testing was done in close proximity to the highway in undisturbed terrain, no higher than about 1200 m asl. Brown found that permafrost distribution was patchy and sporadic between Dawson Creek, BC and Whitehorse, YT. Permafrost was present beneath north-facing slopes and in low-lying areas, and it was heavily dependent on climate, vegetation and drainage. South of the -1.1°C mean annual air isotherm, permafrost was rare, while it was patchy between the -1.1°C and -3.9°C isotherm, and widespread north of that (Brown, 1967). Areas with sedges and water at or near the ground surface did not have permafrost, and it only appeared in sphagnum areas that were not wet (Brown, 1967).

1.5 Research

The central objective of this research was to directly evaluate the impact of multi-decadal climate change on permafrost distribution and characteristics along approximately 1300 km of the Alaska Highway from Fort St. John, BC to Whitehorse, YT. The steps necessary to achieve the central research objective were:

- Relocate Brown's sites in order to find out where permafrost is extant.
- Examine permafrost conditions at selected sites using water-jet drilling and electromagnetic induction with an EM31 instrument.

- Probe active layer thickness to examine changes in this parameter.
- Measure climatic conditions at selected sites to investigate the temperature and snow conditions that have allowed permafrost to persist in the area.
- Analyze climate records from communities along the study transect in an effort to link changes in permafrost conditions to recent climate change.

1.6 Thesis Organization

Chapter 2 of the thesis describes the physical geography of the study area. This is followed by a description of the methods used throughout the project (Chapter 3). Chapter 4 contains the results of the study, subdivided into 16 sections according to result type. In Chapter 5, the results are discussed. Chapter 6 summarizes the study's conclusions. Appendices A to H include study metadata and data, and are followed by the list of references.

2.0 Study Area

The study area for this project (Figure 4) extends about 1300 km along the Alaska Highway from approximately 80 km north of Fort St. John, BC (56°N 121°W) to Whitehorse, YT (61°N 135°W). The area's easy access to permafrost-favourable terrain and its latitudinal gradient make it ideal for this investigation.

2.1 Permafrost

Brown's sites traverse discontinuous permafrost zones designated as isolated patches (underlying 0-10%) or sporadic (underlying 10-50% of the landscape) (Heginbottom et al., 1995). These areas can be expected to be the most sensitive to climate change impacts, because a small change in temperature can result in a transition from a cryotic to a non-cryotic state (ACIA, 2005; Kwong and Gan, 1994). However, there is effectively no detailed information on permafrost temperatures in this area of northwest Canada.

2.2 Topography

The topography of the study area is shown in Figure 5. The Alaska Highway crosses through mountains, valleys and plains in the study area. However, since measurements were made near the right-of-way, local relief seldom varies by more than 6 m between what Brown called "high areas" and "low areas" (Brown, 1967). The highest point on the highway in the study area is Summit Lake, at an elevation of approximately 1325 m. According to Brown, the sites he investigated were nearly all below 1220 m (Brown, 1967). The sites investigated in 2007 ranged in elevation from 369 m to 1190 m.

2.3 Climate

The climate of the study region (Figure 6) is subarctic and continental, with short, cool summers and long winters with relatively low precipitation (Taylor, 1997; Wahl *et al.*, 1987).

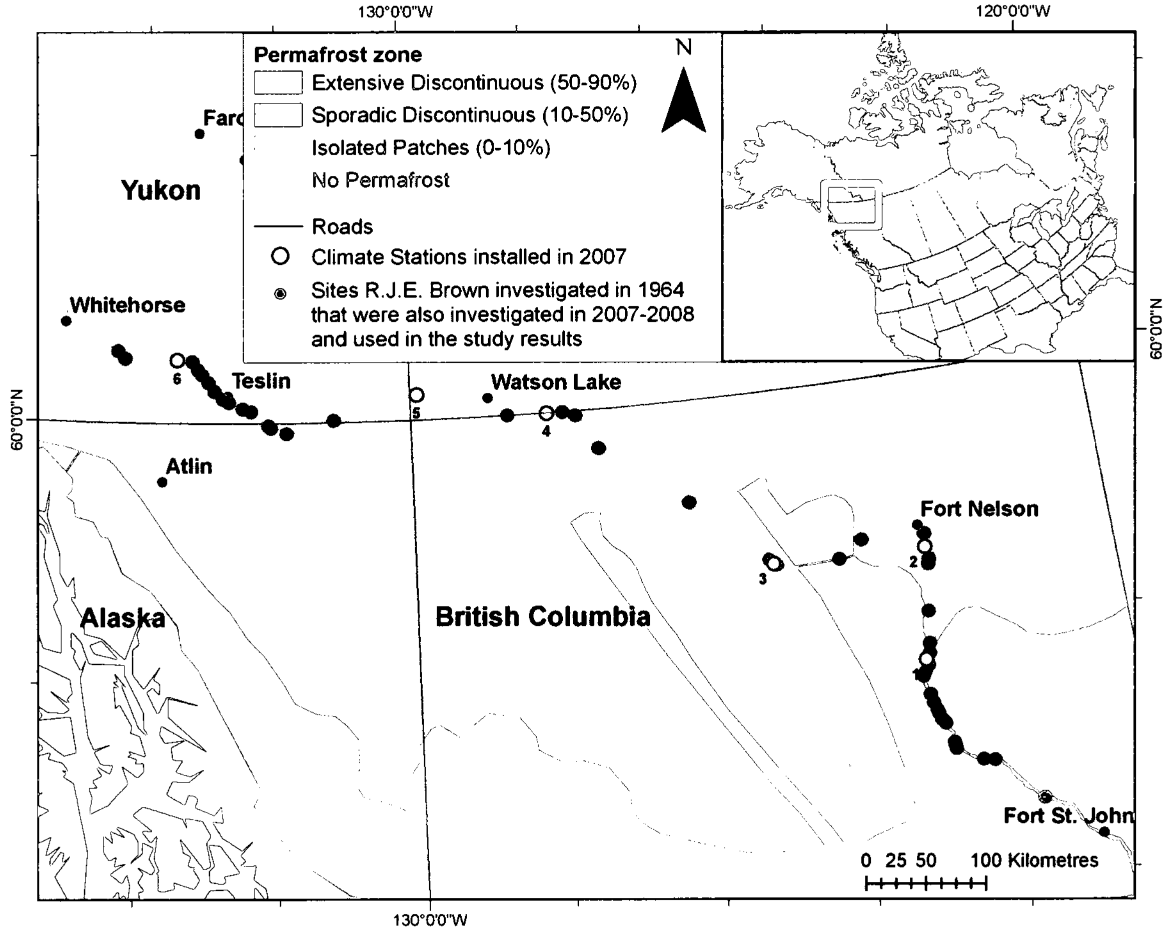


Figure 4. Map of the Study Area, which extends approximately 1300 km from Fort St. John, BC to Whitehorse, YT along the route of the Alaska Highway. Permafrost zones are from the map compiled by Heginbottom and Radburn (1992).

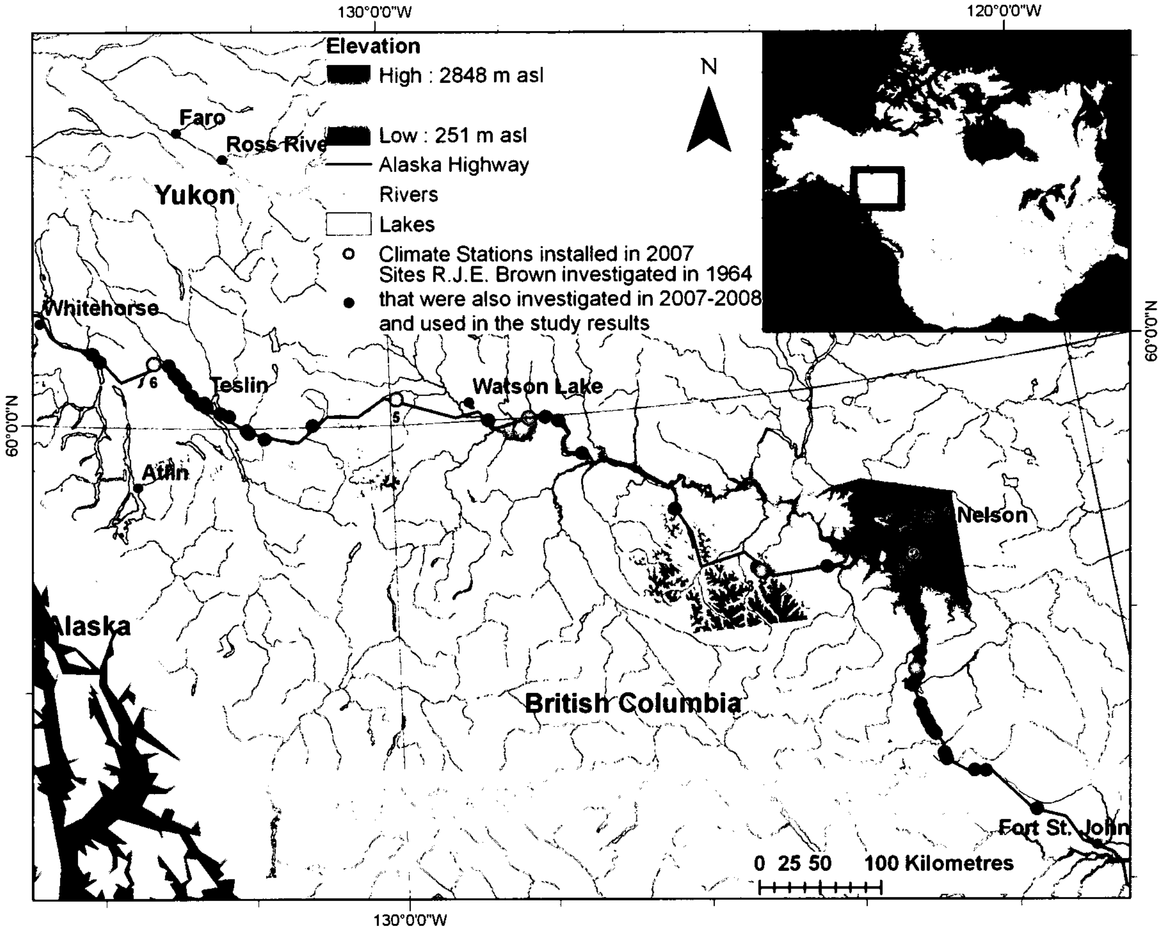


Figure 5. Digital Elevation Model (DEM) of the study transect and its surrounding area (Source: Geomatics Yukon DEM, 2006; Natural Resources Canada, 2007).

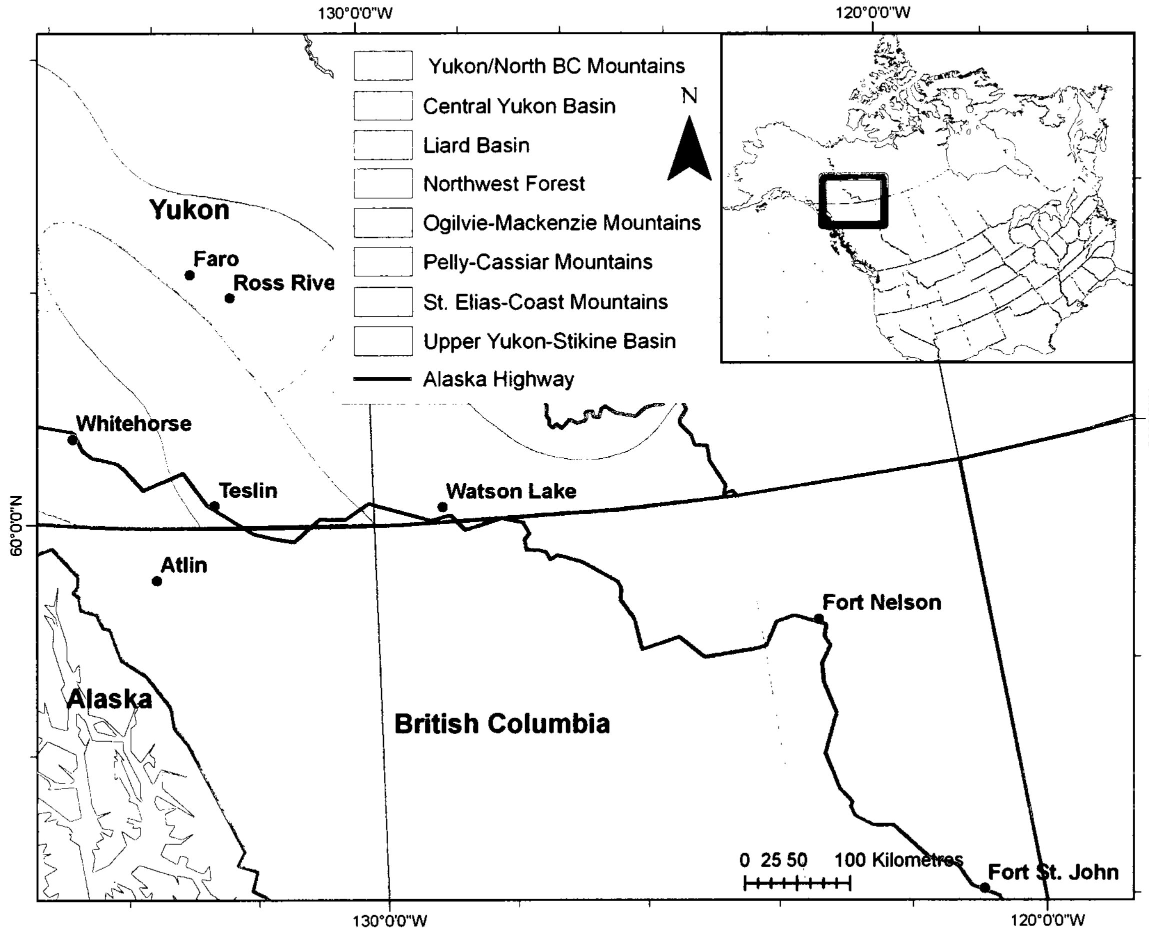


Figure 6. Climate regions of Yukon and British Columbia (Taylor, 1997; Wahl *et. al*, 1987). Only the BC portion of the Yukon/North BC Mountains climate region is shown. The study transect passes through five climate regions. Precipitation is moderate, at 400 mm to 600 mm annually, and the majority of it falls as snow (Wahl *et al.*, 1987). Due to its nature as a basin, long cold spells in winter and warm summers are the norm (Wahl *et al.*, 1987).

The study transect passes through two climate regions in BC on its way into the Yukon. It begins in the Northwestern Forest climate region (Taylor, 1997), and then continues through the BC portion of the Yukon/North BC Mountains region. The three Yukon climate regions of Liard Basin, Pelly-Cassiar Mountains, and Upper Yukon-Stikine Basin (Wahl *et al.*, 1987) are actually fully encompassed by the Yukon/North BC Mountains climate regions described by Taylor (1997), which covers the entire territory.

Mountains characterize the Yukon/North BC Mountains region (see Figure 5), and so there are significant temperature differences with elevation (Taylor, 1997). Higher elevations receive more precipitation than lower ones, and windward slopes receive more than leeward slopes. Annual average precipitation in this region is less than 500 mm (Taylor, 1997). Winters are cold and long, while summers are short and cool.

The Northwestern Forest climate region is east of the Rockies, and has rolling hills, plateaus and plains. Elevations are between 900 and 1200 m (Taylor, 1997). Arctic air dominates winter and spring and helps produce a 40°C difference between the January mean daily minimum and July mean daily maximum (Taylor, 1997). This climate region receives an average of less than 500 mm of precipitation annually (Taylor, 1997). In the Yukon segment of the study area, the Alaska Highway traverses three climatic regions.

The most easterly climate region of the Yukon is the Liard Basin. It is a broad, relatively flat valley with elevations between 700 m and 1000 m (Wahl *et al.*, 1987). Precipitation is moderate, at 400 mm to 600 mm annually, and the majority of it falls as snow (Wahl *et al.*, 1987). Due to its nature as a basin, long cold spells in winter and warm summers are the norm (Wahl *et al.*, 1987).

The Pelly-Cassiar Mountains climate region is an orographic barrier approximately 1000 m to 2000 m in elevation, with some peaks reaching 2500 m (Wahl *et al.*, 1987). Precipitation is greater (500 mm to 700 mm) and mostly accumulates in late fall and early winter. Like the Liard Basin, this region is characterized by less severe winter temperatures than some other areas of the Yukon, with frequent mild spells, and cool summers (Wahl *et al.*, 1987).

The Upper Yukon-Stikine Basin, where Whitehorse is located, is a plateau with elevations from 600 m in river valleys to 2000 m mountain peaks. It is in the rain shadow of the St. Elias and Coast Mountains, and so receives less than 300 mm of precipitation annually (Wahl *et al.*, 1987). The temperature regime is continental, although extreme values are moderated by the high elevations of valley floors (Wahl *et al.*, 1987). The region's proximity to the Pacific Ocean results in more frequent episodes of mid-winter mild weather than elsewhere in the Territory.

Table 1 shows the MAATs of the principal communities along the study transect. Environment Canada climate data show that Brown's survey in 1964 followed roughly 20 years of cooling, especially at Whitehorse (Figure 7) (Environment Canada, 2007). This cooling continued for another decade and there was then a rapid rise in temperatures, with an increase of roughly 1.5°C to 2.0°C over the past 30 years (Figure 7). The differences between MAAT climate normals for 1961-1990 versus those for 1971-2000 also illustrate the increasing temperatures at communities along the study transect (Table 2).

2.4 Quaternary History and Deposits

The study area was last glaciated during the Wisconsinan approximately 80 ka to 10 ka years ago (Bond, 2004; Fulton, 1989). The area now traversed by the highway north of Fort Nelson was covered by an ice sheet advancing from the west, the Cordilleran Ice Sheet, while

Table 1. Climate Normals (1971-2000) of Communities along the Study Transect

Community	Latitude	Longitude	Elevation (above sea level)	Mean Annual Air Temperature	Mean Annual Precipitation	Mean Annual Snow Depth
Fort St. John, BC	56°14’ N	120°44’ W	695 m	2.0°C	466 mm	10 cm
Fort Nelson, BC	58°50’ N	122°36’ W	382 m	-0.7°C	452 mm	18 cm
Watson Lake, YT	60°72’ N	128°49’ W	687 m	-2.9°C	404 mm	21 cm
Whitehorse, YT	60°42’ N	135°04’ W	706 m	-0.7°C	267 mm	11 cm

Source: Environment Canada (2007)

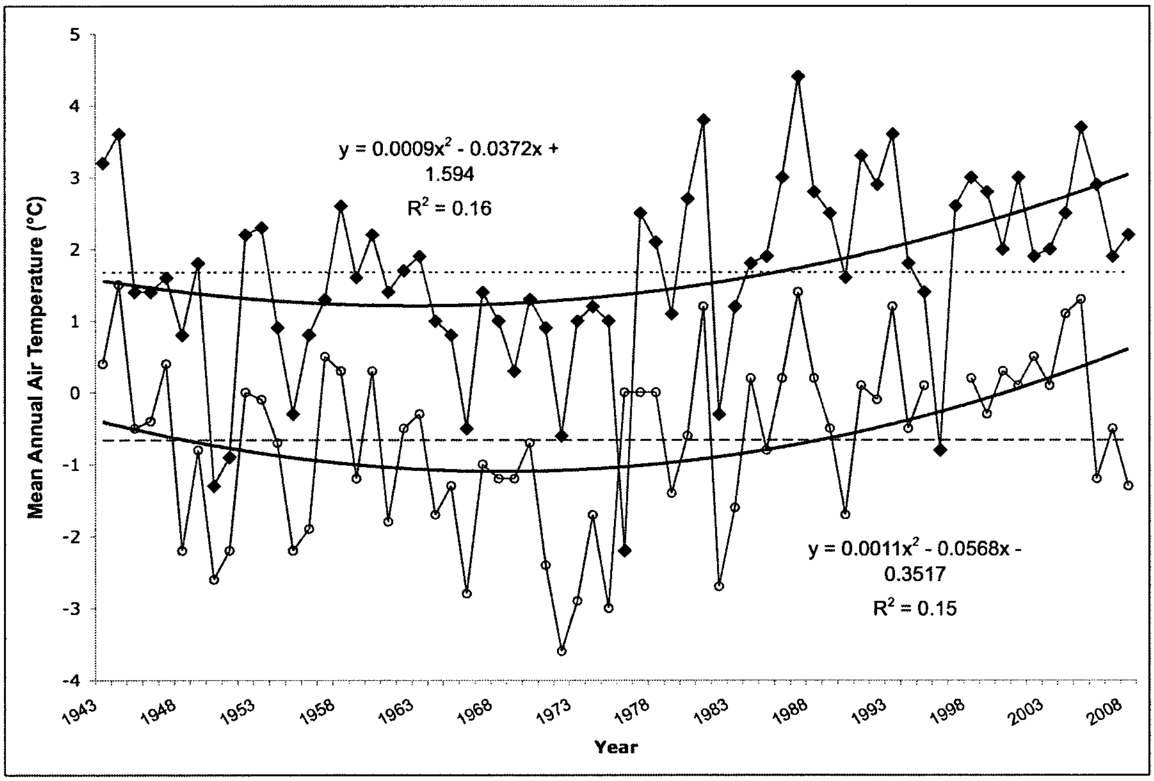


Figure 7. MAATs of Whitehorse, YT (circles) and Fort St. John, BC (diamonds) from 1943-2008 (Environment Canada 2008). The dashed lines are the long-term MAATs over the time period, and the solid black lines are second order polynomial fits.

Table 2. MAAT Normals for 1961-1990 and 1971-2000 for weather stations located in Alaska Highway communities in the study area

Community	1961-1990	1971-2000	Change
Fort St. John	1.6°C	2.0°C	+0.4°C
Fort Nelson	-1.1°C	-0.7°C	+0.4°C
Watson Lake	-3.1°C	-2.9°C	+0.2°C
Whitehorse	-1.0°C	-0.7°C	+0.3°C

Source: Environment Canada (2007b); Environment Canada (2007c) areas in the vicinity and south of Fort Nelson were covered by the Keewatin Sector of the Laurentide ice sheet, advancing from the east (Fulton, 1989). The Cordilleran and Laurentide ice sheets met, coalesced, and separated over the course of the Pleistocene, with Late Wisconsinan glaciations generally more extensive (Bednarski, 2008; Fulton, 1989). The last advance of the Cordilleran and Laurentide Ice sheets into the study area, the McConnell Glaciation, began approximately 24 to 22 ka (Bednarski, 2008; Bond, 2004). The Cordilleran Ice Sheet was at its maximum extent approximately 16 ka, and then rapidly retreated, although some lobes and valley glaciers advanced once or more from 15 ka to 11 ka (Menounos *et al.*, 2009). In the Yukon, this glaciation is considered to have ended by between 10.7 ka and 12 ka (Bednarski, 2008; Bond, 2004). Radiocarbon dating using wood from the Fort St. John area revealed that the area had been deglaciated by approximately 14 ka (Bednarski, 2008). According to Menounos *et al.* (2009), by 11 ka, glacier extent in the Cordillera was no greater than at the end of the 20th century and air temperatures were similar to those of today (ACIA, 2005). The climatic transition (~20°C, ACIA, 2005) from the Pleistocene to the Holocene was very abrupt, and records from Greenland show a warming of 7°C or more over just a few decades (ACIA, 2005). Northwest Canada experienced the Holocene thermal maximum, when temperatures were 1.6±0.8°C higher than the approximate average of the 20th century, from roughly 10.6 ka to between 6.7 and 5.6 ka (Kaufman et al., 2004).

During the Pleistocene, the temperature under an ice sheet in a temperate area would have been the pressure melting point, which under a 1000 m thick ice sheet would have been tenths of a degree to several degrees below 0°C (Brown and Péwé, 1973). Because of the depression of glacier bottom temperatures below 0°C, permafrost was likely widespread, but thin (Brown and Péwé, 1973). After the retreat of the last ice sheets, permafrost in the areas covered by postglacial inundations thawed, and permafrost did not reform in those locations until the bodies of water receded, which was several thousand years later (Brown and Péwé, 1973). Permafrost in areas not covered by water was possibly thawed temporarily due to running melt-water, but likely re-formed in the cold periglacial conditions as the ice sheets retreated (Brown and Péwé, 1973; Romanovsky *et al.*, 2007). The rise in temperatures from the Pleistocene-Holocene transition through the Holocene thermal maximum likely restricted the areas favourable for permafrost.

Sedimentation records in Fort Liard, NWT, roughly 170 km from Fort Nelson, suggest that permafrost may have developed at the site in the last 300-500 years (Bednarski, 2008). This timeframe coincides with the Little Ice Age, a period from A.D. 1550-1850 where temperatures are thought to have been -1°C colder than today (Halsey *et al.*, 1995; Vitt *et al.*, 1994; Zhang *et al.*, 2006). It is thought that past maximum permafrost distribution in peat bogs was related to this cold time interval (Halsey *et al.*, 1995; Vitt *et al.*, 1994). In a study of peatlands of Alberta, Saskatchewan and Manitoba, Halsey *et al.* (1995) concluded that the southernmost instances of permafrost are in disequilibrium with current climate, and likely formed during the Little Ice Age. It is therefore likely that some of the marginal permafrost in the study area formed at the same time.

The soils in the study area vary from coarse-grained sands, to gravels, to fine-grained materials such as silts and clays (Brown, 1967; Denny, 1952, Fulton, 1989). The coarse-grained soils are associated with till and moraine deposits, while the fine-grained ones are associated with alluvial and lacustrine deposits (Brown, 1967; Denny, 1952, Fulton, 1989). There are large areas with peaty soils, which are generally less than 5 m thick and are located mainly in shallow, closed depressions, at the margins of shallow lakes, and on poorly drained land with low to moderate slope (Fulton, 1989).

2.5 Vegetation

The study area falls within 3 ecozones: the Boreal Cordillera, the Taiga Plains and the Boreal Plains (Figure 8) (Environment Canada, 2005). Because the Alaska Highway, and therefore the sites studied, generally follows valleys, vegetation was quite similar along the entire transect, with subtle and gradual changes as climate regions were traversed. The entire route was forested or wooded (except in human-made clearings) because trees cover most valleys and plateaus in the southeast Yukon and northern BC up to elevations of 1350 m to 1500 m, and the highest 2007 study site was at 1190 m. All of the sites that Brown (1967) investigated are beneath stands of black spruce, often stunted, and poorly drained, as he was biased toward permafrost-probable sites. These factors, as well as the fact that the climate regions are more appropriate in scale make a distinction between ecozones unnecessary for this project.

Common species in the area are white spruce (*Picea glauca*), black spruce (*Picea mariana*), tamarack (*Larix laricina*), Subalpine fir (*Abies lasiocarpa*), lodgepole pine (*Pinus contorta*), aspen (*Populus tremuloides*), balsam poplar (*Populus balsamifera*) and paper birch (*Betula papyrifera*) (Wahl *et al.*, 1987). Dwarf birch (*Betula nana*) and willow (*Salix* spp.) are common in low-lying, poorly drained areas, as are various mosses, lichens, sedges and Labrador tea (*Ledum palustre*), which are also present as an understorey in forested areas. In the Northwestern Forest climate region of BC, mountain ash (*Sorbus* spp.) also grows, and the area has more deciduous trees than the Yukon/North BC Mountains region or the climate regions in the Yukon Territory (Taylor, 1997).

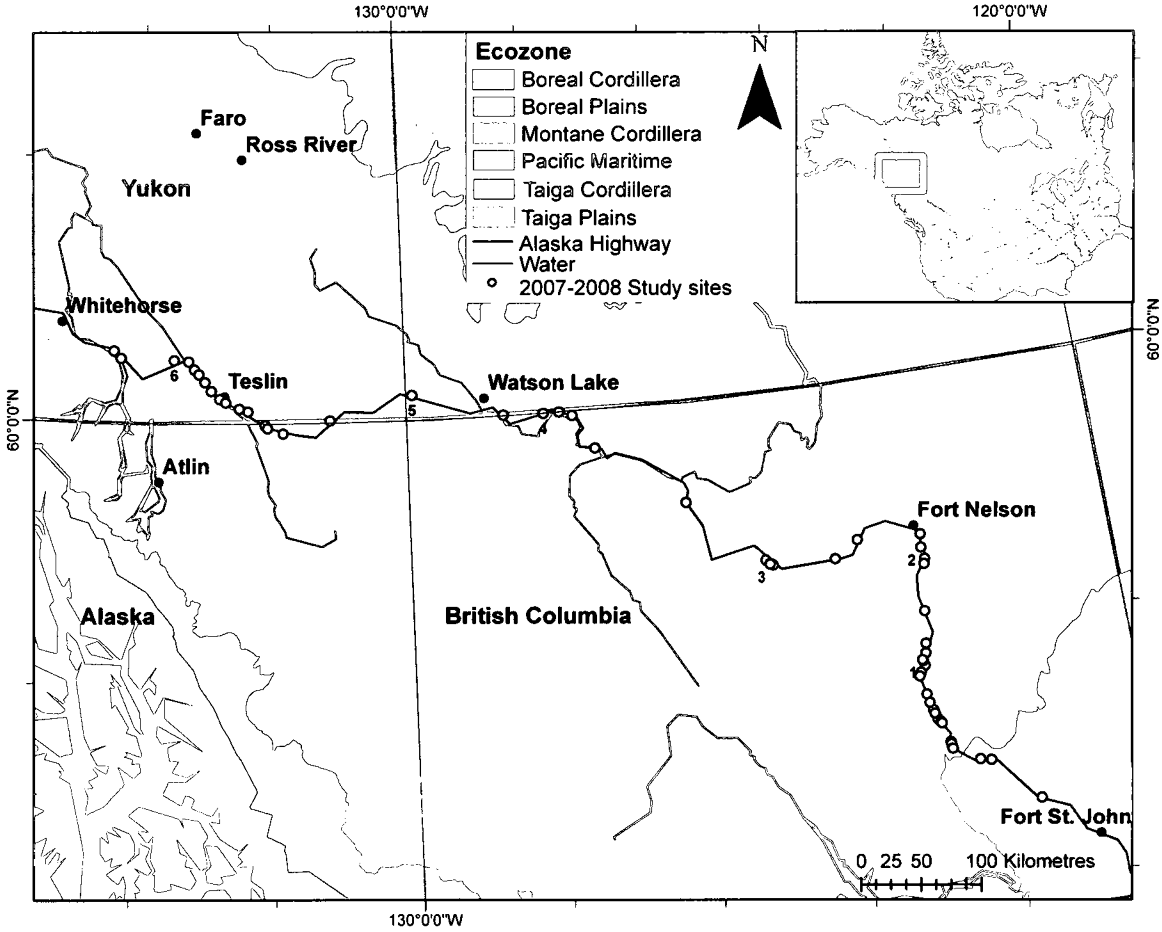


Figure 8. Ecozones of the study area (Source: Government of Canada, 2002)

3.0 Methods

This section contains an overview list of the major steps used to carry out the research in the field and subsequently in the laboratory. It is followed by more a detailed description of each method.

The major steps were to:

1) Retrieve information on Brown's site locations and physically pinpoint his study sites.
2) Conduct manual field investigations verifying the presence or absence of frozen ground in the upper 2 m of ground materials in late summer.
3) Observe and record details about the vegetation, relief and substrate of the study sites and collect soil samples.
4) Analyze soil samples for moisture content, organic content and grain size.
5) Obtain data on air temperatures, ground temperatures and snow depths at sites with permafrost by installing weather stations and, later, downloading their data.
6) Investigate permafrost thickness and obtain ground thermal data by water-jet drilling at two sites.
7) Investigate permafrost presence or absence and continuity using electromagnetic induction by employing a Geonics EM31.

3.1 Site Determination

Brown described 60 locations that exhibited permafrost in 1964, as well as some non-permafrost sites, in sufficient detail that it was possible to relocate most of them using mile-post information, written descriptions, and photographs. This information was retrieved from Brown's 1967 publication, as well as from cartographic and photographic material archived at the National Research Council of Canada in Ottawa. The maps are a set of 1965 Alaska Highway maps from an Alaska Highway Engineering Study by the Development Engineering Branch of the Department of Public Works (Department of Public Works, 1966). Most of the maps have a 1:50,688 scale, but 350 km of the highway, roughly between Toad River and just north of Muncho Lake in the Northern Rockies, is shown at a scale of 1:253,440 scale (Department of Public Works, 1966). The maps show the highway as it was in April 1965, as well as modifications of the route that were planned at the time. They also show UTM grid lines, topographic contour lines, as well as mileposts every five miles. The UTM grid lines were crucial for determining the probable locations for Brown's sites.

The archival photographs used to locate sites are views of Brown's 1964 study sites as seen from the Alaska Highway. Photographs with hills or mountains on the horizon or with a water body were typically more helpful in locating sites than photographs in areas with flat relief (Figure 9). Without water bodies or a distinctive horizon, it was difficult to determine on which side of the road the site was located.

Site investigations began in August 2007. Using UTM coordinates for Brown's sites, derived from the archived maps, and a hand-held Global Positioning System (GPS) device (eTrex Vista Cx (Garmin International, Inc., USA)), the route was driven to within 500 m of the coordinates for a site and driving continued for 500 m past. The landscape on either side of the highway was assessed until a match with Brown's photographs and descriptions could be made. Several hundred metres around the UTM coordinates were assessed for sites most likely to have permafrost (based on vegetation and drainage), which were then investigated. This method of site re-determination was required due to the inherent inaccuracies associated with deriving UTMs from the scale of the maps used and also because of similar indeterminacies associated with Brown's mileage measurement technique, which was likely his vehicle odometer or local

Figure 9. The study site at MP 394.5 in 1964 (left) and 2007 (right)

signage. Several sites could not be relocated due to inadequate descriptions or profound changes in land cover such as conversion of spruce forest to arable land. At sites that were successfully re-located (Appendix C), UTM coordinates were taken in the WGS 84 datum. The accuracy of this device, according to manufacturer specifications, ranges from ± 3 m to ± 15 m (Garmin Ltd., 2006). However, forest cover caused significant difficulty in satellite signals reaching the handheld GPS unit, so the upper end of the accuracy range should be considered very likely.

3.2 Manual Field Investigations

At each relocated site, investigations were performed with a 1.2 m long 1 cm diameter frost probe and a similarly sized soil auger for roughly ten minutes, to see if a frost table could be found in the area. Once the presence or absence of a frost table had been thoroughly manually investigated, two ground temperature profiles were measured to a depth of 1.5 m below ground surface or until the frost table was encountered, at most sites (See Appendix B). The two profiles were undertaken approximately 5 m apart using probes tipped with 44033RC Precision Epoxy NTC thermistors, which have a factory-specified precision of ±0.1°C (Measurement Specialties Inc., 2008). A multimeter (Fluke 27) was used to measure thermistor resistance in kΩ, and which was subsequently converted to degrees Celsius using a polynomial equation fitted to a reference table given by the manufacturer. Readings were done at 5 depths at 20 cm depth intervals, and the thermistors were kept at each depth for at least 5 minutes in order for them to equilibrate. At sites where there was a frost table, 10 ground probings, roughly 1 m apart, were performed to measure active layer thickness and organic mat thickness.

Fieldwork for the project was conducted in the month of August (2007 and 2008) so that the depth of the thawed layer would be near its maximum. This was as late in the thaw season as was practical given other commitments, but was several weeks earlier than Brown, who conducted his investigations in the month of September (Brown, 1967).

3.3 Extrapolation of Temperature Profiles

In 2007, sites were investigated directly to 1.5 m depth due to the length of the frost probes available (1.2 m and 1.35 m) and the time pressures faced by the researchers. Digging a hole to be able to investigate to 2 m at each site would have taken more time than was available. Instead, thermal profiles to 1.5 m were used to extrapolate ground temperatures to 2 m, which, except in bedrock, represents a reasonable depth to distinguish between permafrost and non-permafrost sites. One thermistor reading was taken per minute; they were recorded for at least 5 minutes and then logarithmic functions were fitted and used to predict the equilibrium temperature of a thermistor at its measurement depth. A second order polynomial function was then used with the predicted equilibrium temperatures at each depth to predict the depth at which the temperature would reach 0°C. If that depth was shallower than 1.8 m, it was concluded that permafrost was predicted within the top 2 m of ground. If the depth at which 0°C was met was between 1.8 and 2.2 m, the result was considered 'indeterminate'. If the polynomial fit line crossed 0°C below 2.2 m, permafrost was considered to be absent.

The sites where permafrost was 'indeterminate' were revisited in August 2008 and were investigated to 2 m through a combination of digging holes and using a frost probe. No 'indeterminate' sites that could be penetrated to 2 m had a frost table present within that depth. Two sites were so rocky that 2 m below ground surface could not be reached using the project's investigative methods. However, it was inferred from EM31 measurements that there was no permafrost at either of the sites.

3.4 Site Observations and sampling

Site observations, such as vegetation, relief and mineral soil texture were recorded so they could be compared to Brown's. Photographs were taken of all sites.

Vegetation information was typically recorded to at least the specificity of genus level, while some species-specific types were recorded. Vegetation types were recorded in order of visual dominance at the site, while maximum vegetation heights were estimated qualitatively.

Qualitative assessments of site relief were performed, with details recorded such as whether or not a site was on a noticeable slope, whether or not it was hummocky and whether or not it was on a peat plateau. The estimated amplitude of microtopography was also noted.

Soil samples were collected from as many sites as possible, both with and without frost tables, for analysis in Ottawa of moisture content, organic content and granulometry of mineral soil. Collection was done by digging holes and using a plastic scoop to extract samples at varying depths, typically within 80 cm of the surface. Efforts were made to collect samples not far below the organic mat and close to the frost table if there was one. Some permafrost sites were not sampled because they were organic to the frost table and below. Two non-permafrost sites (MP 214.1 and MP 731), a site where Brown found a frost table in 1964, and a site where he did not, were also entirely in organic material. The samples were weighed in the field to obtain and initial value for moisture content analysis using an Ohaus Portable Advanced Electronic Balance field scale (model CT1200) with a readability of 0.1g (Ohaus Corporation, USA). The scale was calibrated before each use.

3.5 Soil Sample Analyses

Samples from the field were brought to Ottawa to be analyzed for moisture content, organic content and grain size.

For natural moisture content analysis, whole samples were put into beakers and weighed on the field scale. They were then put in a drying oven at 105°C for 24 hours and weighed again (Head, 1992). The bags the samples were originally stored in were also weighed, dried, and weighed again, to prevent loss of sample (Head, 1992). For the weighing of the dried samples the Sartorius L610 laboratory scale (Sartorius Mechatronics, Germany) was used, which has a readability of 0.01 g (Data Weighing Systems, Inc., 2009). The results as a whole are precise to 0.1 g.

For organic content analysis, the loss on ignition (LOI) method was used (Heiri *et al.*, 2001). Small crucibles were dried, and then weighed on the Sartorius L420P scale, which has a readability of 0.001 g (Sartorius Mechatronics, Germany) (Data Weighing Systems, Inc., 2009). Small subsamples (finer than -1ϕ) of each sample were then put in the crucibles and dried at 105°C for 24 hours, then weighed. They were then burned in a 550°C furnace for at least three hours. The subsamples were given time to cool, then weighed again to obtain the percentage of sample that is organic.

For analysis of grain size (based on the methods of Head, 1992), the LOI results were used to determine whether or not samples should have the organics oxidized before grain size analysis. Samples with less than 5% organic content by weight were analyzed without pre-treatment, because impact on the results would be minimal, whereas samples with higher organic content were first treated with hydrogen peroxide (H_2O_2). The effectiveness of this method can vary greatly, from burning off less than 20% to more than 93% of organic content, depending on mineral content of the soil and specific methods used (Mikutta *et al.*, 2005).

Samples with low organic content, were subsampled to approximately 100 g, weighed, then soaked in water for three days to ensure complete disaggregation. Small subsamples were also put in test tubes filled with sodium hexametaphosphate ($(NaPO_3)_6$), a dispersant, at a 5% concentration, and analyzed with the Microtrac S3500 Particle Size Analyzer (Microtrac, 2008). The subsamples soaking in water were washed through a 3ϕ sieve to extract the fines, dried in the drying oven at 105°C for 24 hours, weighed, dry sieved, and weighed again (on the Sartorius L610). The results of dry sieving and laser particle size analysis were then combined for the grain size results (as the Microtrac S3500 gives results for fines).

Samples with an organic content higher than 5% by weight were also subsampled to roughly 100 g, but were submitted to three rounds of treatment with a 30% concentration of hydrogen peroxide. Each sample had 50 mL of hydrogen peroxide applied to it 3 times. The second application was roughly 8 hours after the first, and the third application was roughly 16 hours after the second. After the third application, heat was applied using a hot plate until the sample stopped reacting and reduced in volume. It was then dried in a 105°C drying oven for 24 hours and weighed. After this point, it was dispersed in sodium hexametaphosphate (5% concentration). The sample for the particle size analyzer was gathered at this step, so an extremely small number of coarser grains were lost. The subsample was then wet sieved just like the low organic content samples, and the rest of the granulometry was the same as those from that point onwards.

Some samples were so highly organic or reactive to H_2O_2 oxidation due to their mineral content that they overflowed the sample beaker and a great deal of sample was lost. These were not analyzed for grain size. They were disproportionately from sites with permafrost.

The description of the mineral soil of a subsample was based on the parameters laid out in Appendix 1 (Field Identification of Soils) of the Forest Road Engineering Guidebook (2nd ed.) of the Forest Practices Code of British Columbia (2002). Soil was classified as organic if its sample was 30% or more organic by weight. This is in line with the definition of organic soil horizons used in The Canadian System of Soil Classification, 3rd ed. (Soil Classification Working Group, 1998).

3.6 Climate Station Installation

Six climate stations were installed at permafrost sites along the study transect to collect climatic and ground thermal information from August 2007 to August 2008. The stations (Figure 10) have automatic data loggers to measure air temperature, ground temperatures and snow depths in order to examine the conditions that have allowed permafrost to persist. The stations were installed in undisturbed terrain hidden from view from the highway. Two different types of data loggers were installed, both products of Onset Corporation. Air temperatures (measured at about 1.6 m above ground surface) and ground surface temperatures were measured by HOBO Pro data loggers (model U23-003), which have an accuracy of ±0.2°C (Onset Computer Corporation, 2008). The air temperature thermistor was sheltered within a radiation shield. Ground temperature profiles from the ground surface to the frost table or less than 15 cm above it were measured using Onset's H-08 four-channel data logger, which has an accuracy of ±0.5°C (Onset Computer Corporation, 2008). Snow depths were interpreted from a series of Thermochron® iButtons® temperature loggers (Model DS1921G, Dallas Semiconductor Corporation, USA) installed on stakes at 5, 10, 20, 30, 40, 50, 60, 80 and 100 cm above the ground. The depths were inferred by comparing the records of pairs of loggers: those covered by snow produce a very different signal than those still exposed in the air (Lewkowicz, 2008). The climate stations were downloaded in August 2008 after a year of data had been collected. Data was also downloaded in September 2009 where possible.

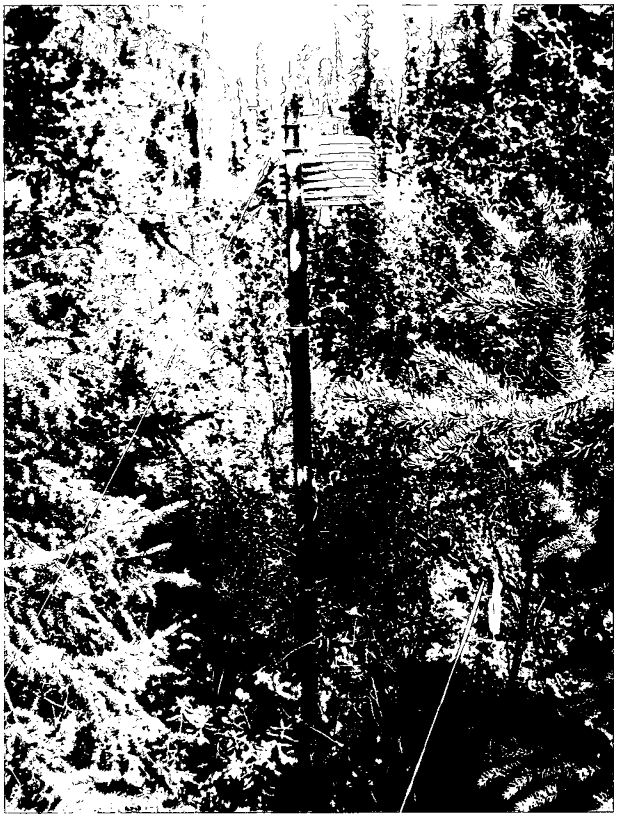


Figure 10. Example of a climate station, this one at MP 681.1.
Note the white radiation shield for the air temperature thermistor.

3.7 Water-jet Drilling

Water-jet drilling can be a useful method for determining permafrost thickness. This method requires the availability of a water source such as a pond within 60 m of the site to be drilled, since the ground is penetrated using water pumped through a hose and into ¾" diameter iron pipes. Water availability determined site selection for this method. Up to six boreholes were planned, to be preserved for temperature measurements. However, only two boreholes were successfully drilled, due to difficulties in penetrating stony ground. Both boreholes, located at historic mileage points MP 825.2 and MP 286 were drilled and encased with 1" iron pipes. They were then given time to equilibrate (forty-eight and eight days, respectively), and thermal profiles were recorded within the casings. In September 2008, at MP 825.2, Antoni Lewkowicz installed a multi-thermistor temperature cable connected to an eight-channel data logger manufactured by RBR Ltd (2009). There is now a full year of data from MP 825.2. Hobo loggers were installed at MP 286 in July 2009, but there is no data yet available.

3.8 Geophysical Investigations

The EM31 (Geonics Limited, Canada) uses oscillating electromagnetic energy to penetrate the ground and induce secondary electromagnetic fields in regions of elevated electrical conductivity (Geonics, 2005). The EM31 can be used to map geologic variations and any other subsurface feature (such as ice) that affects ground conductivity (McNeill, 1980). This is done inductively, so there is no need for electrode contact with the ground. The EM31 has been used in both alpine and arctic lowland permafrost regions and is considered a convenient way to obtain qualitative results about permafrost's extent horizontally, as well vertically, depending upon the method's application (Hauck and Vonder Mühll, 1999; Kneisel *et al.*, 2008; Sartorelli and French, 1982).

Different scientists report different effective exploration depths of the EM31. Several reports indicate penetration depths of roughly 6 m when operated in the vertical dipole configuration at approximately waist height, and roughly 3 m when operated at that height in the horizontal dipole configuration (Geonics, 2005; Hauck and Vonder Mühll, 1999; MacNeill, 1980). A study by Sartorelli and French (1982), however, used effective exploration depths of 2.1 m in the horizontal dipole configuration with the instrument at ground level, 4.6 m in the vertical dipole configuration with the instrument at ground level, and 3.7 m in the vertical dipole configuration with the instrument 0.9 m (waist height) above the ground. Sartorelli and French consider the effective exploration depth to be the depth at which the primary field falls to 37% of its value at the surface (1982).

The EM31 takes discrete, point readings and has an intercoil spacing of 3.66 m. This means that each reading is an average conductivity (in mS/m) of approximately 4 m of linear ground surface.

The EM31 was used at eleven sites, some with a frost table within 2 m, some without a frost table within 2 m and indeterminate sites. At each site, a linear ten point transect, with the points 4 m apart, was traversed. Two sets of three readings were taken at each transect point. With the instrument turned so that the transmitter and receiver were in line with the transect, measurements were taken with a vertical dipole configuration at a height of approximately 0.9 m. Measurements were then taken at ground level with a vertical dipole configuration and a horizontal dipole configuration. Instrument readings with these dipole configurations and heights were then repeated at each transect point with the transmitter and receiver perpendicular to the transect. The parallel-to and perpendicular-to-transect readings at each transect point were averaged together to obtain the apparent conductivities for each point. The apparent conductivities measured in the different dipole configurations and instrument heights, when compared to one another, enabled inferences to be drawn regarding the presence or absence of permafrost, and a rough estimation of its thickness (Geonics, 1977; McNeill, 1980, Sartorelli and French, 1982). This is because electrical conductivity decreases as freezing takes place due to the change from electrically conductive water to much less conductive ice. Also, as the ground temperature drops further below zero, conductivity values continue to drop as there is a decreasing amount of unfrozen moisture (Kneisel *et al.*, 2008).

Each of the transect points at a given site was inferred to be in a one, two or three-layered state (Figure 11). A one-layered state means that the ground is unfrozen to the deepest effective exploration depth. In a two-layered state, permafrost is present whose base is deeper than the deepest effective exploration depth. A three-layered state implies thin permafrost whose base falls within the depth of exploration. Figure 11 Table 3 show the criteria for determining the number of layers present at a transect point.

Manual investigation of the site conditions also aided in the interpretation of EM31 readings. At each point along the geophysical transect, a photograph was taken of the vegetation, the organic layer thickness was measured and, where there was a frost table, its depth was recorded. However, some transects were so underlain by rocks and roots that organic mat and active layer measurements were limited in number. Also, due to instrument malfunction, two of the eleven sites where the EM31 was used have incomplete transects.

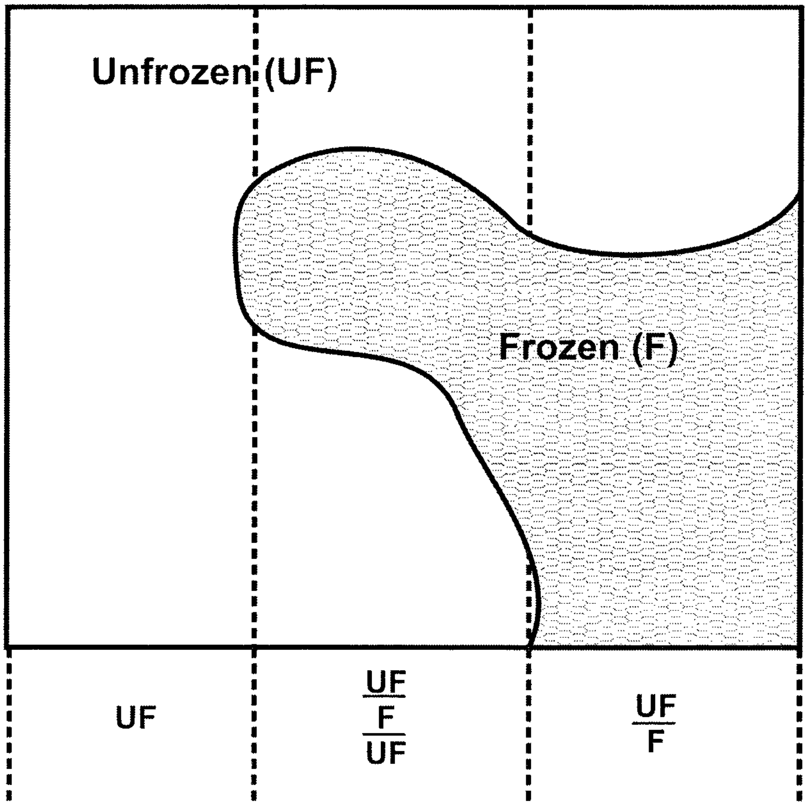


Figure 11. Model of layered terrain in summer (*after* Sartorelli and French, 1982).

Table 3. Criteria for determining terrain layering. HG = horizontal dipole configuration on ground; VG = vertical dipole configuration on ground; VZ = vertical dipole configuration at 0.9 m above ground. *HG can have a higher conductivity if there is standing water, and one layer would still be inferred. Also 1 layer was inferred only if no frost table was encountered during manual investigation.

If:	Then:
HG≈VZ≈VG*	Unfrozen (1 layered)
HG>VZ>VG	Unfrozen/Frozen (2 layered)
VG>VZ	Unfrozen/Frozen/Unfrozen (3 layered)

4.0 Results

4.1 Changes in near-surface permafrost distribution

Permafrost conditions were assessed in August 2007 at 86 sites along the Alaska Highway first examined by Roger Brown in 1964. The results of these investigations can be seen in Figure 12, and are summarized in Tables 4 and 5. Brown found a permafrost table at 57% of sites, and no evidence of a frost table at 43% of sites (Brown, 1967). About one-third of these sites were not considered in the 2007-2008 surveys due to inaccessibility (because of relocation of the highway) or low certainty over location. Of the 55 sites used in the results, 56% had near-surface permafrost in 1964 and 44% had no near-surface permafrost in 1964, almost the same percentage as the entire group sampled that year (see Appendix D) (Brown, 1967).

Almost half of the sites with near-surface permafrost in 1964, no longer exhibited it in 2007 (Table 4). None of Brown's non-permafrost sites had a frost table within the 2 m of the ground surface during the 2007-2008 investigations.

Sites south of Fort Nelson (58°48"21' N, 122°41"47' W) represent 67% of the sites where permafrost appears to have thawed, in spite of representing only 48% of where Brown found permafrost. Only one of Brown's permafrost sites (representing a 17% change) between Fort Nelson and Watson Lake changed to non-permafrost by 2007. Between Watson Lake and Whitehorse, 40% of sites with near-surface permafrost in 1964 exhibited none in 2007.

The southernmost occurrence of permafrost that was found during the 2007-2008 investigations was milepost (MP) 178, at 57°25"32' N, 122°8"3' W. Brown found a frost table at MP 154.7 (57°9"51' N, 123°18"6' W), which was investigated but found to have no frost table within 2 m, as well as at MP 94.4, his southernmost permafrost site, which could not be located in 2007-2008.

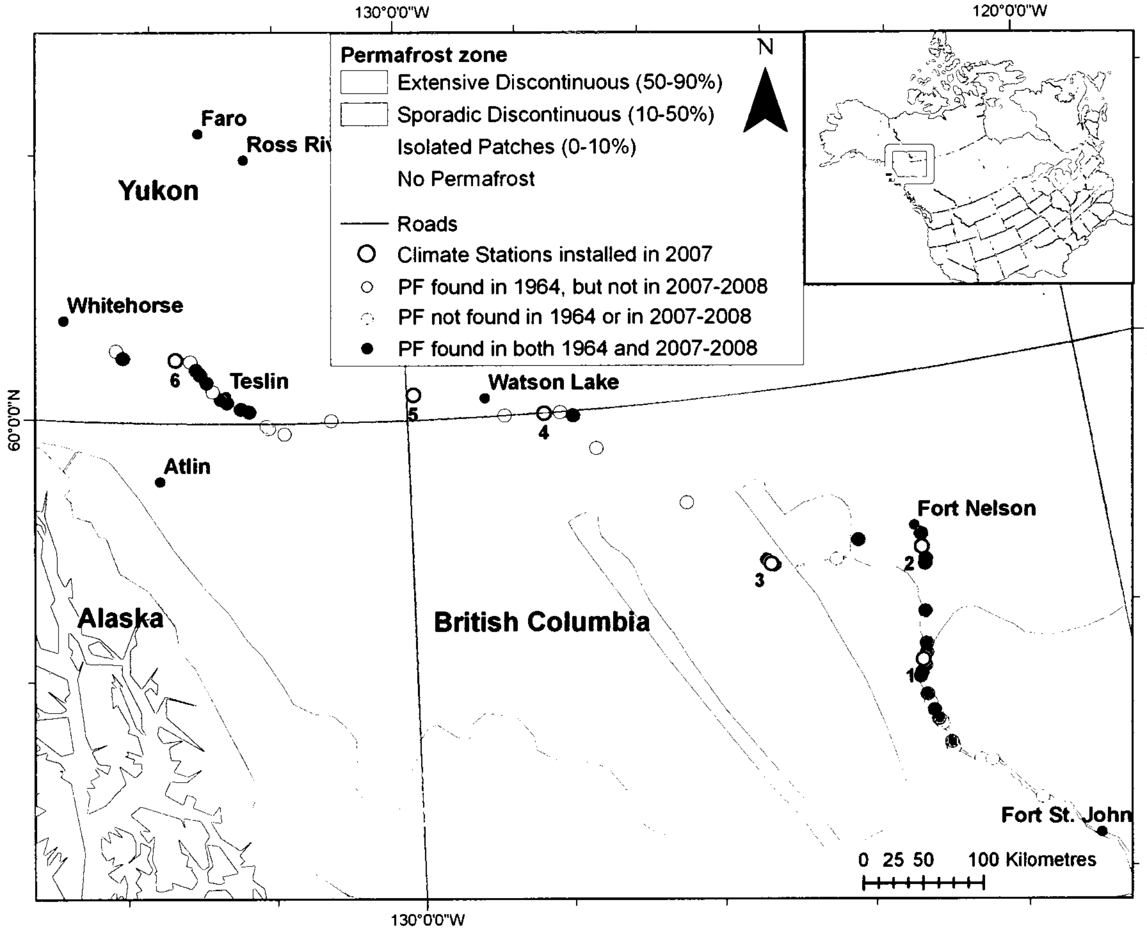


Figure 12. Study area showing field observations of changes in permafrost conditions

Table 4. Results of 1964 (Brown, 1967) and 2007-2008 investigations. Thirty-one sites were not considered in the 2007 survey due to inaccessibility (because of relocation of the highway) or low certainty over location.

Investigation results	Sites	Permafrost found	No permafrost found
1964 results in study area	86	49 (57%)	37 (43%)
1964 results for sites investigated in 2007	55	31 (56%)	24 (44%)
2007 results	55	16 (29%)	39 (71%)

Table 5. Sites investigated, broken down by route segment. Percentages are the percent of the number of sites investigated in a particular route segment. The southernmost route segment had more than twice as many sites as the segment from Fort Nelson to Watson Lake, and 30% more sites than the segment from Watson Lake to Whitehorse.

		1964		2007	
Route Segment	Sites	Permafrost found	No permafrost found	Permafrost found	No permafrost found
Fort St. John to Fort Nelson (390 km)	26	15 (58%)	11 (42%)	5 (19%)	21 (81%)
Fort Nelson to Watson Lake (565 km)	11	6 (55%)	5 (45%)	5 (45%)	6 (55%)
Watson Lake to Whitehorse (450 km)	18	10 (56%)	8 (44%)	6 (33%)	12 (66%)

There was a relatively low number of usable sites between Fort Nelson and Watson Lake (Figure 12). This is due to the presence of the Northern Rocky Mountains and the associated stony terrain and low organic cover for part of the route segment, as well as suspected forest fires, which made some sites impossible to locate and others impossible to penetrate. Five sites in that area were rejected from the study because the ground was so rocky it could not be penetrated with the tools available (MP 394 to MP 488.5). North of these sites, there was evidence of fairly recent forest fires, such as burn scars on trees, and small saplings of early re-colonizing trees and shrubs like willow and trembling aspen. This made it impossible to find sites close to Brown's mileage points. His descriptions and pictures were not similar to the current landscape and the researchers could not locate four sites.

4.2 Active Layers

Active layers as measured in 2007 and 2008 were highly variable, both within and between sites. It appears that many active layer thicknesses in 2007-2008 were greater than in 1964 (Figure 13), even though they were sampled one month earlier in the thaw season. 1964's active layer measurements had a mean depth of 54.6 cm (Brown, 1967), whereas the measurements done in 2007 and 2008 have a mean depth of 63.0 cm, a statistically significant difference (p=0.003). However, a lack of knowledge about Brown's sampling methods makes it impossible to conclusively determine whether or not the active layer thickness at a given site has actually changed significantly. While in 2007 and 2008, several active layer measurements were taken at each site and the mean of these measurements was calculated, it is unknown whether Brown's values represent the mean of multiple measurements per site to take into account a high degree of local variability (evidenced by the large standard deviation bars for the 2007 and 2008 measurements in Figure 13), or a single measurement. Due to these uncertainties, comparisons

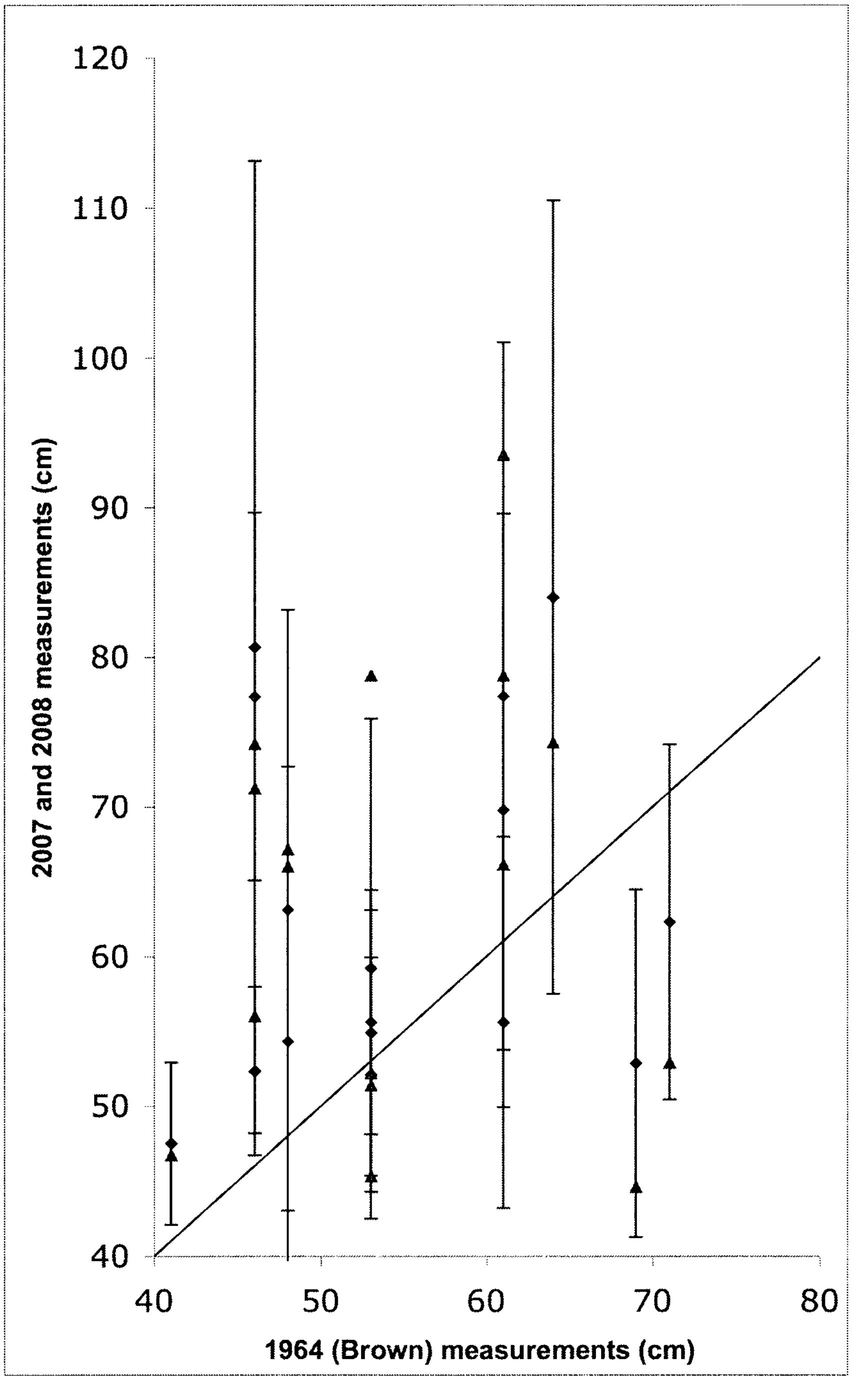


Figure 13. Scattergram of active layer thicknesses in September 1964 and August 2007 and 2008. Diamonds represent comparisons between 1964 and 2007; triangles represent those between 1964 and 2008. Bars represent standard deviations of the 2007 and 2008 data. The *n* for the 2007 and 2008 measurements ranges from 3 to 20. The 1:1 line is shown.

between the investigations in 1964 and those in 2007-2008 are tenuous.

However, analysis of climate conditions in the measurement year provides interesting information for comparison with the active layer thickness. If it is indeed true that active layer thicknesses have increased between 1964 and 2007, it is likely that they reflect a trend of increase over time, rather than a particularly early or warm spring and summer of 2007 or 2008. Air temperature is a major forcing variable on ground temperatures, and so is an important factor in summer thaw-depths (Karunaratne and Burn, 2004). Because thawing of the ground typically begins as soon as snow cover has completely receded (Carey and Woo, 1999), the length and intensity of a particular thaw season (annual period in which ground surface temperatures are at or above 0°C) has a direct impact on the thaw depth of the active layer in that year (Shur *et al.*, 2005). In a particularly warm year, the active layer may reach a greater than normal thickness not consistent with longer-term climate trends. These fluctuations in active-layer depth have led to the concept of the *transition zone*, a layer of uppermost permafrost between the active layer and underlying permafrost that experiences freeze/thaw cycles at much lower temporal frequencies (sub-decadal to multi-centennial in scale) than the active layer (Shur *et al.*, 2005). It should be noted the thawing index (the number of thawing degree days, or TDDs, and in this case the number of TDDs as measured using air temperatures) is not the only factor to cause differences in active-layer thicknesses. Variations can also result from changes in the thermal conductivity of the thawing portion of the active layer, and from the latent heat potential of its frozen portion, which is typically more ice-rich than the upper portion (Shur *et al.*, 2005). However, since soil moisture is very site specific and there is no data available for the project sites for 1964 or 2007, only the thawing index is examined here.

The number of thawing degree days as measured at Environment Canada weather stations for the entire thaw seasons of 1964, 2007 and 2008 and the number of thawing degree days measured in those years to the dates of investigation of the project sites with climate stations were calculated (Figure 14 and Figure 15). The 1964 active-layer measurements were made on average at 89% of the accumulated TDD that year, whereas 2007 and 2008 measurements were made at 74% and 76% of the respective accumulated TDD. For the complete thaw season, no one year was warmer than the others for all of the sites (Figure 14), but for the thawing degree-days accumulated prior to the date of active-layer investigation, 1964 was always the greatest (Figure 15).

For the thawing degree day data measured to the dates of site investigation, the largest thawing degree day difference between the 1964 data and the modern investigations was 312 TDD at Teslin when 1964 and 2007 were compared (Figure 15). The smallest difference was 42 TDD at Watson Lake when the same years were compared. The influence of this small variation in number of thawing degree days (as measured in the air) is all but eliminated in ground surface temperatures, due to the properties of the Stefan equation (1).

$$z = \sqrt{2kI / \rho Wl} \qquad (1)$$

Where: z = active layer thickness (m), k = soil thermal conductivity ($\mathrm{Wm^{-1}\ K^{-1}}$), I = thawing index (K· s), ρ = density, W = water content fraction and l = latent heat of water fusion (0.334 MJ $\mathrm{kg^{-1}}$ at 0°C) (Shur *et al.*, 2005). If it is assumed that soil conditions remained constant between Brown's year of measurement (1964) and the years 2007 and 2008, then dividing the square root of the thaw index of the earlier year by that of the later one, indicates the amount of active layer thickness change that can be attributed to differences in temperature during the two thaw seasons. Using the thawing degree-days accumulated up to the respective

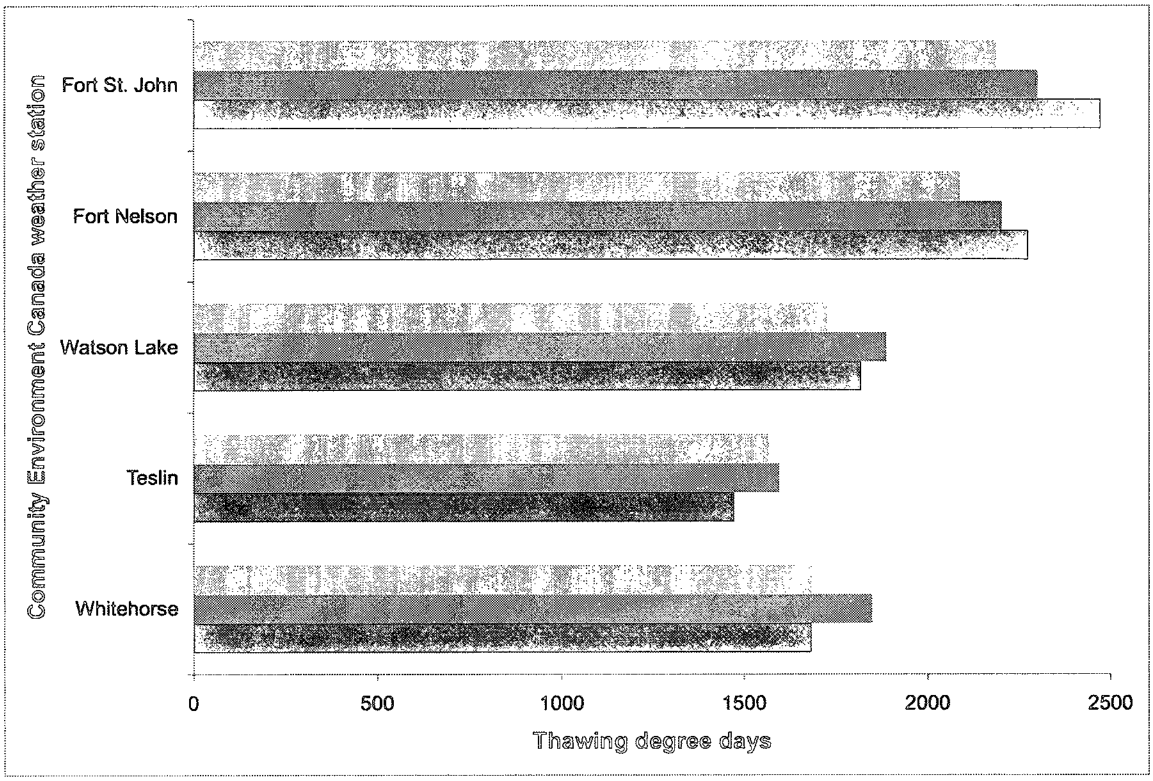


Figure 14. Thawing degree days at Environment Canada weather stations for the complete thaw seasons of the years 1964 (light grey), 2007 (dark grey) and 2008 (black)

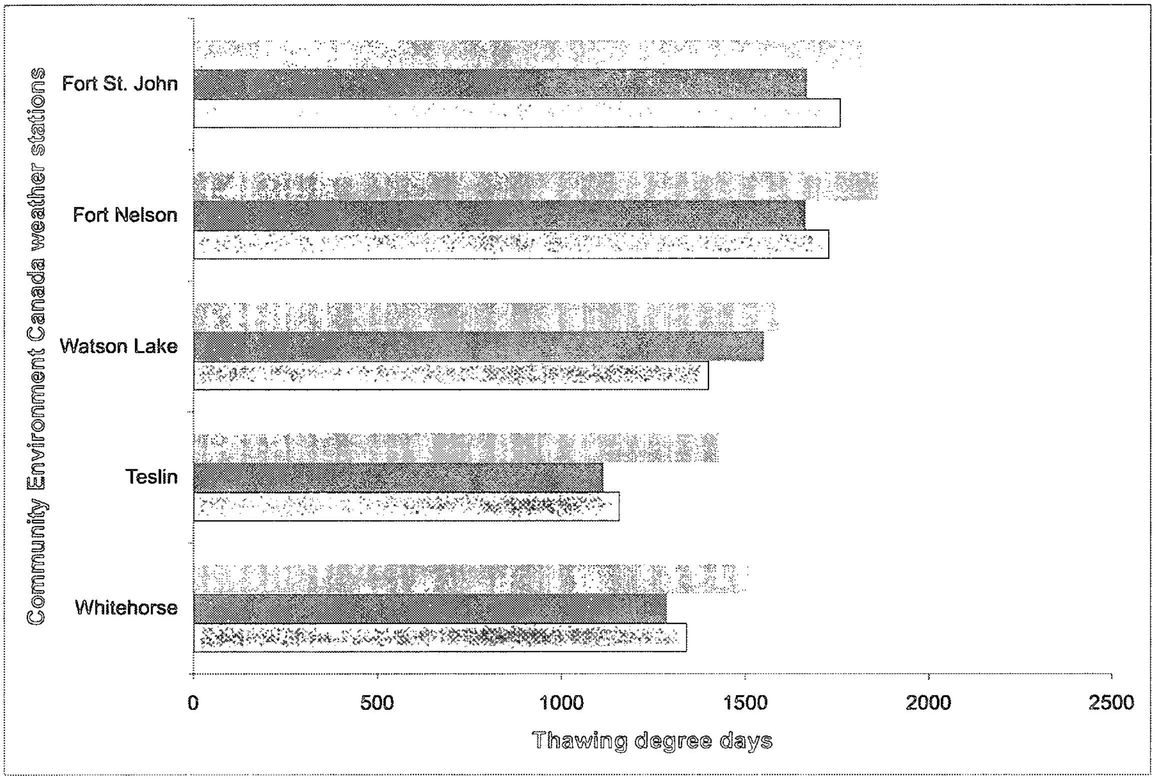


Figure 15. Thawing degree days at Environment Canada weather stations from January 1 to the date of investigation of the nearest project site with climate station installed, for the years 1964 (light grey), 2007 (dark grey) 2008 (black)

measurement dates of 2007 and 2008, and using the known or estimated measurement dates of 1964, thaw depths should have decreased by 1% to 13% due to the relative warmth of the individual years of measurement (Table 6).

These percentages of change attributable to the summer climate of the individual years of measurement do not explain the trend of increasing active layers. The mean increase in active layer thickness as measured in 2007 and 2008 was 13%, showing that differences in thaw depths between 1964 and 2007-2008 should not relate to the summer climate in the year of observation. Instead, it is possible that there has been overall warming of permafrost between the two periods of observation. A warming trend between 1964 and 2007-2008 would permit deeper active layers in 2007-2008 even if the particular year's TDDs did not differ greatly from those in Brown's year of investigation. As noted above, however, in the absence of information about Brown's sampling methods, the conclusion that change has occurred should be treated as highly tentative.

4.3 Mean Annual Temperatures

MAATs at the 6 climate stations that were installed ranged from -3.8°C to -1.2°C for 2007-2008 (Table 7). The coldest air temperatures were at MP 681.1 and MP 597.5, which are located near the town of Watson Lake in the Liard Basin, a broad valley that Wahl *et al.* (1987) note can have Arctic air settle in it for long periods of time in winter, causing prolonged cold spells. MP 844.1, located between Whitehorse and Teslin in the Upper Yukon-Stikine Basin, had a MAAT of -2.6°C, possibly due to the fact that the region's proximity to the Pacific Ocean results in more frequent mid-winter mild spells than elsewhere in the territory (Wahl *et al.*, 1987). The station with the next lowest MAAT, MP 208.5, is the southernmost climate station in the study area, yet it is colder than two that are north of it, one of which has an elevation over

Table 6. Change in active layer thickness that can be attributed to summer climate during the particular year of measurement. Data is from January 1 to the measurement date of the closest project site with a climate station. Results in this table are derived from data from Environment Canada weather stations in the communities in the table. (Environment Canada, 2008)

Community	2007 vs. 1964	2008 vs. 1964
Fort St. John	-4%	-2%
Fort Nelson	-6%	-4%
Watson Lake	-1%	-7%
Teslin	-13%	-11%
Whitehorse	-8%	-6%

Table 7. **Mean annual temperatures for the period August 19, 2007 to August 18, 2008 at the project's climate stations. Annual data for MP 400.5 are unavailable due to failure of a data logger. Recently available data with averages calculated for August 1, 2008 to July 31, 2009 are also included, and appear in brackets.**

			Depth below surface (cm)									
Site	Elevation	Air	0	10	20	25	30	40	50	65	75	100
MP 208.5	771 m	-2.2°C (-2.6°C)	0.7°C (1.3°C)	1.1°C (1.7°C)		0.5°C (1°C)		-0.2°C (0.0°C)	-0.4°C (-0.4°C)			
MP 286	417 m	-1.2°C (-2.1°C)	0.6°C (0.9°C)		0.4°C (0.8°C)		0.4°C (1.1°C)	-0.1°C (0.2°C)	-0.4°C (0.3°C)	0.0°C (0.0°C)		
MP 400.5	1043 m	-1.8°C	0.5°C									
MP 597.5	682 m	-3.2°C	1.6°C	1.3°C		1°C		0.1°C	-0.5°C			
MP 681.1	849 m	-3.8°C (-4.5°C)	-0.5°C (0.8°C)	-0.7°C	-0.9°C		-1°C	-1.3°C	-0.9°C (0.5°C)			
MP 844.1	813 m	-2.6°C	1.1°C	0.5°C (1.2°C)		0.4°C			-0.2°C (-0.2°C)		-0.5°C (-0.3°C)	0.0°C (0.1°C)

270 m higher. MP 286 was the warmest site, with a MAAT of -1.2°C. MP 208.5 and MP 286 are within the same climate region (Northern Forest) and are only about 100 km apart, yet had a difference in MAAT of 1°C for the year of measurement. MP 400.5, in the Yukon/Northern BC Mountains climate region, had a MAAT of -1.8°C.

Mean annual ground surface temperatures varied between sites from -0.5°C (MP 681.1) to 1.6°C (MP 597.5). The ground temperature loggers at MP 400.5 did not operate past April 2008, so there is no below ground surface data for that site. The site with the second lowest MAAT for the year of measurement had the highest MAGST (MP 597.5). Ground temperatures confirm that the permafrost at all the sites is close to 0°C (Table 7 and Figure 16). Some of the deepest measurements were not quite at the top of permafrost, and so are not quite representative of TTOP, but all show values warmer than -1°C, and some are warmer than -0.5°C. At MP 286 and MP 844.1, where the deepest logger was at the frost table (as of the installation date), the MAGT at the frost table was 0°C. Since the mean annual ground temperature at the depth of zero annual amplitude (the level at which permafrost temperature is frequently defined, usually 10 to 20 m below ground surface) is commonly 0.2°C to 0.4°C higher than TTOP due to the geothermal gradient (Smith and Riseborough, 2002), the temperature of permafrost at the depth of zero annual amplitude is likely only a fraction of a degree below zero.

Surface offsets (MAGST-MAAT) ranged from 1.8°C to 4.8°C, with thermal offsets (TTOP-MAGST) ranging from -2.1°C to -0.7°C (Table 8). The results show that at all sites except MP 681.1, it may be the thermal offset that allows permafrost to exist (Figure 16 and Table 7). The thermal offset is a function of the differing thermal conductivities of frozen and thawed ground (Karunaratne and Burn, 2004). It is primarily affected by soil properties, soil

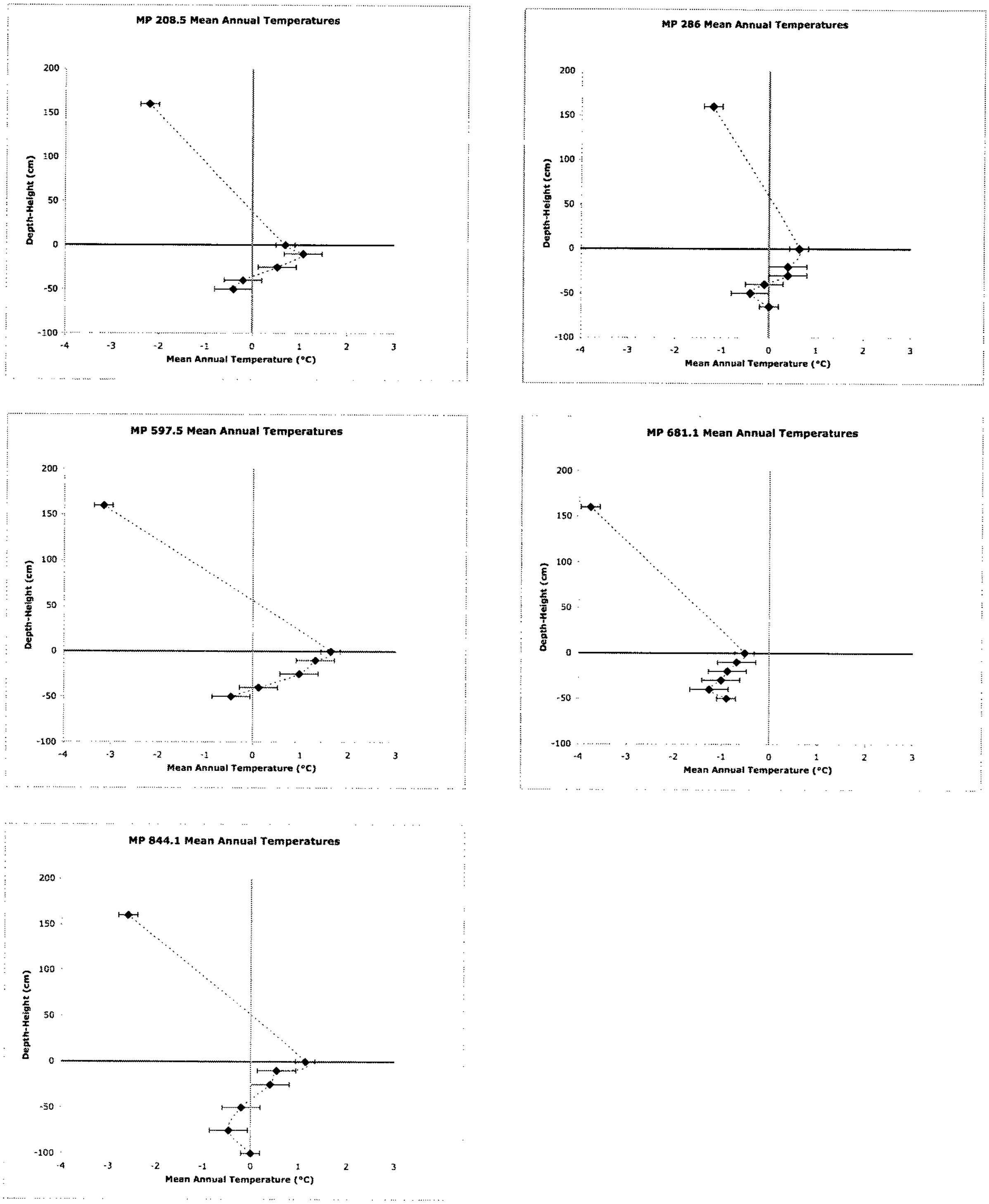


Figure 16. Thermal profiles (mean annual temperatures from August 19, 2007 to August 18, 2008), at the study's climate stations

Table 8. Surface and thermal offsets measured at project's climate stations from August 19, 2007 to August 18, 2008

Site	Surface Offset	Thermal Offset (approx.)
MP 208.5	2.9°C	-1.1°C
MP 286	1.8°C	-1.0°C
MP 400.5	2.2°C	M
MP 597.5	4.8°C	-2.1°C
MP 681.1	3.2°C	-0.7°C
MP 844.1	3.7°C	-1.6°C

moisture, and vegetation. At all these measurement sites, the large difference in summer and winter ground thermal conductivity is likely due to the surface layer of peat. This organic material has a low apparent thermal conductivity when its near-surface is relatively dry and unfrozen in the summer months, and a high thermal conductivity in the winter, when it is saturated and frozen (Smith and Riseborough, 2002). This means heat is more easily transferred in the winter from the ground to the atmosphere through the frozen, saturated peat than from the atmosphere to the ground when the peat is unsaturated (Brown, 1970; Kwong and Gan, 1994). At sites where permafrost has persisted, such as at all six sites equipped with weather stations, the permafrost could be extant for two reasons. If it is in disequilibrium with the current climate, permafrost could be present because of the lag effect associated with high latent heat of the frozen soil (Smith *et al.*, 2005). If the permafrost is in equilibrium with the climate, then it is present because the thermal offset is sufficiently great to preserve it. The results for these sites, showing that the thermal offset is a critical factor if the sites are in equilibrium,, are consistent with the conclusion reached by Smith and Riseborough (2002) that it is this factor that determines the occurrence of permafrost at the southernmost margin of the discontinuous zone. At MP 681.1, the one climate station site where the MAGST is below 0°C ,the MAAT for August 19, 2007 to August 18, 2008 was -3.8°C. This site's surface offset of 3.2°C is not enough to bring the MAGST above 0°C, so it appears that permafrost exists at this site due to a cold MAAT in spite of a reasonably large surface offset and a small thermal offset. This site, in particular, may still be in equilibrium with the current climate whereas this remains an open question for the other sites that could only be resolved by long-term monitoring.

4.4 N-Factors

N-Factors, which are ratios of the ground surface freezing index to the air freezing index (n_f = freezing n-factor) and of the ground surface thawing index to the air thawing index (n_t = thawing n-factor), were calculated for each site (Table 9). Freezing n-factors were calculated for the winter spanning 2007 and 2008, while n_t values were calculated for the 2008 thaw season. Ground surface temperatures were used to determine freezing and thawing seasons. N-factors are used to summarize the relation between air and ground temperatures, and are site-specific due to the influence of local factors such as snow cover (Burn, 1998; Lunardini, 1978). The freezing n-factor is theoretically equal to unity when there is zero snow cover, and becomes numerically smaller with increasing snow depth (Smith and Riseborough, 2002). Variations in n_t can be attributed to the effects of vegetation (such as shading, evapotranspiration, impacts on albedo), and n_t typically varies less than n_f (about 0.8 to 1.0 for natural surfaces as opposed to between 0.1 to 1.0 for n_f) (Jorgenson and Krieg, 1988; Klene *et al.*, 2001; Smith and Riseborough, 2002). Thawing n-factors near 1.0 indicate there is little difference between the TDD sum at the ground surface and in the air.

The n_f values at the project's climate station sites ranged from 0.29 to 0.56, which are similar to those measured at forested sites in Takhini River valley (50 km west of Whitehorse) in the late 1990s (Karunaratne and Burn, 2003). The n_t values ranged from 0.74 to 0.95. MP 286 and MP 681.1 had lower n_t values (0.74 and 0.78, respectively), and so their thawing air temperatures were considerably warmer than their thawing ground temperatures.

Table 9. N-factors, mean annual snow depths and snow depth days for project sites with climate stations. Freezing n-factors are for the winter spanning 2007 and 2008, while nt are for the thaw season of 2008.

Site	n_f	n_t	Mean Snow Depth (cm)	Snow Depth Days
MP 208.5	0.48	0.88	9.8	3592
MP 286	0.51	0.74	12.0	4412
MP 400.5	0.56	0.92	8.2	3015
MP 597.5	0.29	0.88	25.4	9313
MP 681.1	0.46	0.78	28.8	10522
MP 844.1	0.36	0.95	18.4	6737

There was an inverse correlation, as expected (Karunaratne and Burn, 2004; Smith and Riseborough, 1998; Smith and Riseborough, 2002; Taylor, 1995), between n_f and mean annual snow depth, as well as between n_f and snow depth days. Snow depth days are a representation of both the depth and duration of a snowpack on an annual basis, and are calculated in much the same way as freezing or thawing degree-days (Karunaratne and Burn, 2003). The r^2 value was 0.44 for both the relationship between n_f and mean annual snow depth and between n_f and snow depth days, but neither of the relationships were statistically significant ($p=0.153$ for both). However, MP 681.1 appeared to be an influential observation. When it was removed from the regression analysis, there was a strong inverse correlation between both n_f and mean annual snow depth and between n_f and snow depth days. The r^2 values for the relationship between n_f and mean annual snow depth and between n_f and snow depth days were 0.94 and 0.93, respectively, and the relationships were statistically significant ($p= 0.007$ for both). The inverse correlation is because snow's low thermal conductivity restricts heat loss from the ground during cold periods and reduces n_f (Karunaratne and Burn, 2004, Smith and Riseborough, 1998; Smith and Riseborough, 2002). The relatively high (given its snow depth) n_f at MP 681.1 may be because this site has a colder MAAT (-3.8°C for the year of measurement). For a given snow depth, n_f becomes lower with rising MAAT, so snow cover impacts MAGST less at colder MAATs (Smith and Riseborough, 1998; Smith and Riseborough, 2002).

The freezing n-factor is also influenced by subsurface temperatures, particularly by the presence or absence of permafrost (Karunaratne and Burn, 2004). Sites with seasonally frozen ground have relatively warmer ground surfaces due to latent heat being released throughout the winter (Karunaratne and Burn, 2004; Smith and Riseborough, 2002). At sites with permafrost, latent heat is released only during the early part of the winter, when the active layer is freezing. Similarly, active layer thickness impacts n_f. At sites with thicker active layers, it takes longer to complete the freeze-back process. This prolonged subsurface heat flow prevents the ground from becoming very cold until the active layer has totally refrozen (Burn, 2000; Smith and Riseborough, 2002). MP 681.1's thaw depth was less than those at the other climate station sites, roughly 5 to 35 cm shallower at the time of climate station installation. Also, its MAGTs were colder by roughly 1.5°C to 2°C at a depth of 20 cm. These subsurface factors allowed MP 681.1 to experience freeze-back one to three weeks earlier than the other climate sites, in 2007. The earlier freeze-back may have contributed to MP 681.1's relatively high $n_{f,}$, given its high number of snow depth days.

There are several theories concerning the primary influences on n_t. Taylor (1995) concluded that n_t was mainly controlled by canopy cover, as n_t values were found to be high at open sites and lower at more shaded sites. Based on qualitative assessments of canopy cover in the field, n_t values did tend to be lower at the sites with denser canopies (such as MP 286 and MP 681.1). Klene *et al.* (2001) found n_t values to be primarily controlled by soil moisture. According to Karunaratne and Burn (2004), thawing n-factors are determined by near-surface thermal diffusivity, and vary directly with it. Karunaratne and Burn (2004) found that due to a very strong inverse correlation between organic layer thickness and n_t values, near-surface thermal diffusivity must control n_t, as organic soils typically have lower thermal diffusivity than mineral soils. Efforts were made to test this relationship with the n_t values and organic mat thicknesses at the study's climate station sites. However, because the frost table at each point of station installation was entirely within organic material, the thickness of the organic material is unknown. Regression analysis was done using the mean organic layer thicknesses calculated with all 2007 and 2008 data at each site, but this revealed no relationship (r^2= 0.0003, p=.973).

4.5 Borehole Measurements

Attempts at water-jet drilling at permafrost sites with water within 60 m yielded only two successes, due to stony ground at the other sites. Both sites are within the sporadic discontinuous permafrost zone (Heginbottom and Radburn, 2002).

At MP 286, also a climate station location, a 2.4 m borehole was drilled and a casing was installed on August 12, 2008. The borehole is in a shallow depression on a hummocky peat plateau. There are non-sphagnum and sphagnum mosses, lichen and Labrador tea at the site, as well as scattered 7.5 m spruce and tamarack. The frost table was encountered at 64 cm below ground surface and was within organic material.

The frozen layer, presumed to be permafrost, was found to be about 45 cm thick at that time, as indicated by the sudden advance of the drill stem. Mineral soil was reached within the borehole depth. The thermal profile at MP 286, measured manually about a week after drilling, on August 20, 2008 resulted in data supporting the interpretation that the permafrost is warm and thin at that location (Figure 17).

The thermal profile actually shows temperatures very slightly above zero (a minimum of 0.13°C, at 1.5 m depth), but this is likely due to imperfect thermal contact from the thermistor being suspended in air in the borehole casing. It is also possible that temperatures were measured before the borehole had time to equilibrate with surrounding ground temperatures after the thermal disturbance of drilling. In addition, the thermistor used (44033RC Precision Epoxy NTC thermistor) had a precision of ±0.1°C at best (Measurement Specialties Inc., 2008). The climate station at MP 286 had a mean annual ground temperature of -0.4°C (subject to ±0.4°C error) at 50 cm depth below surface, so the site has very warm permafrost. With a mean annual air temperature of -1.2°C for the year of measurement and a fairly low amount of snow (12 cm mean annual snow depth), the site is clearly near the limit of permafrost existence. It has long been theorized that the southern limit approximately coincides with a MAAT of -1°C (Brown, 1970; French and Slaymaker, 1993; Smith and Riseborough, 2002).

At MP 825.2, a borehole was drilled on a mound 1.5 m by 2 m wide, with a height about 30 cm above the surrounding ground surface. It had about a 50% canopy cover, with 10 to 15 m spruce and some willow shrubs around the mound. The mound itself had a ground cover of non-sphagnum mosses and Labrador tea. While no organic layer thickness was measured at the precise mound, a sample of 20 organic thicknesses at the site revealed a range of 18 to 56 cm, with a median organic layer thickness of 33 cm. At the nearest climate station, the project climate station at MP 844.1, the MAAT was -2.6°C for the year of measurement. At Whitehorse, where the closest Environment Canada weather station with a full year of data is located, MAAT was -0.7°C for the same time period (Environment Canada, 2008). The borehole reached a depth of 4.6 m below ground surface, which was within permafrost, so the maximum thickness of the permafrost there is unknown. At the time of drilling, on July 9, 2008, the frost table was 37 cm below the ground surface.

The mean thermal profile (Figure 18) shows that the permafrost at the site is very warm. The measured values are actually positive at depths in the top 2 m. However, this

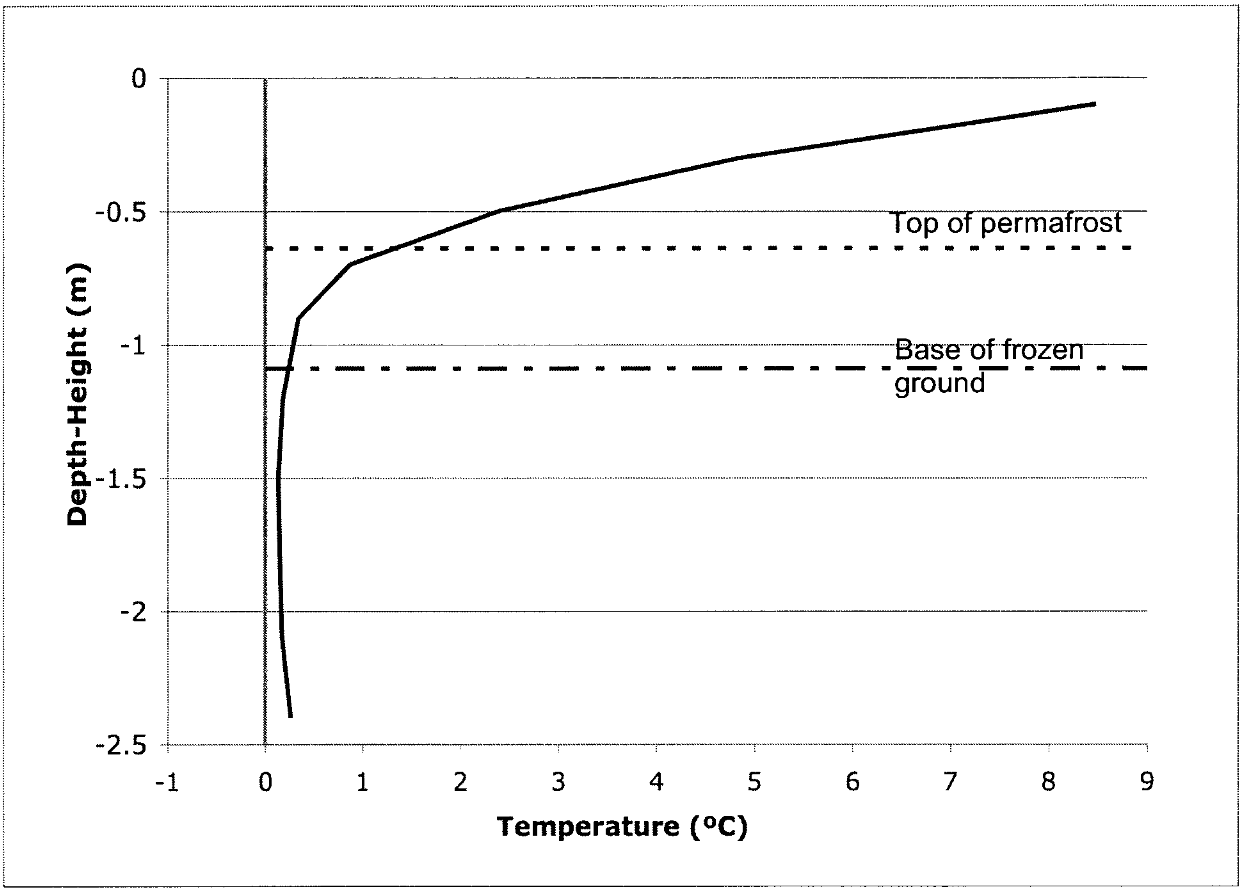


Figure 17. Thermal profile at Site 286, as measured on August 20, 2008. The frost table and base of frozen ground based on the behaviour of the drill stem are shown.

is likely due to inaccuracy in the measurement system, because the permafrost table is certainly less than 1 m depth based on probing to frozen ground of 68 cm in September 22, 2008 (A. Lewkowicz, personal communication, 2009). All values are within ±0.1°C of 0°C. Temperature amplitudes at the site are almost 30°C in the near-surface, but decrease to almost 0°C at a depth of only 1.5 m (Figure 19). This very shallow depth of zero annual amplitude must relate to high latent heats and changes in unfrozen moisture at temperatures very close to 0°C. The high permafrost temperatures at this site show that it may be vulnerable to active layer deepening and permafrost loss in the event of quite small climatic or surficial changes.

These observations show that permafrost thicknesses over the study area are highly variable, in this case from 45 cm to greater than 4.59 m, but that permafrost temperatures are very close to 0°C. Climate changes that at one site may only cause active layer deepening may eliminate a perennially frozen layer at another. No matter what the permafrost thickness, both of these sites are vulnerable to increases in local air temperatures and changing surface conditions, and appear to have experienced active layer deepening since 1964. Brown measured 53 cm and 48 cm to the frost tables at MPs 286 and 825.2, respectively (Brown, 1967), whereas the average thaw depth for the modern measurements were 79 cm and 68 cm. However, it has been noted that these comparisons must be treated with some degree of reserve due to Brown's unknown sampling methods.

4.6 Electromagnetic Induction

Eleven sites were visited for purposes of geophysical investigation via electromagnetic induction with an EM31 (Table 10). These included five of the climate

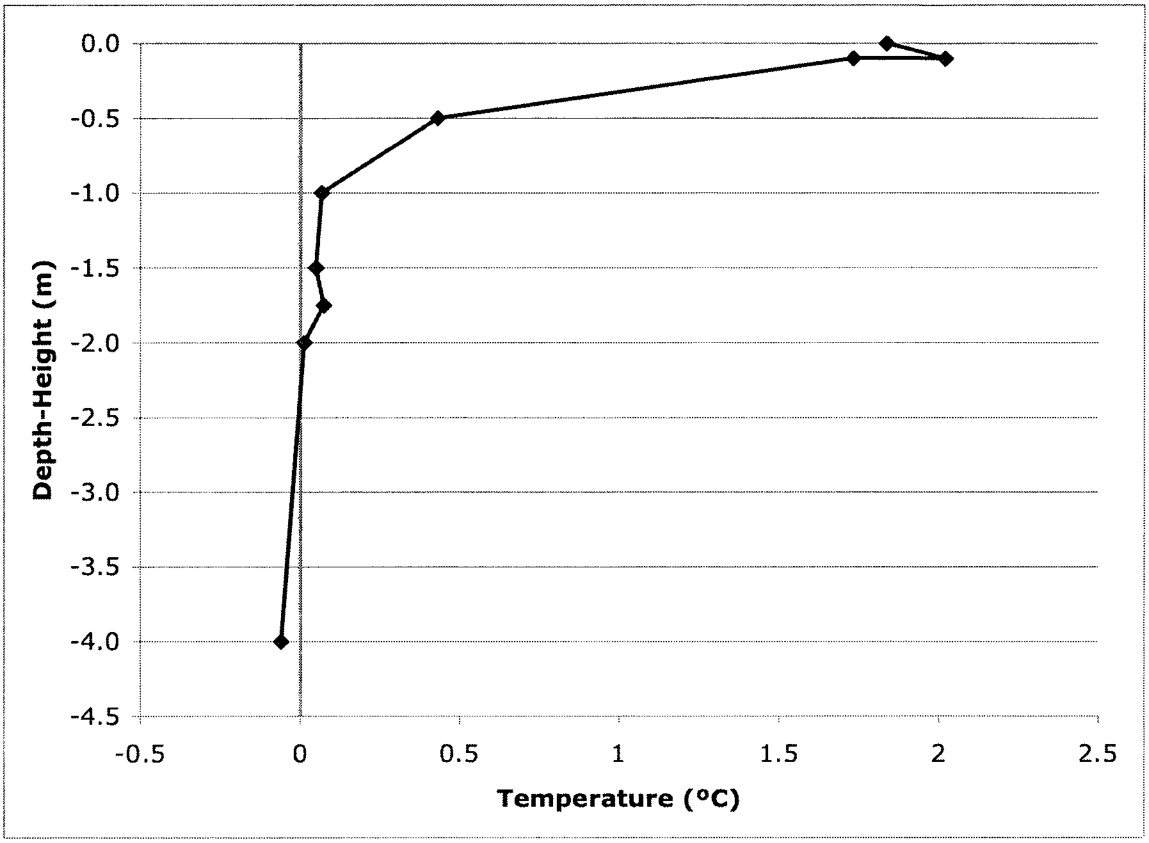


Figure 18. Mean temperature profile at MP 825.2 for a period of 360 days from September 2008 to September 2009. The diamonds represent the points of temperature measurement.

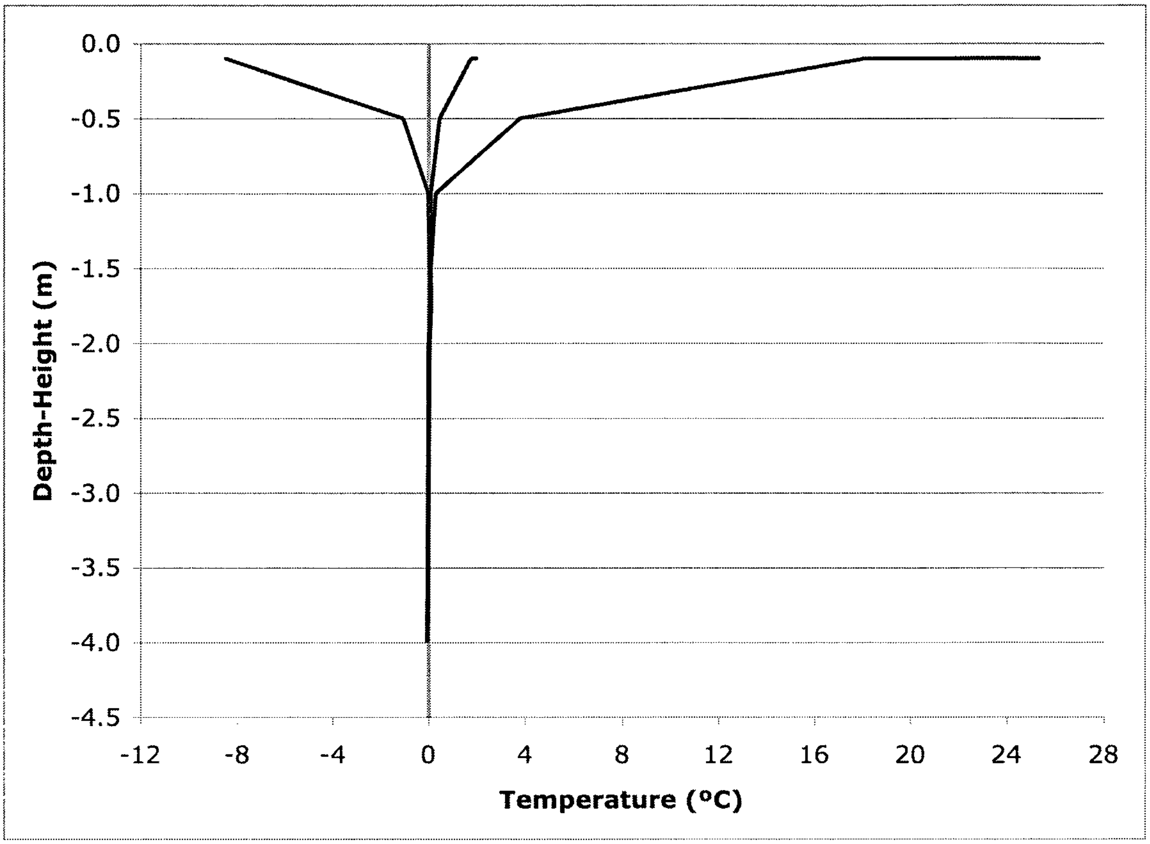


Figure 19. The minimum, mean and maximum temperatures logged at MP 825.2 for the 360 day period from September 2008 to September 2009. The grey line is 0°C.

station sites, three other sites with permafrost, and one site with no frost table within 1.82 m of the ground surface. Near-surface permafrost was unlikely at two other sites, but its absence could not be confirmed manually due to a gravel layer about 30 cm below the ground surface.

The actual conductivity values obtained through the investigations are relatively unimportant for this analysis, as it is how apparent conductivities of the three sets of measurements (vertical dipole configuration at 0.9 m above the ground surface, vertical dipole configuration on the ground and horizontal dipole configuration on the ground) compare to one another that allow inferences to be drawn concerning the presence or absence of permafrost and rough estimates to be made of its thickness (Table 10) (McNeill, 1980).

In addition to looking at apparent conductivity values varying by dipole configuration and instrument height, deviations from a measured mean conductivity of the transect were examined in order to detect anomalies (Hauck and Vonder Mühll, 1999). Interpretation of differing apparent conductivities based on dipole configuration and instrument height was done in a manner similar to that described by Morris (2009), Hoekstra and McNeill (1973), and Sartorelli and French (1982) (see Methods). Site surface and drainage conditions were also taken into consideration.

Of the eight sites investigated that were known to have permafrost, five were inferred to have thin permafrost (with a base shallower than the instrument's maximum depth of exploration of 4.6 to 6 m), and three were variable in their layering, with the transect having points with evidence of one, two, and three layers. Figure 20 shows one of the inferred three layered sites in which the measurements taken with a vertical dipole

Table 10. Results of EM31 surveys. MP 587.6 was manually impenetrable past 182 cm due to highly cohesive clay, whereas MPs 771.6 and 774 were impenetrable past roughly 30 cm due to a gravel layer.

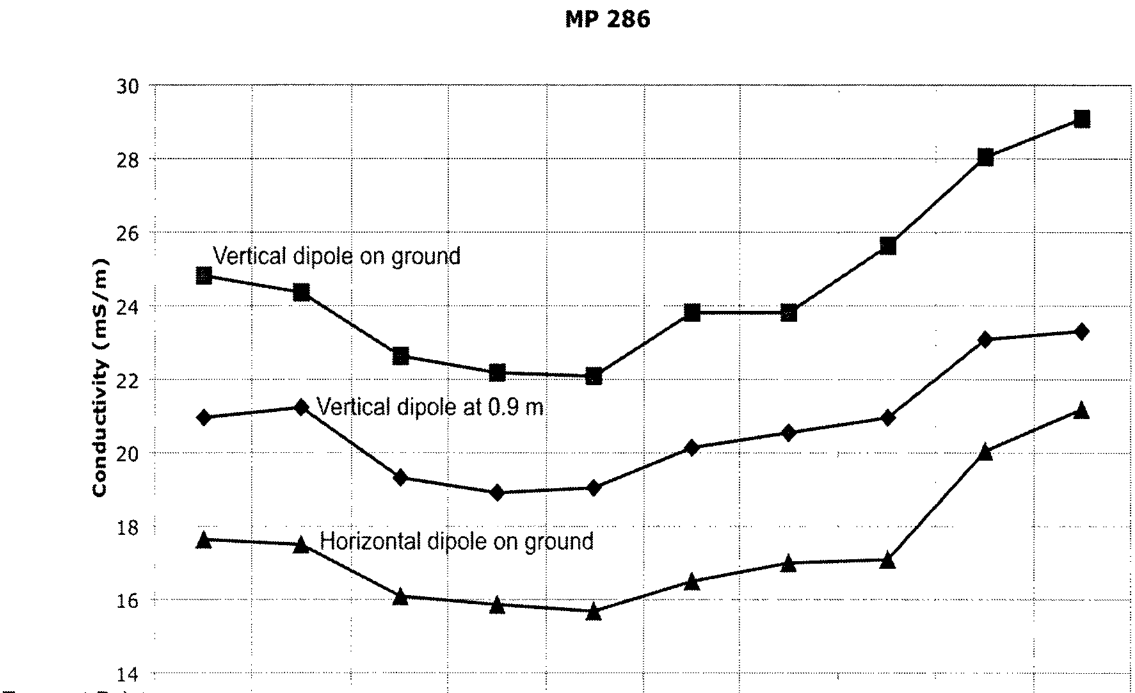
Site	2007/2008 Manual Investigations	Frost Table Depths on EM31 transect (cm)	Inferred Ground Conditions
MP 178	permafrost present	86 to >150	thin permafrost (3 layered)
MP 208.5	permafrost present	41 to 58	thin permafrost (3 layered)
MP 286	permafrost present	52 to 133	thin permafrost (3 layered)
MP 341.3	permafrost present	51 to >135	thin permafrost (3 layered)
MP 400.5	permafrost present	45 to 115	variable (2 and 3 layered)
MP 587.6	No permafrost to 182 cm	none	no permafrost (1 layered)
MP 597.5	permafrost present	37 to 51	thin permafrost (3 layered)
MP 681.1	permafrost present	35 to 135	variable (1, 2 and 3 layered)
MP 771.6	indeterminate	none	no permafrost (1 layered)
MP 774	indeterminate	none	no permafrost (1 layered)
MP 825.2	permafrost present	36 to >135 cm	variable (1, 2 and 3 layered)

configuration on the ground were greater than those taken with a vertical configuration at 0.9 m above the ground surface. As described in the Methods, this implies thin permafrost or a change in the permafrost properties to become more conductive with depth.

Three of the sites with frost tables showed lateral discontinuities in permafrost, as well as permafrost thickness varying from less than to deeper than the maximum effective depth of exploration. It was common for the points with no evidence of permafrost at these sites to be in ground wetter than at other points on the transect, sometimes in standing water (e.g. Figure 21).

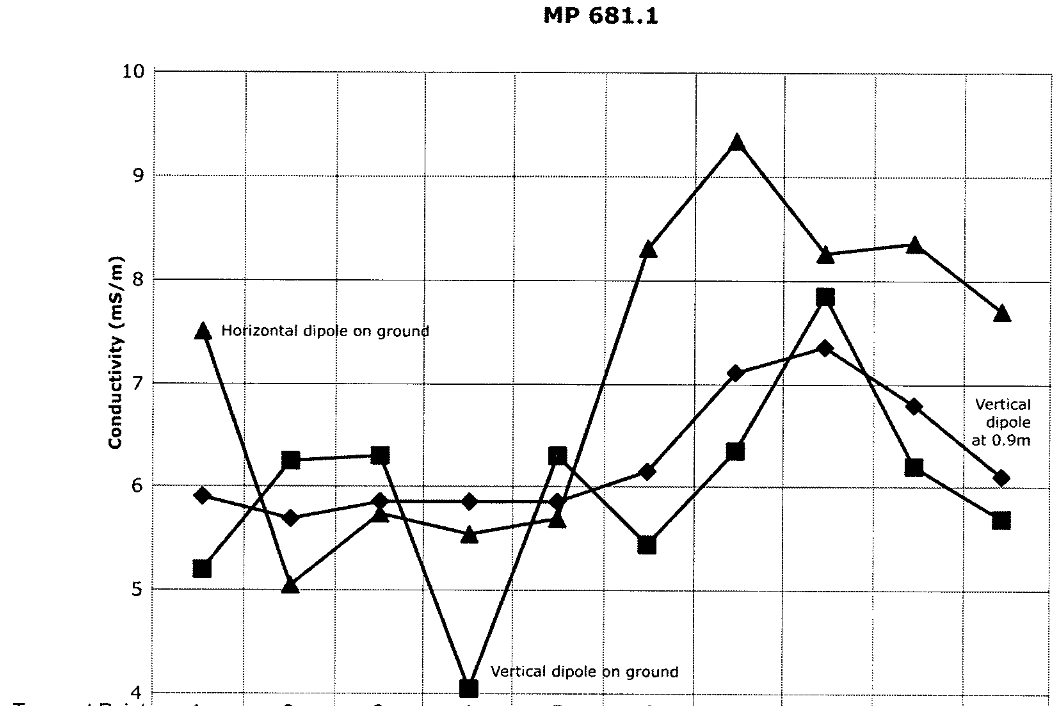
Three sites were investigated that were considered unlikely to have permafrost in the upper 2 m of soil. At one site (MP 587.5), prior manual investigations resulted in penetration to only 1.82 m due to very cohesive clay that was difficult to probe. At MPs 771.6 and 774, a layer of gravel at roughly 30 cm below ground surface prevented manual investigation to 2 m. Brown failed to find evidence of permafrost at any of the three sites, and the EM31 results support his findings. Figure 22 shows MP 587.5, a one layered site.

Figures showing the results of EM31 investigations at the other eight sites can be found in Appendix G. The EM31 results suggest that permafrost is thin, largely less than 6 m thick (and possibly less than 4.6 m depending on the effective depth of exploration considered). The results also demonstrate that at sites with permafrost, permafrost can be highly variable in continuity and thickness. The EM31 investigations were useful in allowing an expanded knowledge of the permafrost conditions where permafrost has persisted in the study area.



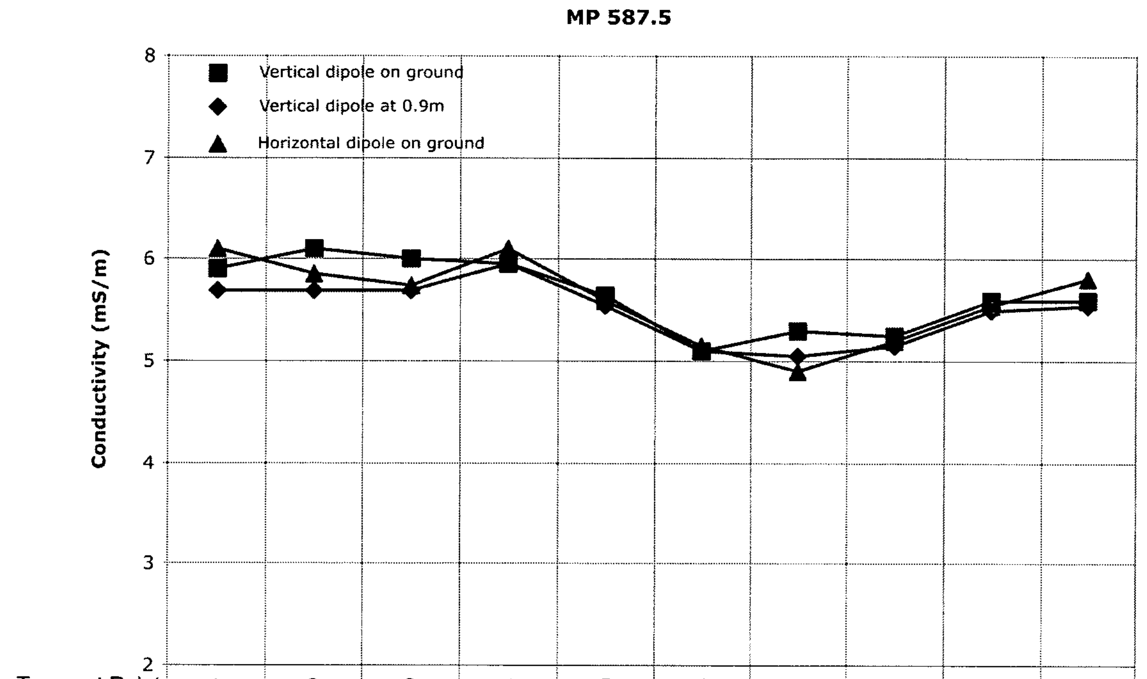
Transect Point	1	2	3	4	5	6	7	8	9	10
Layers	3 layer									
Organic Mat	> 56	> 52	> 67	> 61	114	60	85	60	> 54	60
Frost Table	r	52	67	61	133	r	92	r	r	r
Relief	d	h	h	d	h	h	d	h	d	h
Drainage	Ground moist, but no standing water									
Vegetation	ST(p)HMSphLtLn									

Figure 20. MP 286, showing 3 layered terrain as inferred through interpretation of EM31 readings. The 'r' means that rocks or roots prevented penetration to the frost table. The 'd' and 'h' symbolize whether the measurement was taken in a depression or on a hummock, respectively. 'S' symbolizes spruce trees, while 'T' symbolizes tamaracks. The 'p' denotes a peat plateau, 'H' denotes hummocky terrain, 'M' represents non-sphagnum mosses, 'Sph' represents sphagnum mosses, 'Lt' symbolizes Labrador tea, and 'Ln denotes lichens.



Transect Point	1	2	3	4	5	6	7	8	9	10
Layers	1 layer	3 layer	3 layer	2 layer	3 layer	1 layer	1 layer	1 layer	1 layer	1 layer
Organic Mat	>135	27	32	26	21	60	66	86	53	64
Frost Table	>135	r	36	35	44	r	r	r	r	r
Relief	d	d	h	h	h	d	d	h	h	h
Drainage	standing water	moist	moist	moist	moist	moist	standing water	wet	wet	wet
Vegetation	STWHSph MGLtB	STWHM lnLtB	STWHSph MLnLtGB	STWH BMLn	STWHM LtLn	STWH SphGLt	STWH SphGLt	STWHSph MGLt	STWH SphMLtB	STWHG SphMLt

Figure 21. MP 681.1, showing 1, 2, and 3 layered terrain as inferred from the EM31 readings. Although one layered points do not have similar apparent conductivities, they were inferred to be unfrozen due to their extreme wetness. The 'r' means that rocks or roots prevented penetration to the frost table. The d' and 'h' symbolize whether the measurement was taken in a depression or on a hummock, respectively. 'S' symbolizes spruce trees, while 'T' symbolizes tamaracks. The 'p' denotes a peat plateau, 'H' denotes hummocky terrain, 'M' represents non-sphagnum mosses, 'Sph' represents sphagnum mosses, 'Lt' symbolizes Labrador tea, and 'Ln denotes lichens. 'G' represents grasses.



Transect Point	1	2	3	4	5	6	7	8	9	10
Layers	1 layer	1 layer	1 layer	1 layer	1 layer	1 layer	1 layer	1 layer	1 layer	1 layer
Organic Mat	70	39	29	27	21	33	32	30	24	24
Frost Table	>182	>182	>182	>182	>182	>182	>182	>182	>182	>182
Relief	h	d	h	h	d	h	d	h	h	h
Drainage	Ground wet to saturated with no standing water.									
Vegetation	SWHMLtLnHt									

Figure 22. MP 587.5, showing 1 layered terrain as inferred through interpretation of EM31 readings. The d' and 'h' symbolize whether the measurement was taken in a depression or on a hummock, respectively. 'S' symbolizes spruce trees, while 'W' symbolizes willows. The 'p' denotes a peat plateau, 'H' denotes hummocky terrain, 'M' represents non-sphagnum mosses, 'Sph' represents sphagnum mosses, 'Lt' symbolizes Labrador tea, and 'Ln denotes lichens. 'G' represents grasses, and 'Ht' represents horsetail.

4.7 Climate in the Study Area 2007-2008

Data from five Environment Canada weather stations situated in the study area can be compared to measurements made at the six climate stations set up specifically for this project (Table 11 and Figure 23). The Environment Canada stations are situated on permafrost-free ground while all the study climate stations were installed on permafrost terrain. Differences between the air temperatures and precipitation measured at the project climate stations and the Environment Canada stations nearest to them may indicate reasons why permafrost is able to persist at the project climate station sites. Moving from south to north along the highway, there is a roughly linear trend of decreasing TDDs, and a curvilinear trend of FDDs that peaks at MP 681.1 (Figure 23). Snow depth days (see Table 9) show a similar curvilinear trend, and would buffer the ground from the colder winter temperatures experienced at the stations from MP 597.5 to MP 681.1. Table 12 shows the distance between the study climate stations and the closest, or two closest Environment Canada weather stations, as well as the elevation difference and predicted and actual temperature differences. Differences in temperature between adjacent stations are to be expected, due to differences in elevation. However, when elevational differences are accounted for using an average environmental lapse rate of 0.65°C/100 m, and there is a larger or smaller than expected temperature difference between Environment Canada weather stations and study climate stations, it suggests that there are different microclimatic factors at play. Since there is only one year of climate data available at the project climate stations, however, differences between the two sets of measurement stations must be treated as tentative. Although the Environment Canada

Table 11 Location and 2007-2008 climate data from Environment Canada weather stations and project climate stations. Stations are listed in order of occurrence along the study transect, from south to north.

Station	Latitude	Longitude	Elevation	MAAT	TDD	FDD
Fort St. John (MP 47)	56° 14' 17" N	120° 44' 25" W	695 m	2.2°C	1757	1566
MP 208.5	57° 48' 47" N	122° 54' 41" W	771 m	-2.2°C	1327	2459
MP 286	58° 39' 48" N	122° 41' 36" W	417 m	-1.2°C	1649	2460
Fort Nelson (MP 300)	58° 50' 11" N	122° 35' 50" W	382 m	-0.5°C	1726	2352
MP 400.5	58° 41' 29" N	124° 51' 28" W	1043 m	-1.8°C	1172	2090
MP 597.5	59° 59' 45" N	127° 57' 16" W	682 m	-3.2°C	1300	2753
Watson Lake (MP 635)	60° 06' 59" N	128° 49' 20" W	687 m	-2.6°C	1400	2652
MP 681.1	60° 11' 19" N	129° 53' 56" W	849 m	-3.8°C	1213	2837
Teslin (MP 804)	60° 10' 27" N	132° 44' 09" W	705 m	-2.1°C	1158	2228
MP 844.1	60° 28' 35" N	133° 29' 03" W	813 m	-2.6°C	1123	2322
Whitehorse (MP 918)	60° 42' 34" N	135° 04' 08" W	706 m	-0.7°C	1341	1938

Note: MAATs are for the year from August 19, 2007, to August 18, 2008. Air TDDs are for the 2008 thawing season, until the measurement date of the project climate station. For the Environment Canada stations, the measurement date of the closest project station was used. Air FDDs are for the freezing season spanning 2007 and 2008. Thawing and freezing seasons, for the purposes of this comparison table, were defined using only air temperatures. (Environment Canada, 2008)

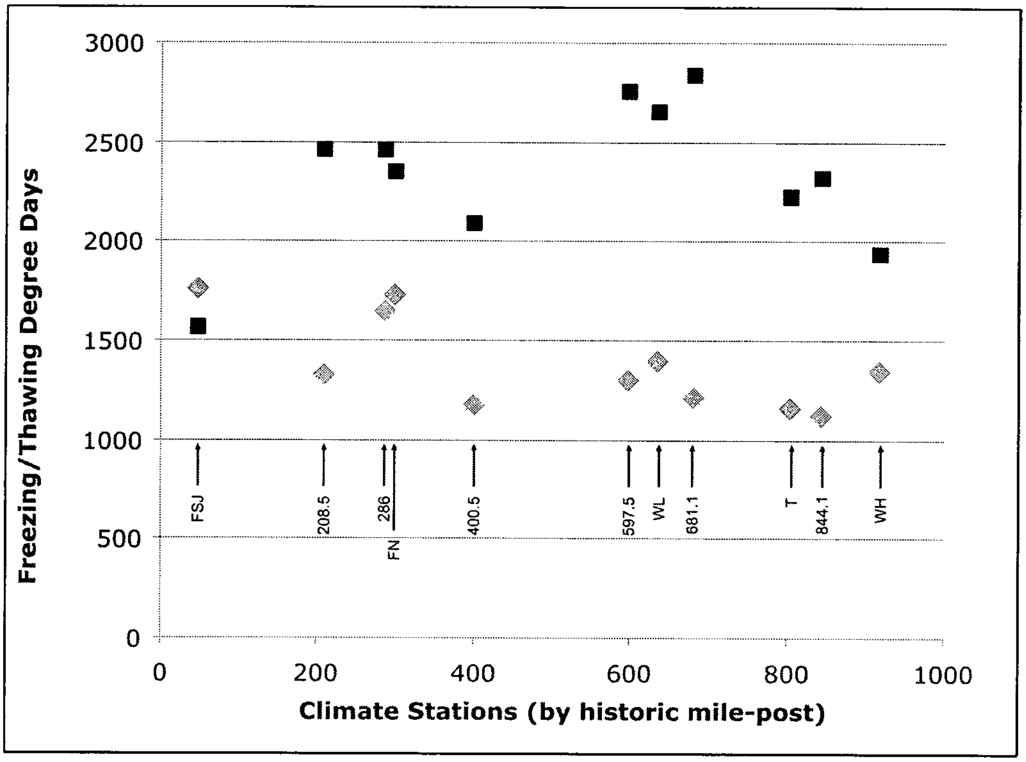


Figure 23. FDDs and TDDs at the study climate stations and Environment Canada weather stations during 2007 and 2008. Air FDDs are for the freezing season spanning 2007 and 2008, while the TDDs include 2008 data to August 18. The black squares represent FDDs, and the grey diamonds are TDDs.

stations were within ±0.3°C of their 1971-2000 MAAT Climate Normals (Environment Canada, 2008), it is still possible that this year of measurement did not represent typical temperatures at project climate stations.

Fort St. John had a MAAT 4.4°C warmer (from August 19, 2007 to August 18, 2008) than its nearest project climate station, at MP 208.5, 3.9°C warmer than would be expected given their elevational differences (Table 12). The data show that Fort St. John had nearly 900 FDDs fewer than MP 208.5, while it had 430 more TDDs (Figure 23). Figure 24 compares the mean, maximum and minimum daily temperatures of MP 208.5 and Fort St. John for 2007-2008. While the two stations exhibit similar maximum temperatures (as the line of best fit is close to 1:1), the minimum daily temperatures at MP 208.5 averaged 8°C colder than those at Fort St. John in all seasons. As a consequence, the mean daily temperature is about 4°C colder. Hourly data from the two stations (Figure 25) show that MP 208.5 experienced temperatures up to 23°C colder than at Fort St. John.

The hourly data indicate that frequent atmospheric temperature inversions, at night and in winter, are probably the primary reason MP 208.5 has such a much colder MAAT than Fort St. John. Such inversions occur frequently in the Arctic due to the negative radiation balance over snow and ice for large parts of the year, and are most common on calm, clear nights ideal for longwave radiative heat loss (Taylor *et al.*, 1998). Cold air drainage or pooling can occur in areas of large topographic relief and contribute to the temperature inversion (Harris, 1982; Harris, 1986; Pypker et al., 2007; Taylor et al., 1998). The data suggest that comparatively mild winter temperatures (due to a lack

Table 12. Differences in orthodromic distance and elevation between climate stations, as well as temperature expectations for the study sites, based on the nearest Environment Canada weather station, and using an average environmental lapse rate of 0.65°C /100 m increase in elevation. An assumption was made that adjacent sites experience similar large-scale weather patterns. Elevations were derived from 30 resolution DEMs (Source: Geomatics Yukon, 2006; National Topographic Database).

Station	Orthodromic Distance	Elevation Difference (study station – Environment Canada station)	Expected difference in MAAT	Actual difference in MAAT	Predicted to actual difference
Fort St. John to MP 208.5	219 km	+76 m	-0.5°C	-4.4°C	-3.9°C
MP 208.5 to Fort Nelson	115 km	+389 m	-2.5°C	-1.7°C	+0.8°C
MP 286 to Fort Nelson	20 km	+35 m	-0.2°C	-0.7°C	-0.5°C
Fort Nelson to MP 400.5	131 km	+661 m	-4.3°C	-1.3°C	+3.0°C
MP 597.5 to Watson Lake	50 km	-5 m	0.0°C	-0.6°C	-0.6°C
Watson Lake to MP 681.1	60 km	+162 m	-1.1°C	-1.2°C	-0.1°C
Teslin to MP 844.1	53 km	+108 m	-0.7°C	-0.5°C	+0.2°C
MP 844.1 to Whitehorse	90 km	+ 107 m	-0.7°C	-1.9°C	-1.2°C

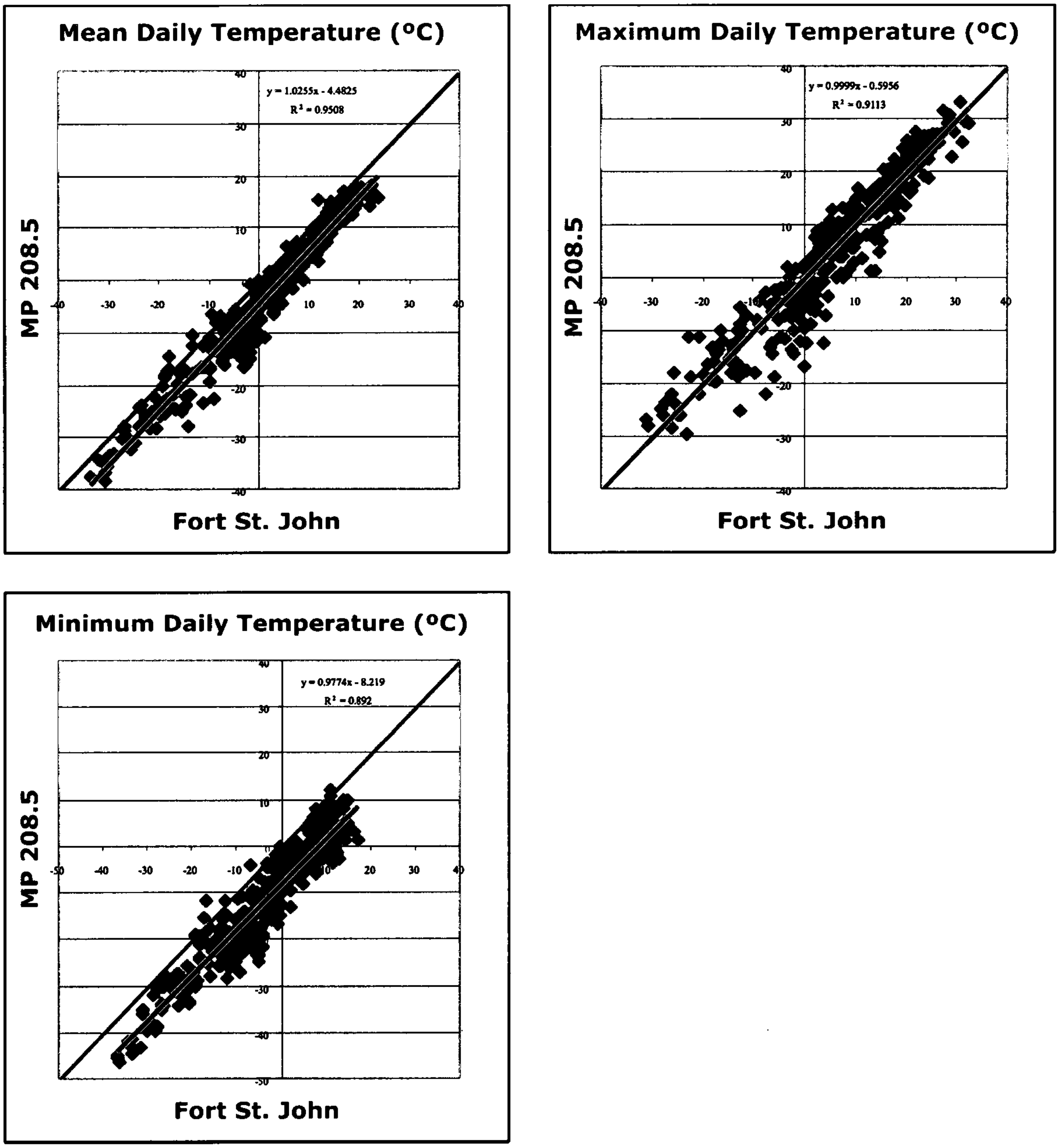


Figure 24. Comparison of mean, maximum and minimum daily temperatures between the MP 208.5 climate station and the Environment Canada weather station at Fort St. John from August 19, 2007 to August 18, 2008 (Environment Canada, 2008). The red line represents the predicted temperatures of the project station based on the Environment Canada station and an average Environmental lapse rate of 0.65°C / 100m.

of, or lesser amount of cold air pooling) prevent the presence of permafrost at the Fort St. John Environment Canada station.

The Environment Canada weather station closest to MP 208.5 is actually in Fort Nelson, located 115 km to the north. MP 208.5 had 400 fewer TDDs and 100 more FDDs than Fort Nelson, leading it to have a MAAT 1.7°C colder than Fort Nelson, with most of the difference due to summer temperatures. However, based solely on their elevations, MP 208.5 is 0.8°C warmer than would be expected with an average environmental lapse rate of 0.65°C/100 m due to the difference in elevation between the sites. Maximum daily temperatures were similar for the two sites at temperatures above roughly 12°C, but below that, temperatures were colder at the MP 208.5 station by up to 10°C (Figure 26). The mean temperature of the two sites is quite close to a 1:1 relationship, but above 0°C, Fort Nelson is slightly warmer. Since MP 208.5 site appears to have cold air drainage throughout the year based on the comparison with Fort St. John, and Fort Nelson exhibits similar nocturnal minima at low temperatures, it is likely that Fort Nelson also experiences some cold air drainage in winter. However, in summer, nocturnal temperatures at MP 208.5 are consistently colder (Figures 26 and 27).

Fort Nelson had TDD and FDD values very similar to MP 286, which is 20 km from the town, yet had a MAAT (from August 19, 2007 to August 18, 2008) 0.7°C warmer than MP 286 (0.5°C warmer than would be expected with a standard environmental lapse rate of 0.65°C/100 m) (Table 12). The accuracy of the HOBO data logger at MP 286, ±0.2°C, could account for some of the difference. However, the generally tight relationship shown in Figure 28 for these proximate stations gives

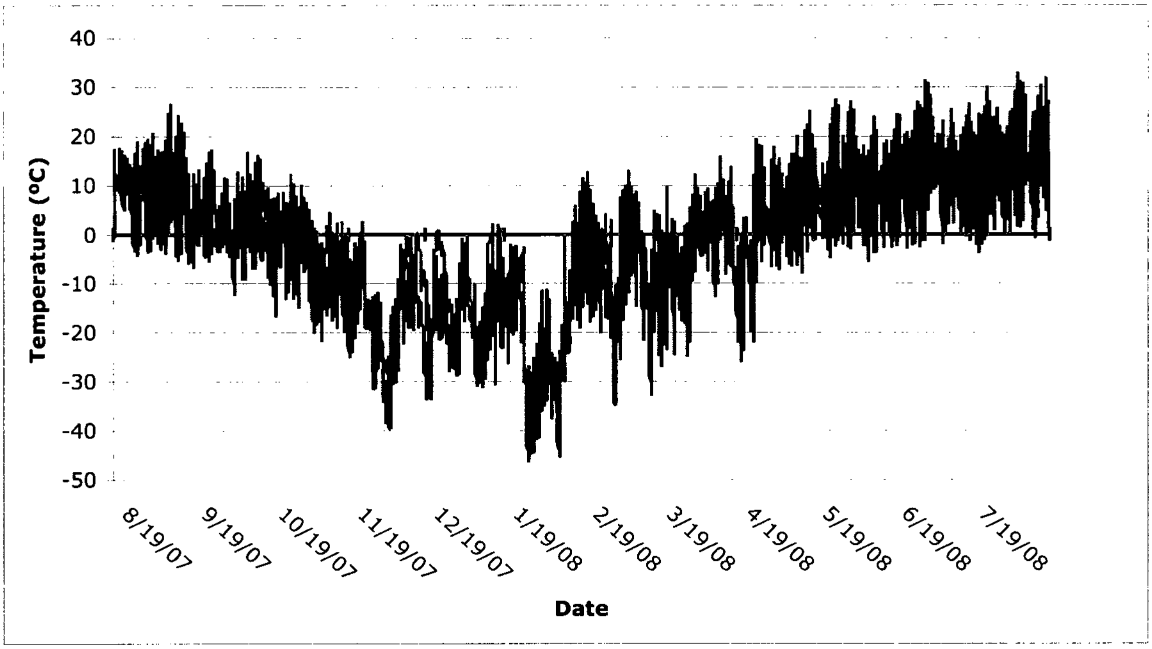
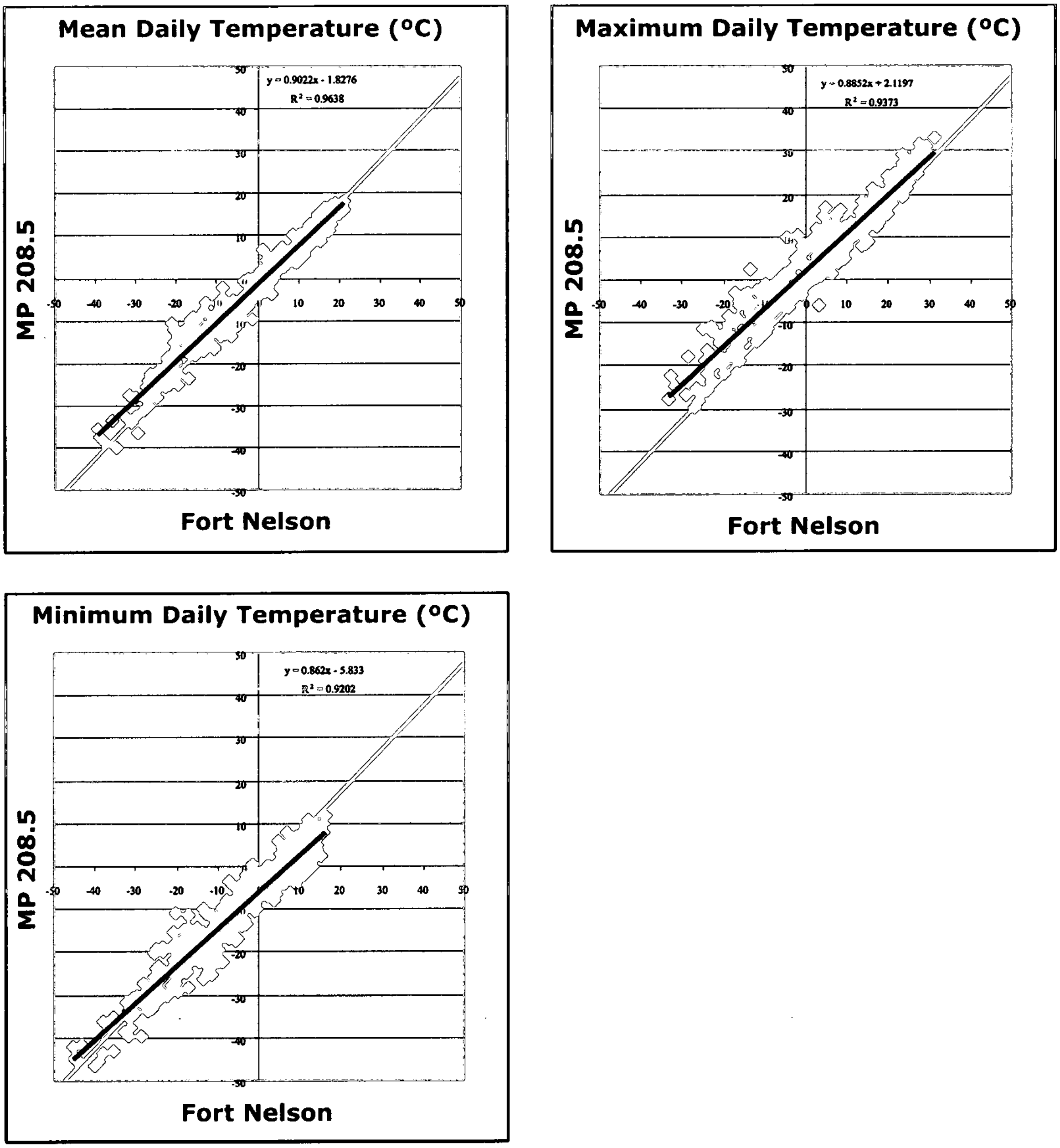


Figure 25 Hourly temperatures at the MP 208.5 climate station and the Environment Canada weather station in Fort St. John from August 19, 2007 to August 18, 2008. M 208.5 is red and the station at Fort St. John is blue (Environment Canada, 2008).



Mean Daily Temperature (°C)

Maximum Daily Temperature (°C)

Minimum Daily Temperature (°C)

Figure 26 Comparison of mean, maximum and minimum daily temperatures between the MP 208.5 climate station and the Environment Canada weather station at Fort Nelson from August 19, 2007 to August 18, 2008 (Environment Canada, 2008). The red line represents the predicted temperatures of the project station based on the Environment Canada station and an average Environmental lapse rate of 0.65°C / 100m.

confidence that the MAAT measurement methods from the Environment Canada stations and the project climate stations are comparable. While the daily mean and maxima follow a 1:1 relationship, the minima are slightly lower at the MP 286 station at temperatures above about -10°C. It appears as though atmospheric temperature inversions could be occurring at both sites. The difference of 0.7°C between the two sites, combined with less snow (see Table 13) and differing substrate conditions are enough to maintain permafrost at MP 286.

MP 400.5, which is located 131 km from Environment Canada's Fort Nelson station, was warmer than the latter during the freezing season, with 260 fewer FDDs. During the thawing season (up to August 20, 2008), however, it had 550 fewer TDDs. The MAAT difference of 1.3°C between the sites is 3°C smaller than would be expected, given the elevational difference of 661 m. A comparison of mean temperatures shows that above roughly 0°C, the MP 400.5 station had cooler temperatures, but close to what would be predicted by the elevation difference (Figure 29). Below 0°C, Fort Nelson was frequently colder, and much colder when the expected difference is taken into account. Higher maxima occurred most frequently at Fort Nelson in the summer, but the MP 400.5 station often had higher daily maximum temperatures in the winter. The minima occurred most often at MP 400.5 at temperature above roughly -10°C. However, at temperatures below -10°C, both stations had very similar minima, with Fort Nelson having the lowest temperature somewhat more often than the station at MP 400.5 (Figure 29). Since Fort Nelson has already been identified as being affected by atmospheric temperature inversions in winter, hourly data (Figure 30) suggest that MP 400.5 is less

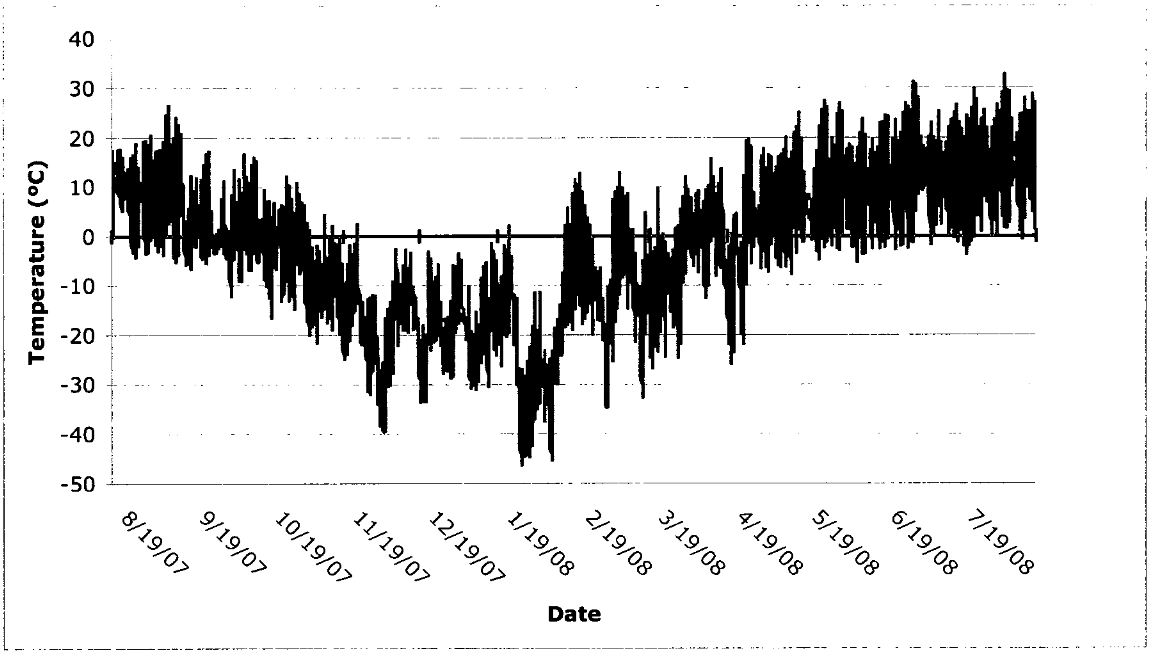


Figure 27. Hourly temperatures at the MP 208.5 climate station and the Environment Canada weather station in Fort Nelson from August 19, 2007 to August 18, 2008. The data for the station at M 208.5 is red, while the Environment Canada weather station at Fort Nelson is blue (Environment Canada, 2008).

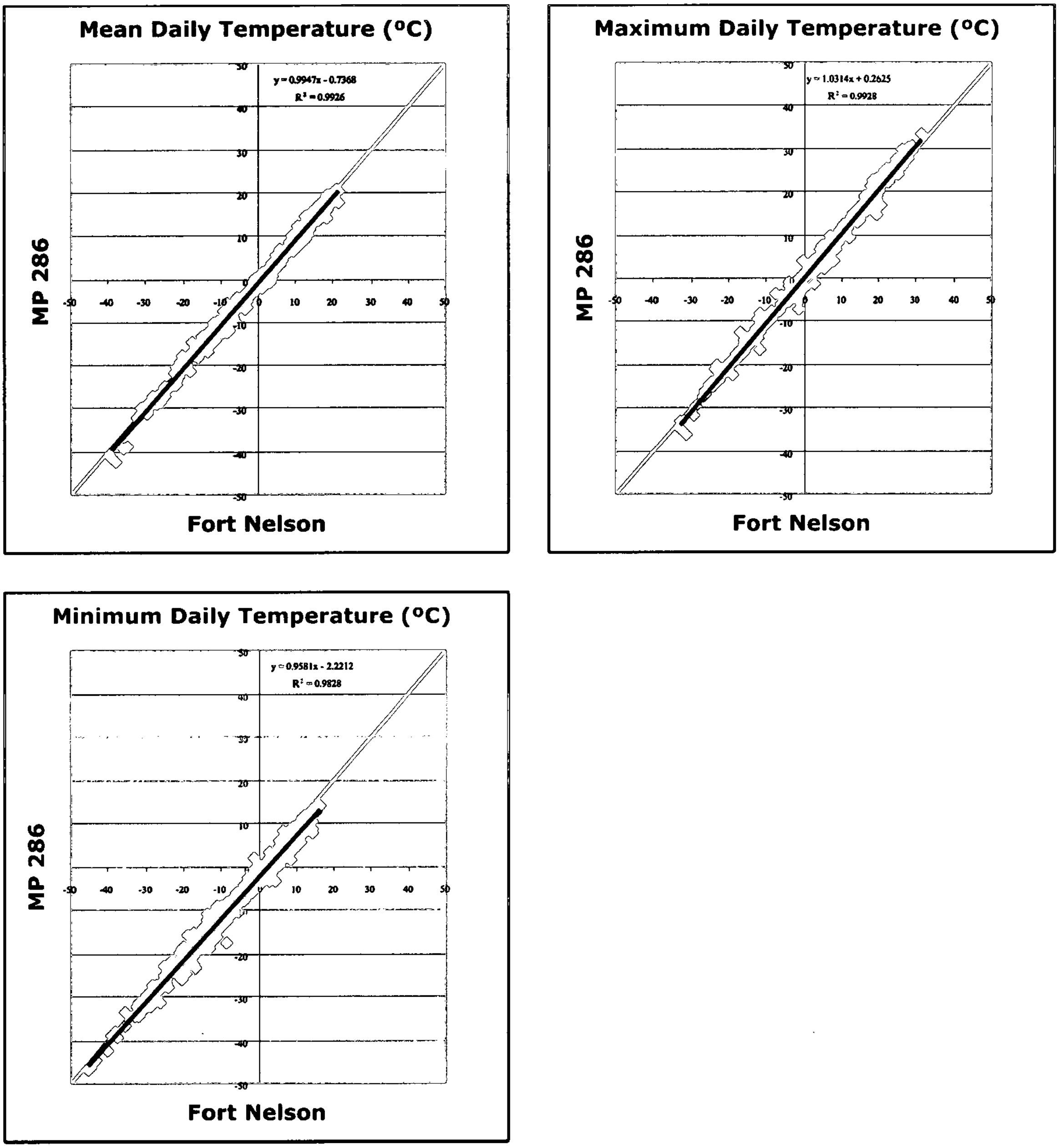


Figure 28. Comparison of mean, maximum and minimum daily temperatures between the MP 286 climate station and the Environment Canada weather station at Fort Nelson from August 19, 2007 to August 18, 2008 (Environment Canada, 2008). The red line represents the predicted temperatures of the project station based on the Environment Canada station and an average Environmental lapse rate of 0.65°C / 100m.

affected by that phenomenon. Permafrost-suitable conditions are maintained by cooler summers, in spite of warmer winters.

The two project climate stations closest to Watson Lake (MPs 597.5 and 681.1) were colder than the Environment Canada station during both freezing and thawing seasons (Figure 23 and Table 12). MP 597.5 is located 50 km away from Watson Lake, and 5 m lower in elevation. It had roughly 100 TDDs fewer than Watson Lake (to August 21, 2008), and about 100 more FDDs than the town during the 2007-2008 freezing season. MP 681.1 differed from the Watson Lake station in a similar fashion, with about 200 fewer TDDs during the thawing season (to August 20, 2008), and about 200 more FDDs during the freezing season.

Figure 31 shows a comparison of the daily temperature means, maxima, and minima at the MP 597.5 station and the Environment Canada weather station at Watson Lake. Both the means and maxima follow the 1:1 line very closely. For the mean temperatures, MP 597.5 is slightly cooler at temperatures above about 10°C. In terms of the temperature minima, MP 597.5 is very slightly cooler.

MP 681.1 is 60 km from Watson Lake and 162 m higher in elevation. Its MAAT was within 0.1°C of what would be expected with an average environmental lapse rate of 0.65°C/100 m, based on data from Watson Lake, which is quite close given the separation. Figure 32 shows a comparison of the daily temperature means, maxima, and minima at the MP 681.1 station and the Environment Canada weather station at Watson Lake. All three datasets have a relationship that is quite close to 1:1, but with slightly more scatter than for MP 597.5 (see Figure 31). The mean daily temperatures of MP 681.1 were typically slightly cooler than those at Watson Lake, particularly at

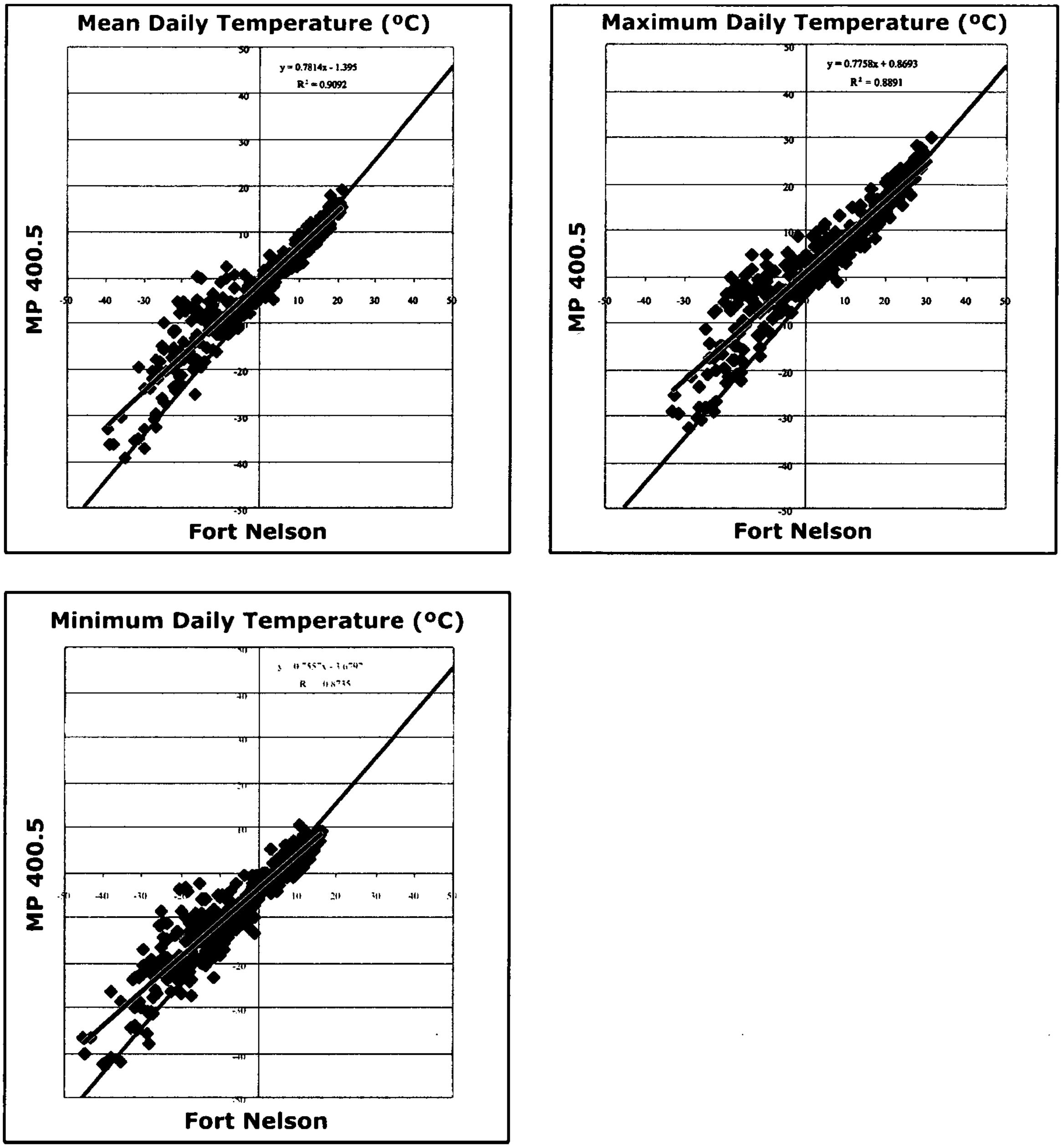


Figure 29. Comparison of mean, maximum and minimum daily temperatures between the MP 400.5 climate station and the Environment Canada weather station at Fort Nelson from August 19, 2007 to August 18, 2008 (Environment Canada, 2008). The red line represents the predicted temperatures of the project station based on the Environment Canada station and an average Environmental lapse rate of 0.65°C / 100m.

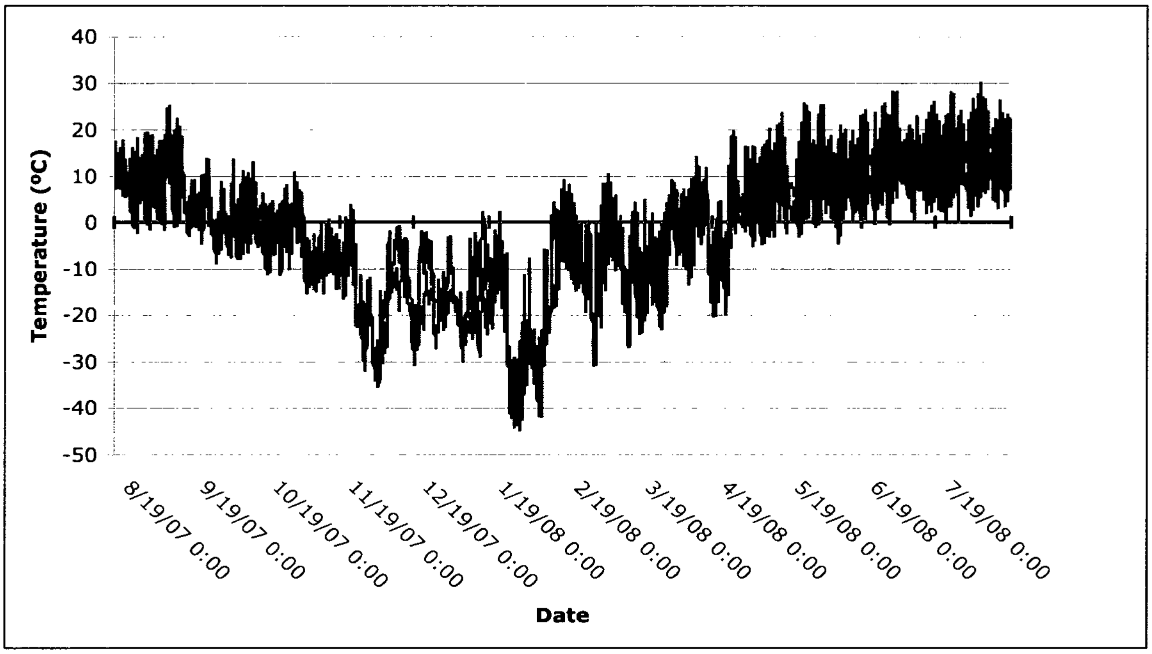


Figure 30. Hourly temperatures at the MP 400.5 climate station and the Environment Canada weather station in Fort Nelson from August 19, 2007 to August 18, 2008. The data for the station at M 400.5 is red; while the Environment Canada weather station at Fort Nelson is blue (Environment Canada, 2008).

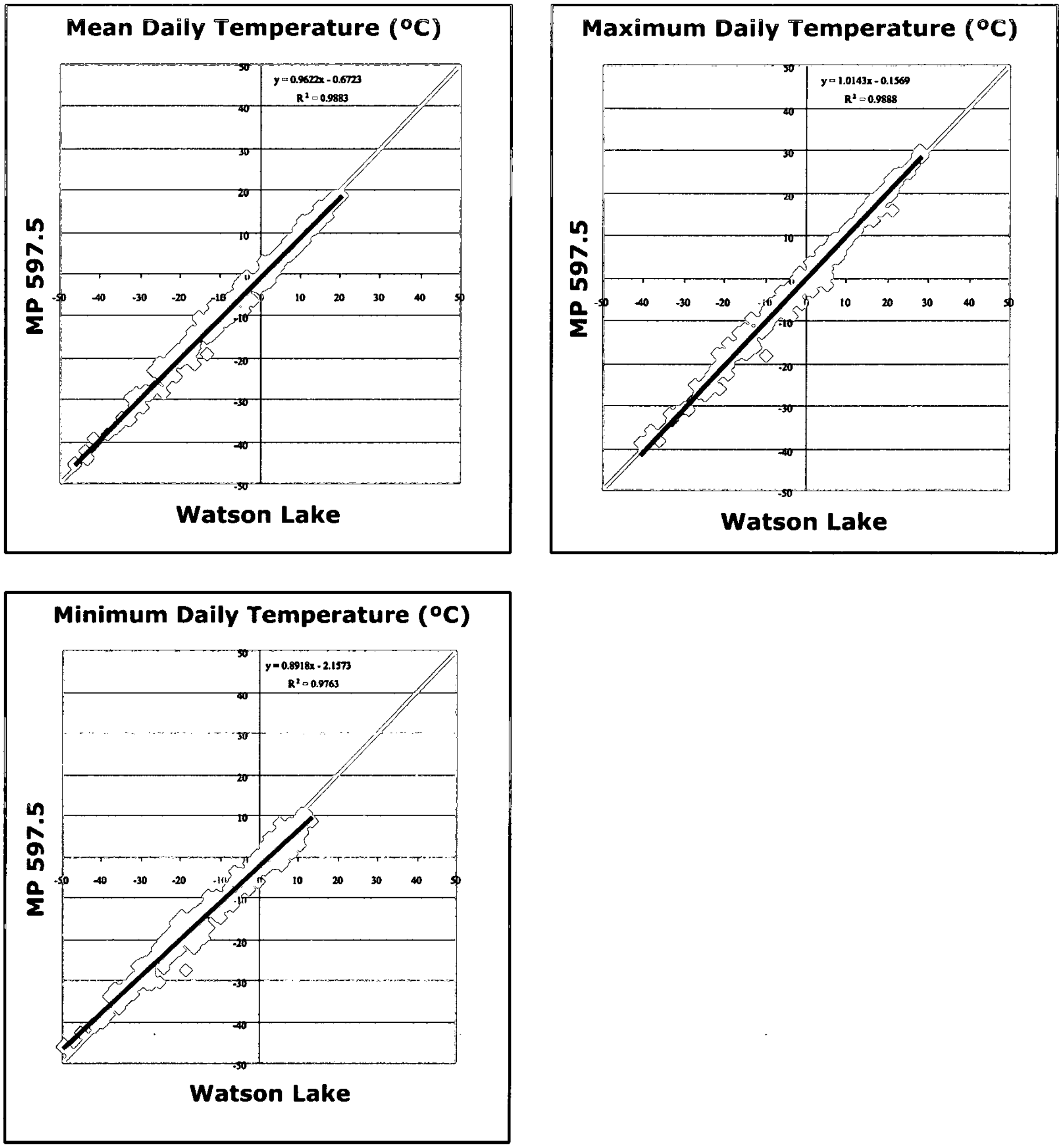
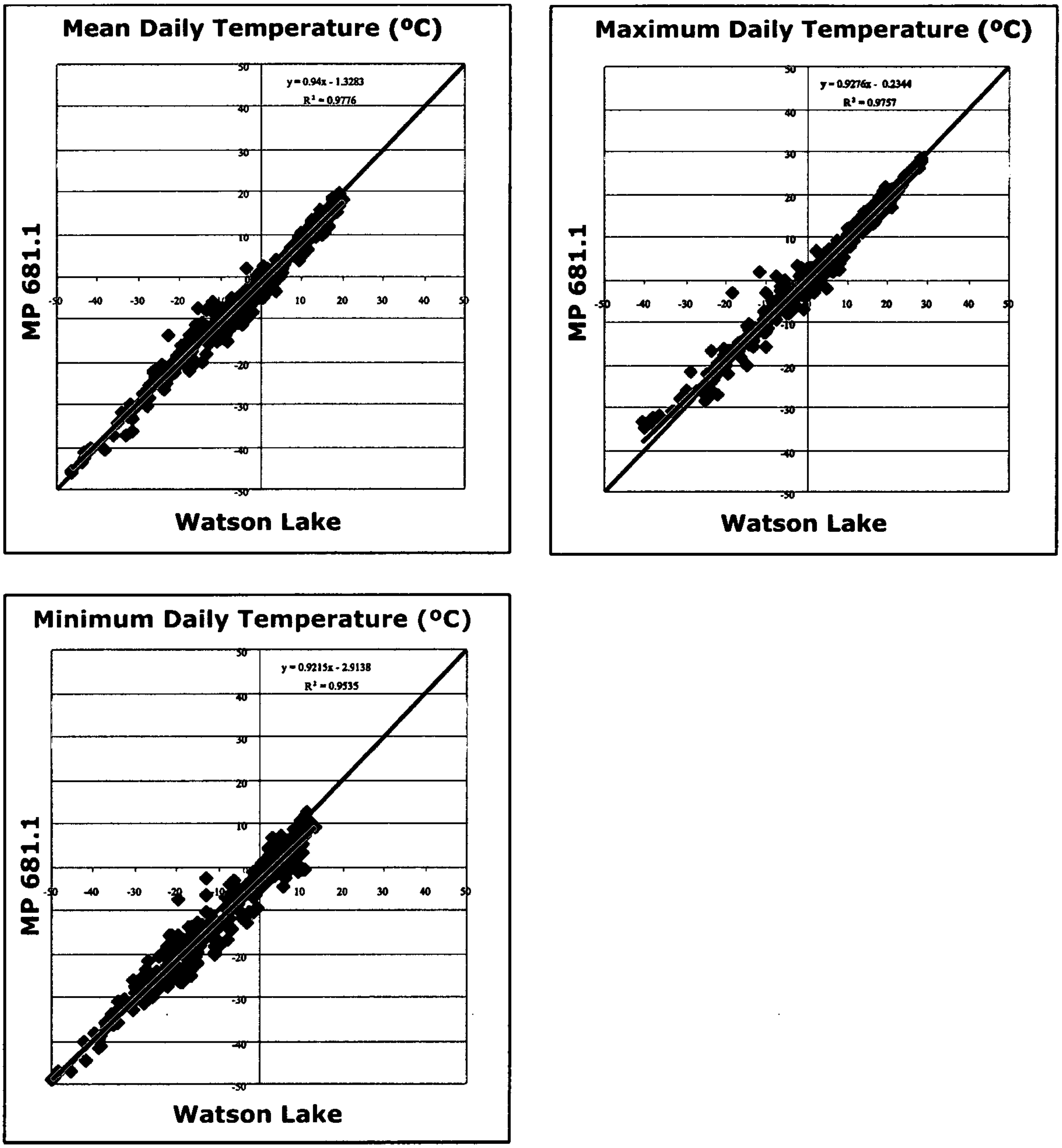


Figure 31 Comparison of mean, maximum and minimum daily temperatures between the MP 597.5 climate station and the Environment Canada weather station at Watson Lake from August 19, 2007 to August 18, 2008 (Environment Canada, 2008). The red line represents the predicted temperatures of the project station based on the Environment Canada station and an average Environmental lapse rate of 0.65°C / 100m.

temperatures above 0°C. The maximum daily temperatures at MP 681.1 were typically lower than those at Watson Lake, through all seasons. Minimum values showed greater differences between the two stations, up to 10°C on some days. MP 681.1, again, was the cooler site in all seasons. These lower minima suggest that it is possible there is some cold air pooling at MP 681.1, but is also possible the difference is primarily due to the difference in elevation.

MP 844.1, between Teslin and Whitehorse, was slightly cooler than Teslin during the thawing season (up to August 25, 2008), and had 100 FDDs more than Teslin during the freezing season (Figure 23). This led MP 844.1 to have a MAAT 0.5°C lower than that recorded at the Teslin weather station, 0.2°C warmer than what would be expected based on Teslin's temperature data and an environmental lapse rate of 0.65°C/100 m. A comparison of daily temperatures at the MP 844.1 station and the Environment Canada weather station at Teslin shows very similar mean temperatures, with MP 844.1 being slightly cooler, particularly in summer (Figure 33). Maximum temperatures show a similarly close relationship, with MP 844.1 being cooler, but the differences between the two sites are greater in winter. Minimum temperatures show a close relationship between the two sites, with, again, MP 844.1 being slightly colder, but typically within 1°C. The temperatures recorded are so similar at both sites that it is difficult to ascertain whether air temperature inversions are occurring at neither or both sites.

MP 844.1 had a MAAT almost 2°C colder than that of Whitehorse, 1.2°C colder than would be expected with an environmental lapse rate of 0.65°C/100 m. The MAAT recorded at Whitehorse 0.7°C, was the same as the its MAAT Climate normal 1971-2000 (Environment Canada, 2007). MP 844.1 had roughly 200 TDDs fewer (up to August 25,



Mean Daily Temperature (°C)

Maximum Daily Temperature (°C)

Minimum Daily Temperature (°C)

Figure 32. Comparison of mean, maximum and minimum daily temperatures between the MP 681.1 climate station and the Environment Canada weather station at Watson Lake from August 19, 2007 to August 18, 2008 (Environment Canada, 2008). The red line represents the predicted temperatures of the project station based on the Environment Canada station and an average Environmental lapse rate of 0.65°C / 100m.

2008) and roughly 400 FDD more than the Whitehorse station during 2007-2008. If the temperatures of that year are representative of other years, it is likely the colder winters at MP 844.1 aid in the persistence of permafrost. Maximum daily temperatures at MP 844.1 are slightly colder than Whitehorse air temperatures (Figure 34). The minima are quite similar at the two sites, but that Whitehorse is likely to have slightly lower minima at cold temperatures. The mean, while closely following the 1:1 line, also supports MP 844.1 having slightly colder temperatures on a year-round basis. There does not appear to be strong evidence that supports differences in cold air pooling between the sites. It is possible that vegetation conditions, such as canopy cover, could be contributing to the temperature differences between the two sites.

The data clearly show that all project climate stations had lower MAATs than the nearest Environment Canada stations from August 19, 2007 to August 18, 2008 (Table 11). With the exception of MP 597.5, the project climate stations are at higher elevations than the Environment Canada stations nearest to them. Adiabatic processes, therefore, could partially explain the temperature differences. The standard environmental lapse rate is approximately 0.65°C/100 m, and since five of the project climate stations are more than 100 m higher in elevation than the nearest Environment Canada station, it is reasonable to infer this could have a measurable impact on air temperatures (Aguado and Burt, 2004). A more detailed analysis showed seasonal trends in air temperature differences for the individual project stations and the closest government station. Some project climate stations, such as MP 208.5 and MP 844.1 exhibited greater temperature differences from the nearest Environment Canada stations in the winter than during the thawing season. Particularly cold winter temperatures at those sites could be an

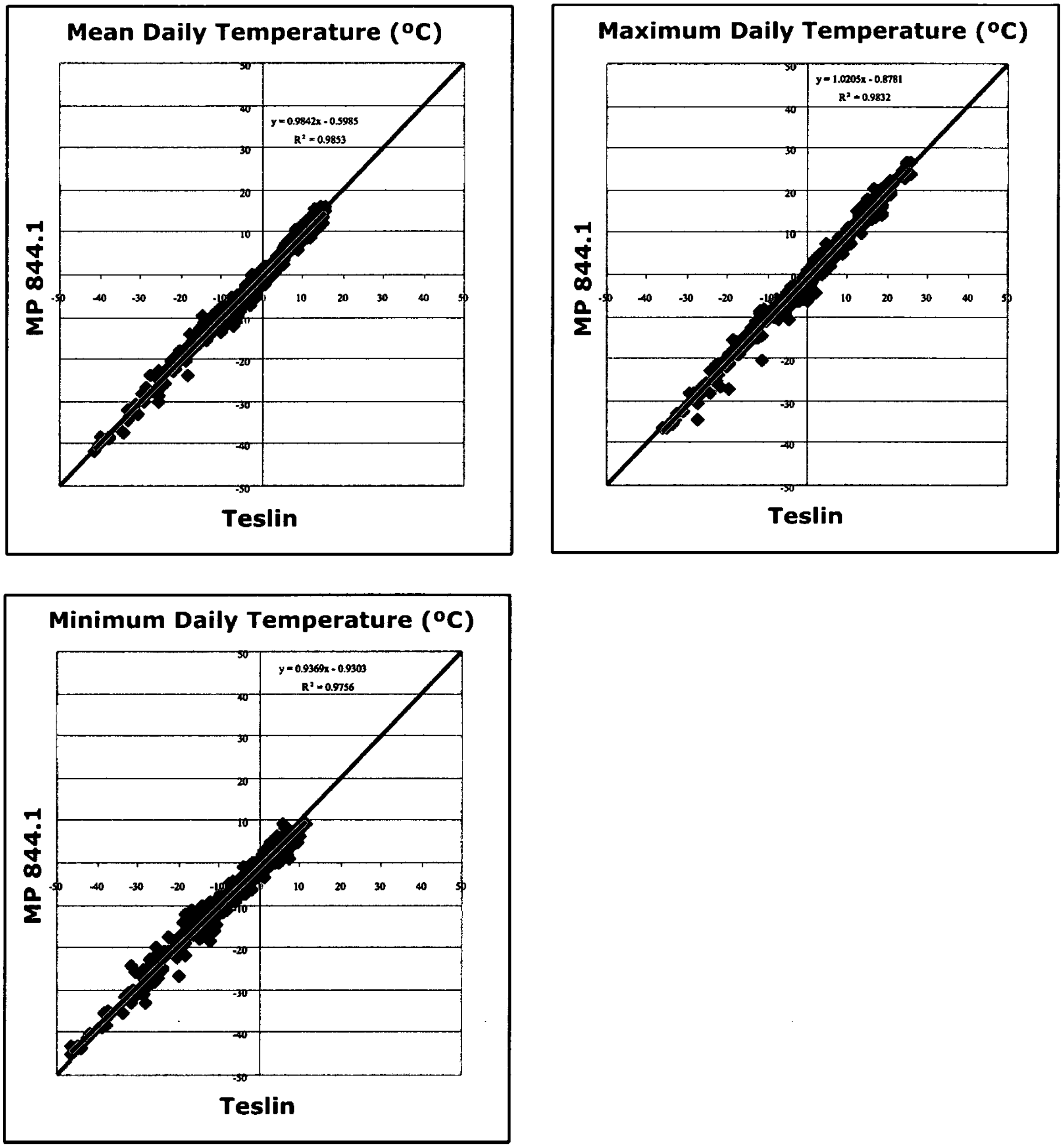


Figure 33. Comparison of mean, maximum and minimum daily temperatures between the MP 844.1 climate station and the Environment Canada weather station at Teslin from August 19, 2007 to August 18, 2008 (Environment Canada, 2008). The red line represents the predicted temperatures of the project station based on the Environment Canada station and an average Environmental lapse rate of 0.65°C / 100m.

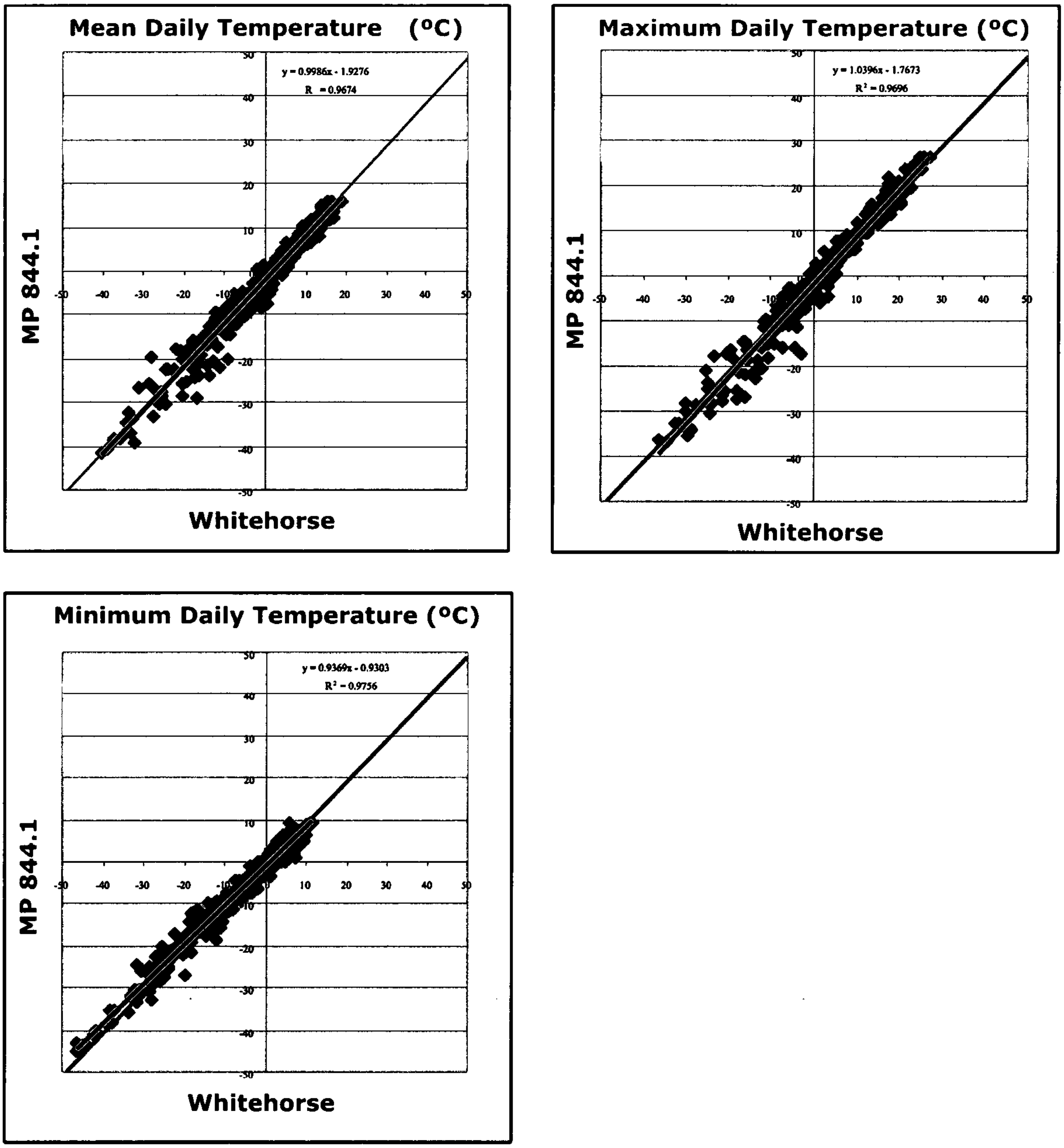


Figure 34. Comparison of mean, maximum and minimum daily temperatures between the MP 844.1 climate station and the Environment Canada weather station at Whitehorse from August 19, 2007 to August 18, 2008 (Environment Canada, 2008). The red line represents the predicted temperatures of the project station based on the Environment Canada station and an average Environmental lapse rate of 0.65°C / 100m.

important factor in allowing permafrost to persist. Other project sites, such as the two near Watson Lake (MPs 597.5 and 681.1), were consistently colder than the Watson Lake station during both the freezing and thawing seasons. MP 400.5 showed summer temperatures that were markedly cooler than the Fort Nelson station, and had a MAAT lower than Fort Nelson in spite of having a warmer winter. Overall, the results indicate that the relatively small differences in air temperatures may not be sufficient by themselves to account for the presence of permafrost at the monitoring sites, and its absence at the Environment Canada station (except for at Fort St. John where the MAAT is greater than 0°C).

4.8 Snow Depth and Duration

An exploration of the depth and duration of the snowpacks at both project and Environment Canada stations was undertaken to see if these snowpack characteristics could help explain why permafrost is able to persist at the project climate station sites. It is shown above (see Figure 16) that at every project station except MP 681.1 it is the thermal offset that allows permafrost to persist (based on the 2007-2008 data). For every site but that one, the surface offset, primarily caused by snow cover, insulated the ground to such an extent that the MAGST was above 0°C. If snow depth and duration at Environment Canada stations are greater than those at the project station sites (all underlain by permafrost), it could be this factor that precludes permafrost from existing at those sites.

Table 13 shows the snow depth days at the project climate stations (inferred using i-buttons) and the Environment Canada weather stations. Individual comparisons are shown in Figures 35 to 40. Mean annual snow depths and snow depth days for 2007-2008 can be seen in Table 9.

MP 208.5 had less snow than its nearest Environment Canada station, Fort Nelson, in 2007-2008 (Figure 35), with an average annual snow depth of 9.8 cm, as compared to Fort Nelson's 15.0 cm. It also had a shorter snowpack duration of 140 days, compared to 171 days of snowcover in Fort Nelson. These two factors resulted in MP 208.5 having 35% fewer snow depth days than Fort Nelson. Because of these snow conditions, it is likely that MP 208.5 had a smaller nival offset than that of the Fort Nelson weather station.

MP 286 (Figure 36) had an average annual snow depth of 12.0 cm, slightly less than Fort Nelson's average of 15.0 cm. The two stations experienced very similar patterns in snowpack accumulation and ablation. Like MP 208.5, MP 286 also had a shorter snowpack duration than the Fort Nelson station, resulting in 20% fewer snow depth days.

MP 400.5 had substantially less snow in 2007-2008 than the nearest weather station at Fort Nelson. While the two followed a very similar accumulation and melt pattern, MP 400.5 had an average annual snowpack of just 8.2 cm, compared to Fort Nelson's average of 15 cm. It also appears to have a shorter snowpack duration (128 days as opposed to 171), but this is difficult to know for certain due to a possible early, extended period of low snow depth that is difficult to detect with the ibuttons. MP 400.5 almost certainly had a lower nival offset than Fort Nelson because it had 45% fewer snow depth days.

Table 13. Snow depth days at project climate stations and Environment Canada weather stations for the winter of 2007-2008 (Environment Canada, 2008)

Station	Snow Depth Days
Fort St. John	5944
MP 208.5	3592
MP 286	4412
Fort Nelson	5490
MP 400.5	3015
MP 597.5	9313
Watson Lake	7917
MP 681.1	10522
Teslin	5905
MP 844.1	6737
Whitehorse	2206

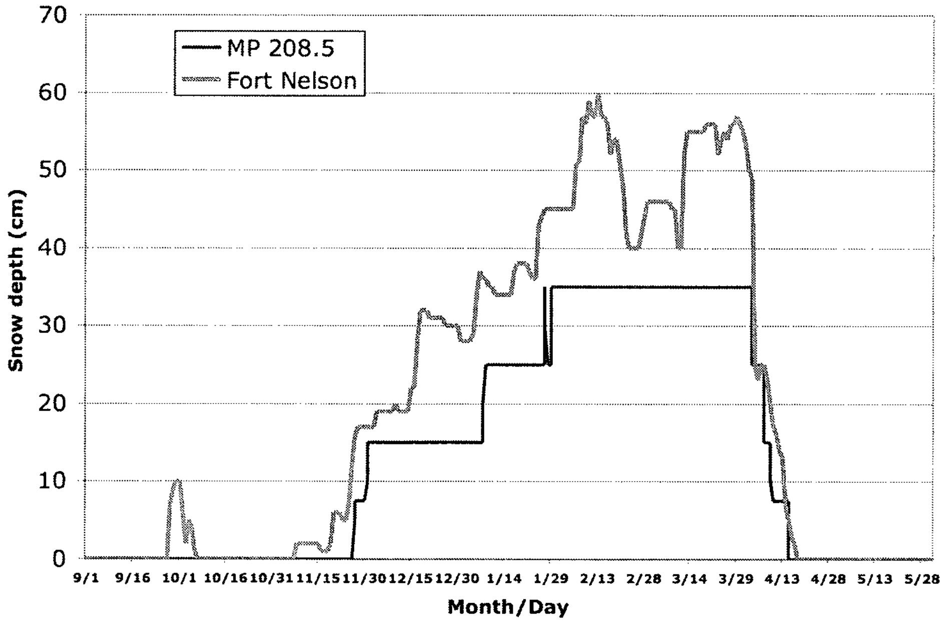


Figure 35. Snow depth for the winter of 2007-2008 at MP 208.5 and Environment Canada's Fort Nelson weather station (Environment Canada,

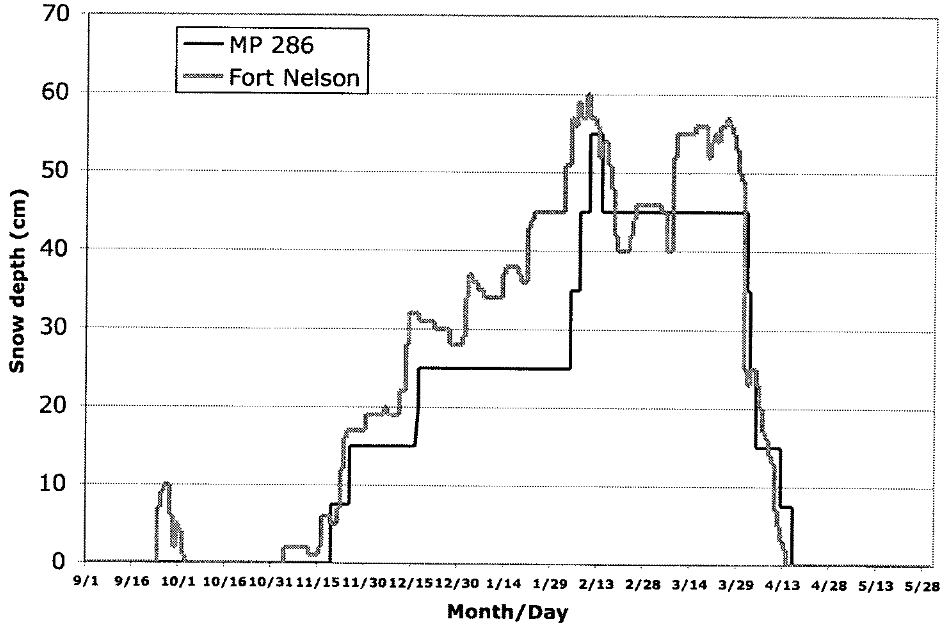


Figure 36. Snow depth for the winter of 2007-2008 at MP 286 and Environment Canada's Fort Nelson weather station (Environment Canada, 2008)

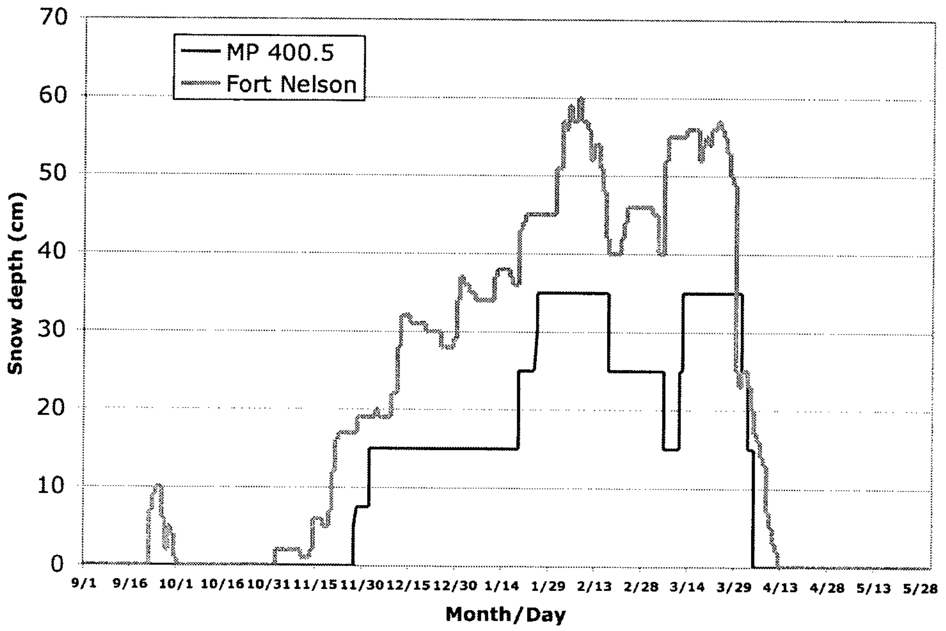


Figure 37. Snow depth for the winter of 2007-2008 at MP 400.5 and Environment Canada's Fort Nelson weather station (Environment Canada, 2008)

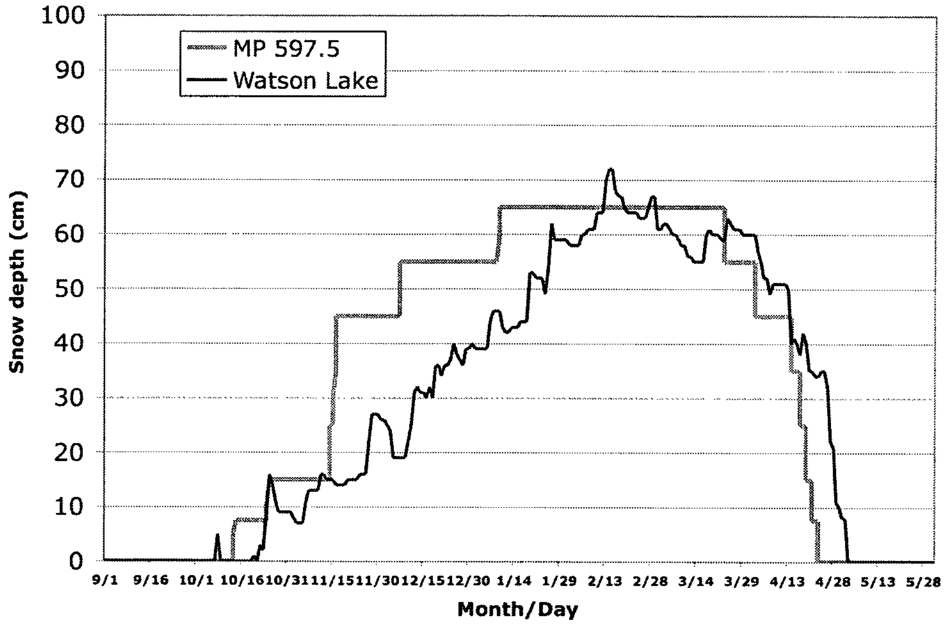


Figure 38. Snow depth for the winter of 2007-2008 at MP 597.5 and Environment Canada's Watson Lake weather station (Environment Canada, 2008)

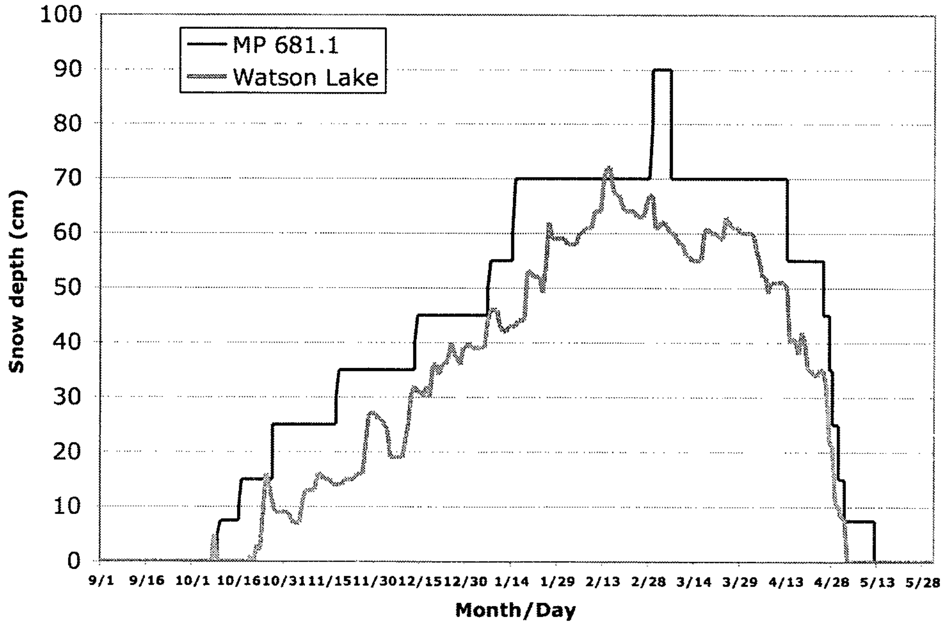


Figure 39. Snow depth for the winter of 2007-2008 at MP 681.1 and Environment Canada's Watson Lake weather station (Environment Canada, 2008).

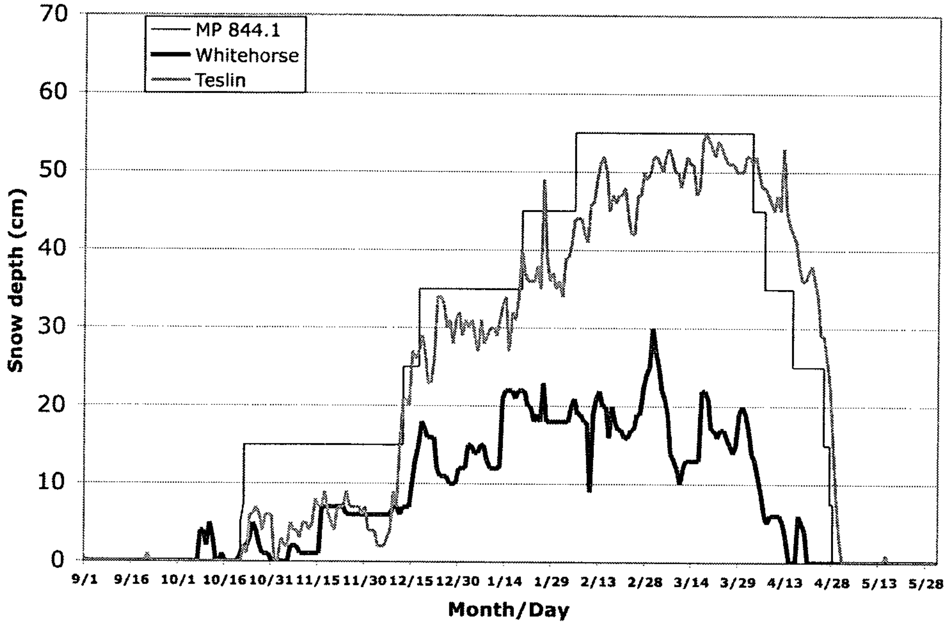


Figure 40. Snow depth for the winter of 2007-2008 at MP 844.1 and Environment Canada's Teslin and Whitehorse weather stations (Environment Canada, 2008).

MP 597.5 (Figure 38) had a similar pattern of snow accumulation and melt to the weather station at Watson Lake, but is inferred to have greater snow depths earlier in the season. The project site had an average annual snow depth of 25.4 cm, compared to Watson Lake's average of 21.6 cm. Snowpack duration at the two sites was within 3 days of one another (192 days to 195 days, respectively). The average annual snow depth was 18% higher at MP 597.5 than at the Watson Lake weather station. MP 597.5 likely had a larger nival offset than Watson Lake; its MAAT was also colder by -0.6°C.

MP 681.1 (Figure 39) followed a similar snow accumulation and melt pattern to the weather station in Watson Lake, but had more snow throughout the winter. It had an average annual snow depth of 28.8 cm, compared to Watson Lake's 21.6 cm. It also had 20 more days of snowcover than the Watson Lake station and altogether had 33% more snow depth days. MP 681.1 was the one project climate station that did not depend on the thermal offset for permafrost to exist. The site had the most snow of any site examined, but the surface offset of 3.2°C was not enough to bring the ground surface temperature above 0°C due to the coldest MAAT (-3.8°C).

MP 844.1 had a snow accumulation and melt pattern very similar to that of its closest Environment Canada weather station, at Teslin. The project climate station had an average annual snow depth of 18.4 cm, versus an average of 16.1 cm in Teslin and 6.0 cm at the next closest station, the station in Whitehorse. Snow depth duration ranged from 190 days at MP 844.1 to 192 days in Teslin, but was only 181 days in Whitehorse. MP 844.1 had 14% more snow depth days than the weather station in Teslin, and 67% more than those recorded at the Whitehorse weather station.

In summary, the three southernmost project climate stations had 20% to 45% fewer snow depth days than their nearest Environment Canada weather stations. The three northernmost project climate stations had 14% to 33% more snow depth days than their nearest Environment Canada weather stations. Therefore, for this year of measurement, there was no consistent pattern in which project sites had lower snowfalls than Environment Canada stations. In contrast, the project sites all had colder MAATs for 2007-2008 than their closest Environment Canada stations. At all project climate stations except MP 681.1, the surface offset is enough to cause the MAGST to be above 0°C. It is likely that thermal offsets at the Environment Canada stations are not enough to compensate for the nival offsets caused by the number of snow depth days, and so permafrost is absent at these sites.

4.9 Relief

Most of the study sites visited in both 1964 and 2007-2008 were low-lying, with only 18% being on a slope, and these faced all directions. There was one south-facing site where permafrost was extant. Three sites where permafrost appears to have disappeared are on slopes, one north facing and the other two with slope direction unknown. The other six sloping sites were sites where no permafrost was found during the investigations in 1964 or the 2007-2008 investigations. The study sites do not have enough variety in relief to be able to determine if it has been an important factor in determining where permafrost has persisted and where it has not (Appendix E).

4.10 Surface Terrain Features

Most study sites had mounded or hummocky terrain, likely because Brown selected sites that looked favourable for the existence of permafrost (Appendix E). Of the sites with near-surface permafrost, 88% had hummocky terrain. Seventy-three percent of sites where near-surface permafrost appears to have disappeared and 79% of sites that were never found to have permafrost had hummocky terrain. Twenty-five percent of sites with permafrost were on peat plateaux, whereas only 7% of sites that appear to have lost permafrost and zero sites where permafrost was never found were associated with such forms.

4.11 Vegetation

Spruce was the dominant tree type at all of the study sites. The maximum spruce heights were very similar at sites where permafrost was found in both years, sites where it appears to have disappeared, and sites where neither investigation found permafrost. Although the maximum tree height data are only visual assessments, the calculated mean maximum tree heights for the three different site types were 9.6 m, 9.2 m and 10.3 m, respectively. The geographic position of the site in the transect does not appear to show in the pattern of maximum spruce tree heights. This is likely because the sites chosen by Brown (1967) were biased toward permafrost-probable terrain, especially boreal peat bogs with tree cover of black spruce and sphagnum and feather mosses (Beilman *et al.*, 2001).

The non-permafrost sites were more likely to have other tree types present, with 83% of them having jack pine, willow, tamarack, aspen, or poplar as secondary tree types. Jack pine and willow were the most common secondary trees at these sites, with the willows being 0.7 m to 2 m in maximum height. Of the sixteen sites where both 1964 and 2007-2008 investigations found near-surface permafrost, 56% had other tree types, mostly either tamarack or willow, with one instance each of alder, and, as a tertiary tree type, poplar. Of the fifteen sites where permafrost appears to have disappeared since 1964, 40% had other tree types. The secondary tree type was willow in 66% of cases, while there was also one instance each of jack pine and poplar as secondary tree types, and of alder and poplar as tertiary tree types.

These results, and Brown's, suggest that tree types alone are not enough to predict where permafrost is present or absent (Brown, 1967). If study sites had been chosen at random along the highway, there might have been a stronger link between tree types and permafrost, but since Brown's site choices were biased towards permafrost-probable sites, most had vegetation that is associated with permafrost (Brown, 1967; Beilman *et al.*, 2008)

Non-sphagnum mosses were present and dominant at all study sites. Sphagnum mosses were far more likely to occur at permafrost sites and sites where permafrost appears to have disappeared than at sites where permafrost was not found during either study (see Table 14). Lichens occurred at the majority of the sites. They were most common at permafrost sites, although they were rarely dominant. Two-thirds of sites where permafrost seems to have disappeared also exhibited lichen, while three-quarters of sites where permafrost was never found did. Labrador tea was extremely common at all site types. All permafrost sites had Labrador tea, while slightly lower proportions of the other site types had the plant (Table 14).

Sites where permafrost was not found during either the 1964 or 2007-2008 investigations were far more likely to have grasses than the other two site types. Grasses were not a dominant vegetation type at any project site. Sedges were not common at any

Table 14. Presence of ground-covering vegetation at site

	Vegetation presence (% of sites)					
Site type	Non-sphagnum mosses	Sphagnum mosses	Lichens	Labrador tea	Grasses	Sedges
Permafrost (1964)/Permafrost (2007-2008)	100%	50%	93%	100%	13%	6%
Permafrost (1964)/Non-permafrost (2007-2008)	100%	47%	67%	80%	33%	13%
Non-permafrost (1964)/Non-permafrost (2007-2008)	100%	17%	75%	92%	46%	17%

site type, but were most common at sites where permafrost was not found in 1964 or 2007-2008 (Table 14). Vegetation data for each site can be found in Appendix E.

4.12 Organic Layers

Organic thicknesses were difficult to compare across the different site types, because in many cases the thicknesses could not be ascertained. At sites with permafrost, the frost table was frequently reached within the organic layer, so the full thickness could not be measured. At non-permafrost sites, some organic layers extended further below surface than could be probed, resulting in only minimum values for organic layer thicknesses. Figure 41 shows box plots for organic layer thicknesses at the different site types. Organic layer data can be found in Appendix E.

There were a total of 17 points of measurement where no permafrost was encountered along transects at sites known to have permafrost. These measurement points were excluded from the analysis because they did not have permafrost, and because at more than half of them, organic thicknesses were so deep that only a minimum value could be obtained. However, they can provide information on organic layer variability. At sites with permafrost, the 17 points with no near-surface frost table had a minimum organic mat thickness of 18 cm, with 47% of the points having organic mats thinner than 54 cm. The remaining 53% of those non-permafrost points had organic layers a minimum of 115 cm thick, with some greater than 150 cm thick. Although these points did not have frost tables, they are so close to points with frost tables (within 4 m) that they likely provide information about organic thickness that cannot be obtained at adjacent points with frost tables. Roughly half of these points without frost tables were taken at points along EM31 transects, which had their first measurement location

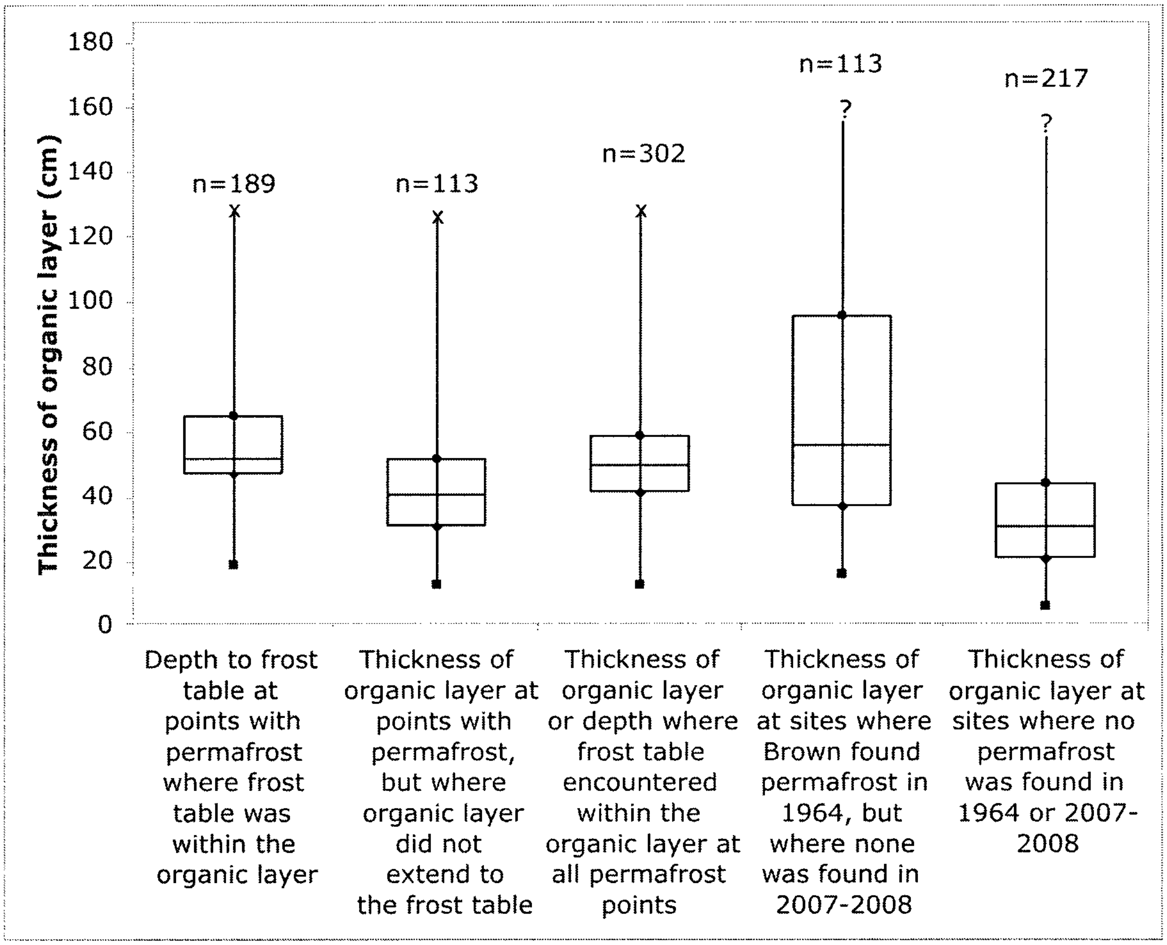


Figure 41. Organic layer thickness at study sites. The black square denotes the minimum thickness, while the diamonds denote the first quartile, the horizontal line in the middle of the box denotes the median organic layer thickness and the black circle denotes the third quartile. Maximum values for some sites are denoted by 'x', but where maximum values are unavailable, known thicknesses are shown as the upper end of the vertical line and question marks are used.

established over areas that looked likely to be unfrozen. The non-permafrost points at permafrost sites show that organic depth can vary greatly at a particular site (e.g. a variation of at least 80 cm at MP 208.5) and that it is likely that some organic layers at points with permafrost exceed 150 cm in thickness. Because many organic thicknesses at permafrost sites could not be determined due to the presence of a frost table within the organic layer, at those measurement points the depth to frost table was analyzed. At these sites, the portion of the organic mat above the frost table is sufficient to provide the thermal offset needed for permafrost to be able to persist. The median depth to frost table where the frost table was within the organic layer was 51 cm, while the mean depth was 56 cm. The maximum depth recorded where a frost table was in the organic layer was 127 cm, and the minimum depth recorded was 18 cm.

Measurements at points with permafrost where the frost table was deeper than the thickness of the organic layer had a median organic layer thickness of 40 cm, while the mean thickness was 43 cm. The maximum organic layer thickness was 125 cm, while the minimum was 12 cm. The latter was found at MP 681.1 and this site illustrates the high spatial variability of organic thicknesses at permafrost sites. In 2007, all the points at MP 681.1 had a frost table within the organic layer, with a mean depth of 53 cm. In 2008, close to those same measurement locations (as the site was returned to using a GPS), the organic layer was found to be shallower than the frost table and had a mean depth of 23 cm. MP 681.1 was the coldest project climate station from 2007 to 2008, with a MAAT of -3.8°C. It is possible that permafrost at sites where MAAT is higher, would not persist with organic mats as thin as 12 cm.

Combining the data of all permafrost points (those with the frost table within the organic layer and those with the frost table below the organic layer), the median depth of the organic layer above a frost table was 49 cm, while the mean was 51 cm. The first and third quartiles were 40 cm and 58 cm, respectively, showing that half the measurements occupied a fairly small range of thicknesses. Maximum and minimum values obtained were 127 cm and 12 cm, respectively.

At sites where permafrost appears to have disappeared since 1964, the median organic layer thickness was 55 cm, while the thicknesses at the first and third quartiles were 36 cm and 95 cm, respectively. The minimum organic layer thickness encountered at these points was 15 cm. The maximum thickness is unknown, although at some points it was at least 155 cm.

At sites where near-surface permafrost was not found in either 1964 or during the 2007-2008 investigations, the median organic layer thickness was 30 cm, much lower than the sites where there is permafrost and the sites where permafrost appears to have disappeared. The minimum organic thickness recorded at sites without near-surface permafrost was 5 cm, while the maximum is unknown, but was at least 150 cm. Half of the points at non-permafrost sites had organic layers between 20 cm and 43 cm thick.

4.13 Organic Content of Soil

Soil samples were collected below the organic layer at a number of study sites, and analyzed for organic content by weight (Table 15). While some study sites were not sampled due to time and other constraints, others could not be sampled because they were organic down to the frost table (Figure 41). Samples at sites with permafrost were found to have much higher organic contents than the other site types. Six of the nine permafrost sites sampled had organic contents higher than 30%, the quantity needed for soil to be considered organic for the purposes of this study (Soil Classification Working Group, 1998). An additional six permafrost sites, which could not be sampled, had organic layers at least as deep as the frost table. Sites where permafrost appears to have degraded had the lowest mean and median organic contents, although caution must be taken to generalize, since there were only six sites sampled. Of those six, there were no soil samples with greater than 30% organic content. The sites where permafrost was not detected during either investigation had mean and median organic contents of 18% and 11%, respectively. Three of those sites had organic contents higher than 30% of the sample weight.

4.14 Soil Moisture

Soil samples, collected in August 2008 at selected sites, were analyzed for natural moisture content (Table 16). Sites with permafrost had mean and median moisture contents higher than other site types. Sites that appeared to have changed from permafrost to non-permafrost had the lowest mean and median moisture contents of any of the site types, while sites where permafrost was not observed during either investigation had mean and median moisture contents of 35% and 30%, respectively.

4.15 Grain Size

There were fewer soil samples to use for grain size analysis than there were for organic content or moisture content analysis, due to the methods used. Two thirds of the sites with permafrost reacted violently to treatment with H_2O_2 (used to oxidize organics) and had to be discarded. One sample from one of the sites where permafrost appears to

Table 15. Mean and median organic contents of soil below the organic layer (by weight). The last column shows the number of sites that could not be sampled and tested for organic content because soil beneath the organic layer was not accessible.

Site Type	n	Mean % organic content	Median % organic content	Site organic to at least the frost table or 135 cm depth
Permafrost (1964)/Permafrost (2007-2008)	9	51%	53%	6
Permafrost (1964)/Non-permafrost (2007-2008)	6	8%	8%	0
Non-permafrost (1964)/Non-permafrost (2007-2008)	18	18%	11%	1

Table 16. Mean and median natural moisture contents of study site soil samples.

Site Type	n	Mean moisture %	Median moisture %
Permafrost (1964)/Permafrost (2007-2008)	9	58%	59%
Permafrost (1964)/Non-permafrost (2007-2008)	6	24%	25%
Non-permafrost (1964)/Non-permafrost (2007-2008)	18	35%	30%

have disappeared and three samples from sites where permafrost was never recorded also had to be discarded. All remaining sites were comprised of sandy silt or silty sand, with some clay. Since Brown biased his sites towards the permafrost probable, it is not surprising that they are all relatively fine-grained (Figure 42). The overlap between the categories suggests that grain-size is poorly related (if at all) to the presence of permafrost. The most telling result of the grain size analysis was that most of the permafrost sites were too highly organic to be included. This reinforces the importance of organic soil in allowing permafrost to persist in climatically marginal locations (Beilman *et al.*, 2001). Soil data can be found in Appendix F.

4.16 Long-term Climate Data in the Study Area

In order to examine whether permafrost loss and apparent active layer deepening in the study area might have resulted from decadal to centennial-scale climate change, 66 years of climate data from four Environment Canada weather stations in communities along the study transect, were examined. Unfortunately, not all records are complete. MAATs, FDDs, TDDs, annual rainfall, annual snowfall and total annual precipitation were examined and subjected to significance testing at a confidence level of 95%. MAATs were chosen for analysis because permafrost is a climatically controlled phenomenon, and is impacted by changes in air temperature (ACIA, 2005; Smith and Riseborough, 2002). Analysis of FDDs and TDDs allows information to be gained about seasonal climate trends. This is useful because the impact of rising air temperatures in the winter is buffered by the insulating snow cover, and so winter warming typically causes a less severe impact to permafrost than if the warming took place in the summer (Smith and Burgess, 1999). As precipitation impacts ground thermal conductivity, the

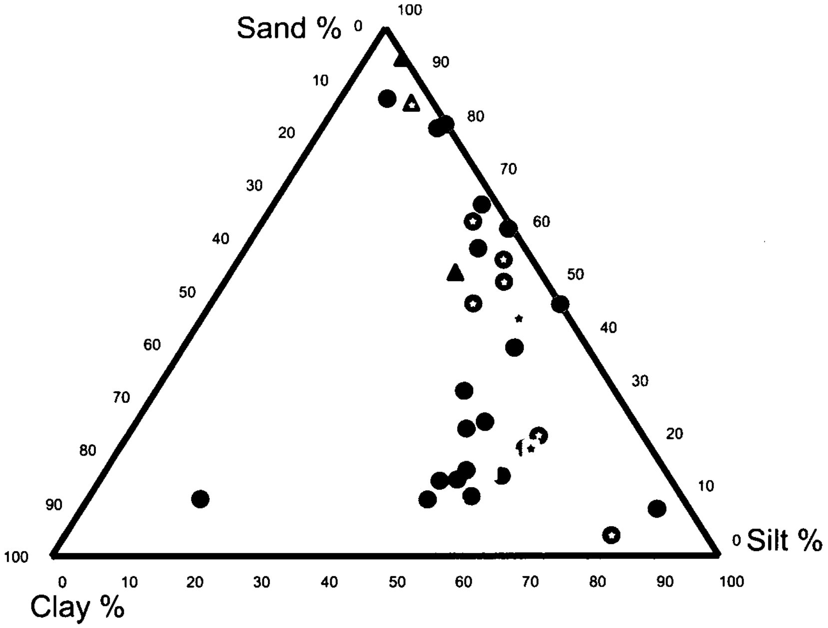


Figure 42. Ternary diagram of soil granulometry at selected project station sites. Blue triangles represent samples taken at permafrost sites that had enough mineral content to be included. Yellow squares represent samples taken at sites where permafrost appears to have disappeared. Red circles represent samples taken at sites where permafrost was not recorded in 1964 or 2007-2008. Stars on any of the symbols indicate that gravel comprised over 10% of the sample weight.

surface offset, and freezing and thawing time, variation in rainfall or snowfall is also highly relevant to ground temperatures. Significance tests were performed for the entire time period, as well as separately for the periods from 1943 to 1964, and from 1965 to 2008. Figures 43 to 48 show the climate data for the four stations. The significance test results are summarized in Table 17, and appear in more detail in Appendix H.

A warming trend was evident in the Arctic (60°N to the Pole), from about 1900 to the early-to-mid-1940s (ACIA, 2005). The MAAT data recorded at Environment Canada weather stations in the study area indeed show a trend of declining MAATs at all stations from 1943 to the early 1950s. MAATs then rose until approximately 1960, before falling to a low during the mid-1970s. Between approximately 1975 and 1979, all stations experienced a step-type rise in MAATs. A continuing trend of warmer MAATs occurred from 1979 to 2008. The record as a whole can be interpreted as a linear increase in MAAT between 1943 and 2008, and with the exception of Watson Lake, this trend was statistically significant (Table 17). Temperatures at the stations with statistically significant trends increased from an average of 0.15°C per decade (Whitehorse) to 0.23°C (Fort St. John). However, Figure 43 demonstrates that temperatures in the early part of the new millennium do not greatly differ from those in the mid-1940s. When the period of examination was broken in two, at the year of Brown's investigation, it was found that none of the four stations showed statistically significant changes in MAATs from 1943 to 1965 (Table 17), although there were rising and falling trends during that period. In contrast, all four stations demonstrated statistically significant increases in MAATs from 1965 to 2008 (Table 17). Fort St. John, Watson Lake and Whitehorse all appear to have experienced similar rates of warming, as MAATs rose an average of 0.5°C/decade. At

Table 17. Slope coefficients resulting from the regression analysis of various climate data from weather stations in the study area (Environment Canada, 2008). Bolded values are statistically significant at a 95% confidence level.

Measured		Fort St. John			Fort Nelson	
parameters	1943-2008	1943-1964	1965-2008	1943-2008	1943-1964	1965-2008
MAAT	**0.023**	-0.018	**0.053**	**0.021**	-0.052	**0.040**
FDD	**-7.293**	-2.326	**-14.025**	**-8.014**	12.070	**-14.879**
TDD	1.182	-4.602	3.188	0.726	**-7.182**	1.951
Rainfall	**1.067**	3.965	0.130	0.917	3.533	1.207
Snowfall	-0.184	6.803	-0.302	-0.203	2.840	0.246
Precipitation	0.191	**10.043**	-0.741	-0.054	3.391	1.131
Measured		Watson Lake			Whitehorse	
parameters	1943-2008	1943-1964	1965-2008	1943-2008	1943-1964	1965-2008
MAAT	0.008	-0.037	**0.051**	**0.015**	-0.036	**0.051**
FDD	-4.286	7.110	**-15.622**	-5.445	9.557	**-15.927**
TDD	0.007	-4.578	**4.437**	0.245	-2.471	**3.723**
Rainfall	**1.037**	1.631	1.208	0.465	-2.000	0.425
Snowfall	-0.506	3.740	-0.256	0.290	2.464	-0.194
Precipitation	0.043	2.655	**1.818**	0.118	-0.647	0.216

Note: Due to the season of measurement spanning more than one calendar year, the time periods for FDD testing are actually 1944-2008, 1944-1964 and 1965-2008

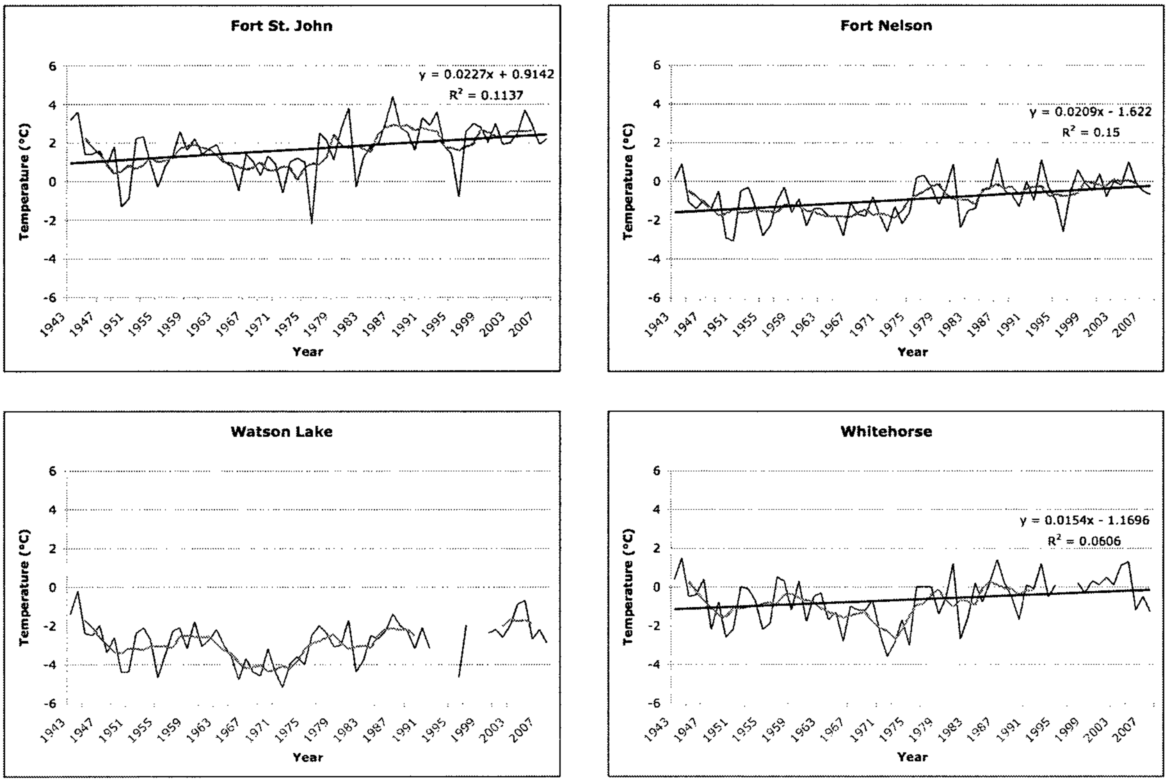


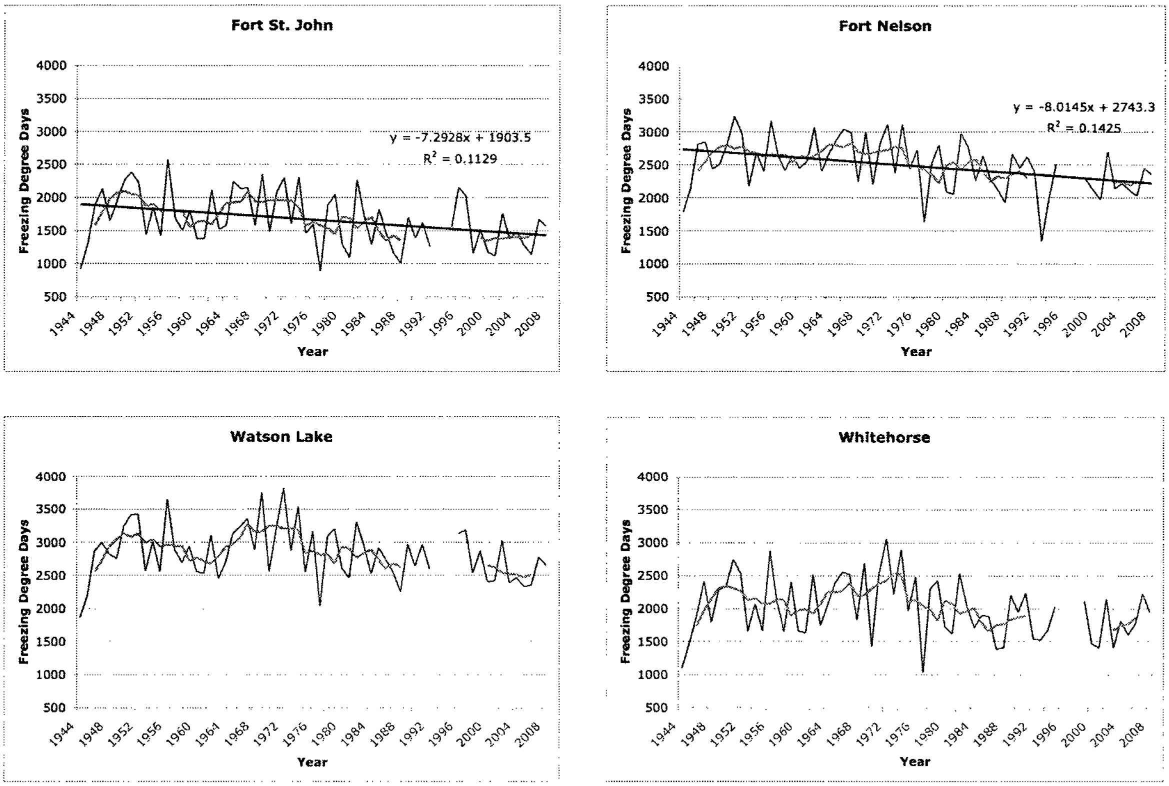
Figure 43. MAATs (°C) from 1943-2008 at Environment Canada weather stations in the study area (Environment Canada, 2008). The thin black line is the MAAT; the grey line is a 5-year running mean. The thick black line is a linear regression, and appears only on the charts of stations showing statistically significant changes in MAAT (using a 95% confidence limit). The figure also allows comparison of spatial temperature patterns along the studied part of the Alaska Highway, with temperatures becoming colder from Fort St. John to Watson Lake, and increasing MAATs to Whitehorse. Missing data in the 1990s at Watson Lake and Whitehorse may have affected the results.

Fort Nelson, MAATs increased on average by 0.4°C/decade. Total increases in MAATs from 1965 to 2008 were roughly 2°C at all stations.

Freezing degree-days (FDDs) are quantified per freezing season, and each freezing season is made up of a winter spanning two calendar years. Freezing degree-days followed a pattern inverse to that of the MAAT pattern from 1944 to 2008, showing rising winter temperatures (compare Figure 43 and Figure 44). As MAATs experienced a rising trend, FDDs decreased, and as MAATs fell, FDDs rose. For the entire period of examination, there were statistically significant decreases in FDDs at both Fort St. John and Fort Nelson, the two southernmost stations. The Watson Lake and Whitehorse stations also show declines, but they were not statistically significant. FDD totals at Fort St. John and Fort Nelson fell on average by 73 and 80 FDDs per decade between 1944 and 2008. Total declines over the time period were between 459 (Fort St. John) and 496 (Fort Nelson) FDDs.

When trends for the periods 1944 to 1964 and 1965 to 2008 are tested separately, the pattern changes. From 1944 to 1964 (Table 17), none of the weather stations exhibited statistically significant changes in FDDs, but from 1965 to 2008, all four stations show statistically significant declines in FDDs. Average rates of decline range from 140 FDDs/decade at Fort St. John to 159 FDDs/decade at Whitehorse. Average rates of FDD decline increase slightly from south to north along the studied part of the Alaska Highway. From 1965 to 2008, FDDs fell by roughly 620 at Fort St. John, 660 at Fort Nelson, 690 at Watson Lake and 700 at Whitehorse.

Fluctuations in TDDs from 1943 to 2008 showed patterns of increase and decline very similar to those of MAAT (Figure 43). Since the early 1990s, however, interannual


Fort St. John

Fort Nelson

Watson Lake

Whitehorse

Figure 44. FDDs from the winter of 1943-1944 (shown as 1944) to the winter of 2007-2008 (shown as 2008) at Environment Canada weather stations in the study area (Environment Canada, 2008). The thin black line is the annual FDDs; the grey line is a 5-year running mean. The thick black line is a linear regression, and appears only on the charts of stations showing statistically significant changes in FDD totals (using a 95% confidence limit). The figure also allows comparison of spatial patterns in FDD totals along the studied part of the Alaska Highway, with increasing FDDs from Fort St. John to Watson Lake, and FDDs becoming fewer from Watson Lake to Whitehorse. Two to four years of missing data in the 1990s at each weather station may have affected the results.

variation in TDDs appears to be greater than at any time since the beginning of the record. When testing the entire period of record (1943 to 2008), none of the stations had statistically significant changes in TDDs (at a confidence limit of 95%) (Table 17). In fact, the 5-year running means at the start and end of the period of examination are within 100 TDDs of one another (Figure 45).

When trends for the periods 1944 to 1964 and 1965 to 2008 are tested separately, Fort Nelson alone exhibited a statistically significant decline in TDDs for the former period, with TDDs decreasing an average of 25 TDDs/decade. From 1965 to 2008, Watson Lake and Whitehorse showed statistically significant increases in TDDs, with average increases of 37 and 44 TDDs/decade, and total increases of roughly 160 and 190 TDDs, respectively.

Rainfall had high interannual variability throughout the study area, but especially in Fort St. John and Fort Nelson (Figure 46). Unlike annual air temperatures, which exhibited similar temporal trends across the four climate stations, rainfall often differed. For instance, at Fort St. John, rainfall was much higher in 1964 than in 2008 (374 mm and 195 mm, respectively), but in Fort Nelson the rainfall in the years of permafrost investigation were quite similar, at 393 mm and 331 mm, respectively. Watson Lake had 1964 and 2008 annual rainfall measurements within 10 mm of one another, whereas in Whitehorse there was roughly 45 mm more rainfall in 2008 than in 1964. From 1943 to 2008, there were statistically significant increases in rainfall in Fort St. John and Watson Lake (Table 17). Fort St. John experienced an average increase of roughly 11 mm per decade, while Watson Lake's rainfall increased an average of 10 mm per decade. The

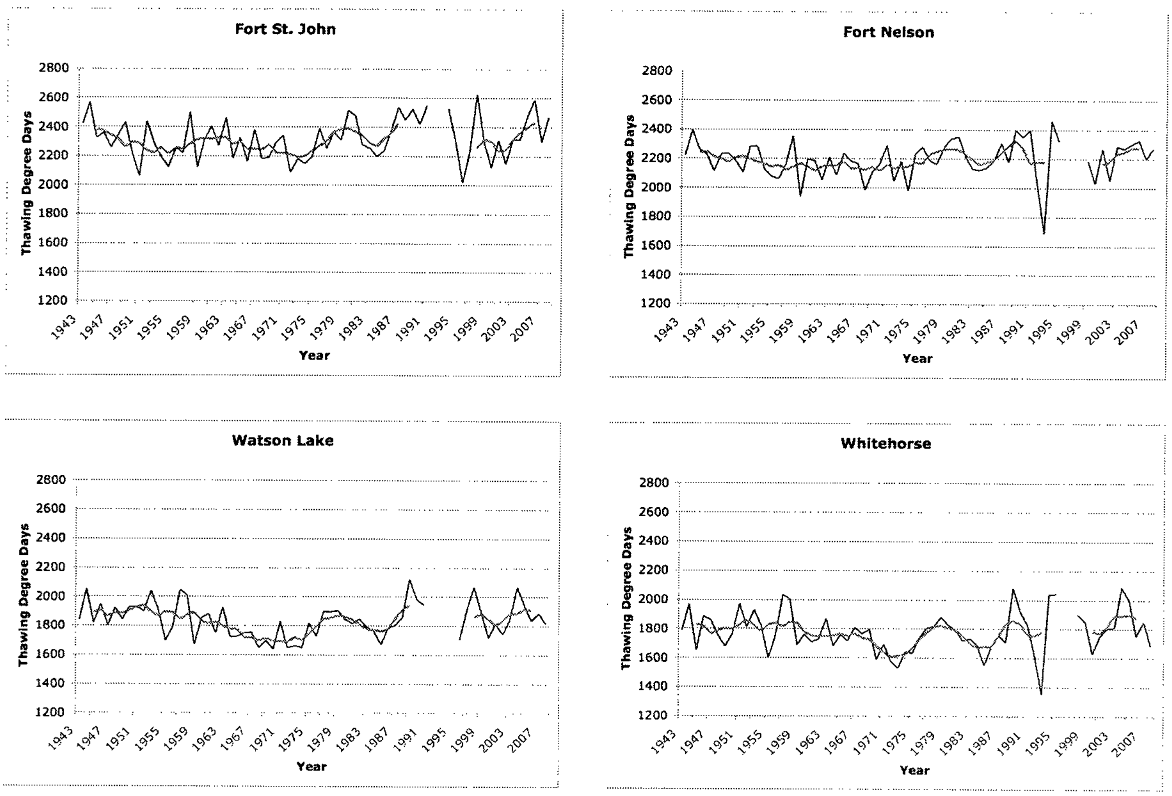


Figure 45. TDDs from 1943 to 2008 at Environment Canada weather stations in the study area (Environment Canada, 2008). The thin black line is the annual TDD totals; the grey line is a 5-year running mean. There was no statistically significant change in TDD totals from 1943 to 2008 (using a 95% confidence limit). The figure also allows comparison of spatial TDD patterns along the studied part of the Alaska Highway, with declining TDDs from Fort St. John to Watson Lake, and slightly increasing TDDs to Whitehorse. Two to four years of missing data in the 1990s at each weather station may have affected the results.

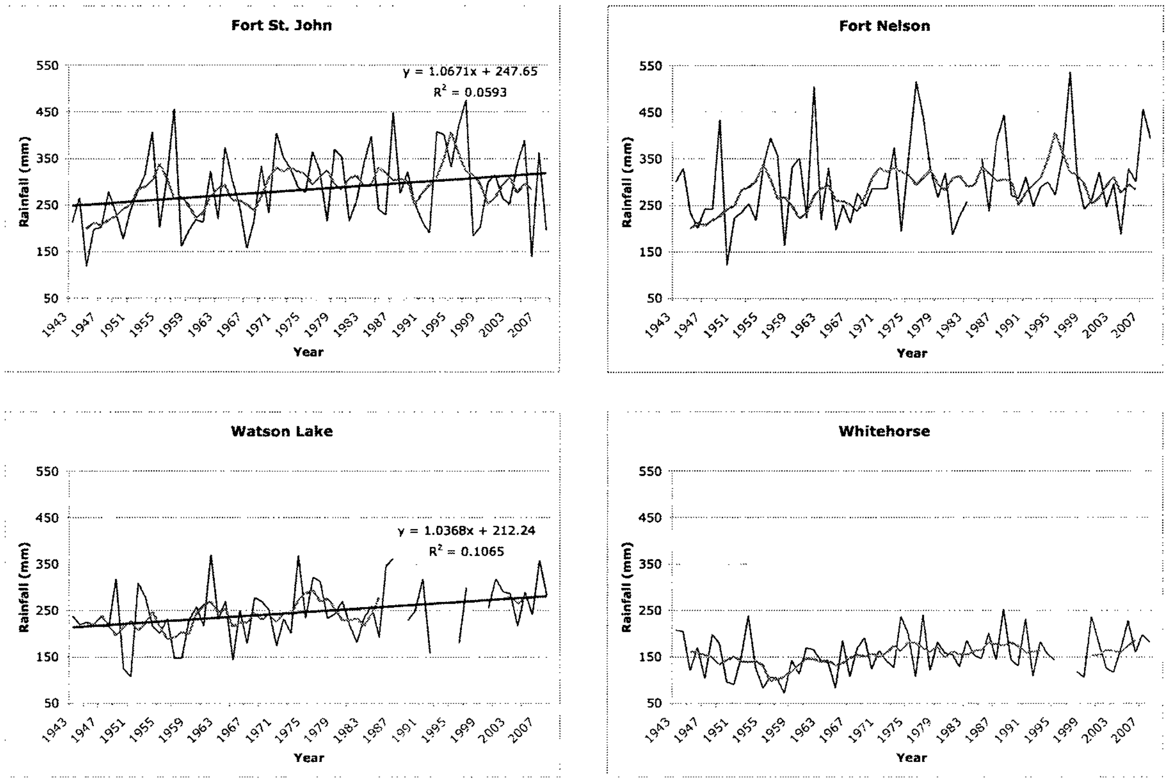


Figure 46. Total rainfall (mm) from 1943 to 2008 at Environment Canada weather stations in the study area (Environment Canada, 2008). The thin black line is the annual rainfall; the grey line is a 5-year running mean. The thick black line is a linear regression, and only appears on the charts of stations with statistically significant changes in rainfall from 1943-2008 (using a 95% confidence limit). The figure also allows comparison of spatial annual rainfall patterns along the studied part of the Alaska Highway, with increasing rainfall from Fort St. John to Fort Nelson, and declining rainfall to Watson Lake and to Whitehorse. Two to six years of missing data in the 1980s and 1990s at each weather station may have affected the results. Watson Lake should be the most affected.

changes at Fort Nelson and Whitehorse were not found to be statistically significant at a 95% confidence interval.

Separating the data into pre- and post-Brown (1967) investigation time periods, from 1943 to 1964 and from 1965 to 2008, respectively, revealed no statistically significant changes in rainfall (Table 17). The fact that when analyzed as a record from 1943 to 2008 there were significant changes, and when analyzed in shorter timescales there was not, is likely due to the high variances of rainfall data.

Snowfall trends were not consistent across weather stations for the time period examined (Figure 47). In Fort St. John, there was a strong rising trend from 1943 to 1957. Annual snowfall then remained at a high level, with annual fluctuations, until the mid-1970s, when it began a steep decline. It remained relatively low until 1990, and then began to increase. From 1990 to 2008, snowfall levels at Fort St. John had larger interannual variations than at anytime since the start of the record.

Fort Nelson experienced a moderate peak in snow levels in the mid-1940s, and there was then a falling trend and relatively low snow levels until approximately 1960. The period from 1961 to 1963 was a period of high snowfall, and there was then a declining trend to the late-1970s. Snowfall since then has had higher interannual variability than at any other time since 1943. The alternation of high and low snowfall years kept the 5-year running mean at fairly consistent level from 1980 onwards.

Watson Lake experienced a rising trend in snowfall from 1943 to the early-1950s, and then a minor reduction to the mid-1950s. Snowfall rose to its highest levels during the early to mid-1960s, then fell to lower levels to the early-1990s. The Watson Lake

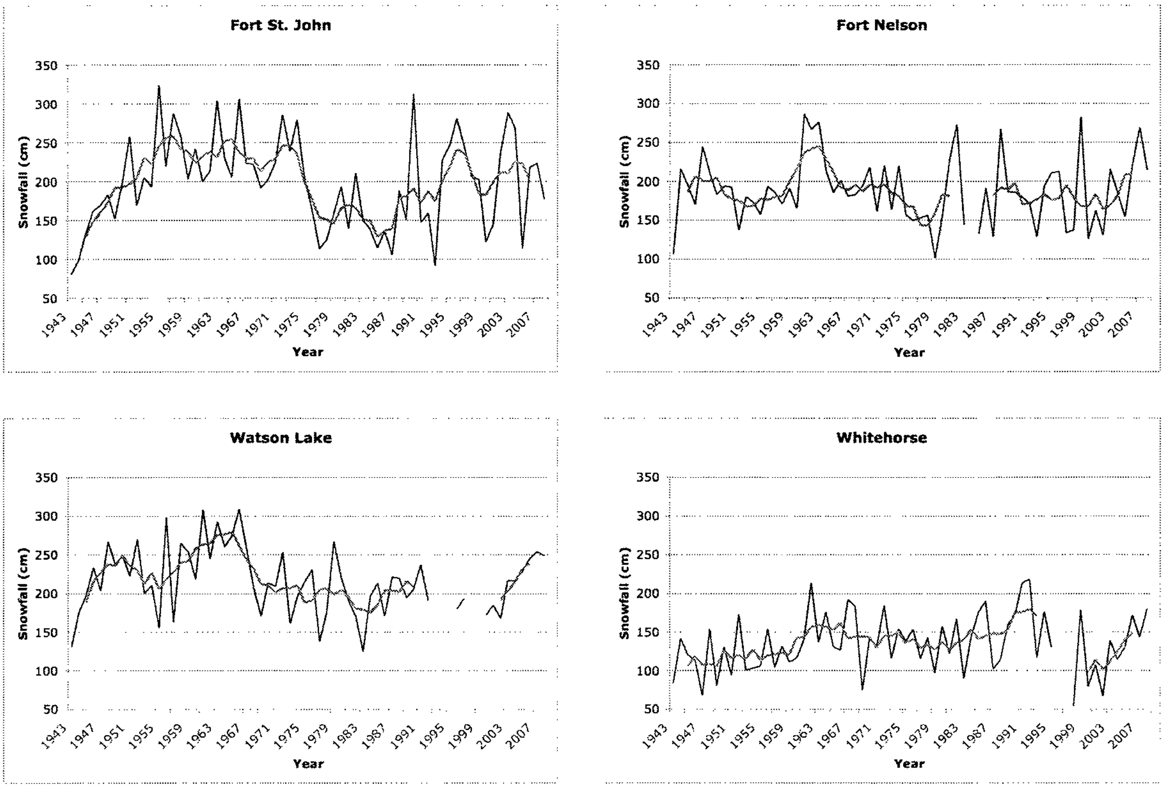


Figure 47. Total snowfall (cm) from 1943 to 2008 at Environment Canada weather stations in the study area (Environment Canada, 2008). The thin black line is the annual snowfall; the grey line is a 5-year running mean. There was no statistically significant change in snowfall from 1943-2008 (using a 95% confidence limit). The figure also allows comparison of spatial annual snowfall patterns along the studied part of the Alaska Highway, with declining snowfall from Fort St. John to Fort Nelson, increasing snowfall to Watson Lake and declining snowfall to Whitehorse. One to six years of missing data in the 1980s and 1990s at each weather station may have affected the results. Watson Lake should be the most affected.

record is missing a great deal of snowfall data for the 1990s. In 2000, snowfall appears to have begun a rising trend.

In Whitehorse, annual snowfall rose from 1943 to the mid-1960s. There was then a period of relative stability in snowfall until the early 1990s. There was then a slight increase, followed by what appears to be a falling trend, which cannot be confirmed due to missing data. Beginning in 1999, there was a rising trend to 2008.

When the full record was analyzed, snowfall levels did not experience statistically significant changes from 1943 to 2008 at any of the four weather stations examined (Table 17). From 1943 to 1964 (Table 17), however, there were statistically significant increases in snowfall at all four weather stations. Snowfall at Fort St. John increased an average of 68 cm/decade, while that Fort Nelson increased an average of 28 cm/decade. Watson Lake and Whitehorse showed average decadal increases of 37 and 25 cm/decade, respectively. For the 1965 to 2008 period, there were no statistically significant changes in snowfall (Table 17).

Both Brown's permafrost investigations and those conducted in 2007-2008 in 1964 and 2008 were conducted during relatively high snow periods. However, snowfall was greater in 1964 than in 2007 at all four weather stations.

Total annual precipitation measured at the four weather stations did not exhibit a consistent pattern along the route (Figure 48). In Fort St. John, there were peaks in the mid-1950s, mid-1960s, mid-1970s, late-1990s and from roughly 2004 to 2007. In Fort Nelson, precipitation was high during the late-1940s, mid-1950s to mid-1960s, late-1970s, early and late-1990s and in 2007. Watson Lake experienced relative peaks in the early-1960s, late-1970s, late-1980s to early-1990s, and in 2007. The station in

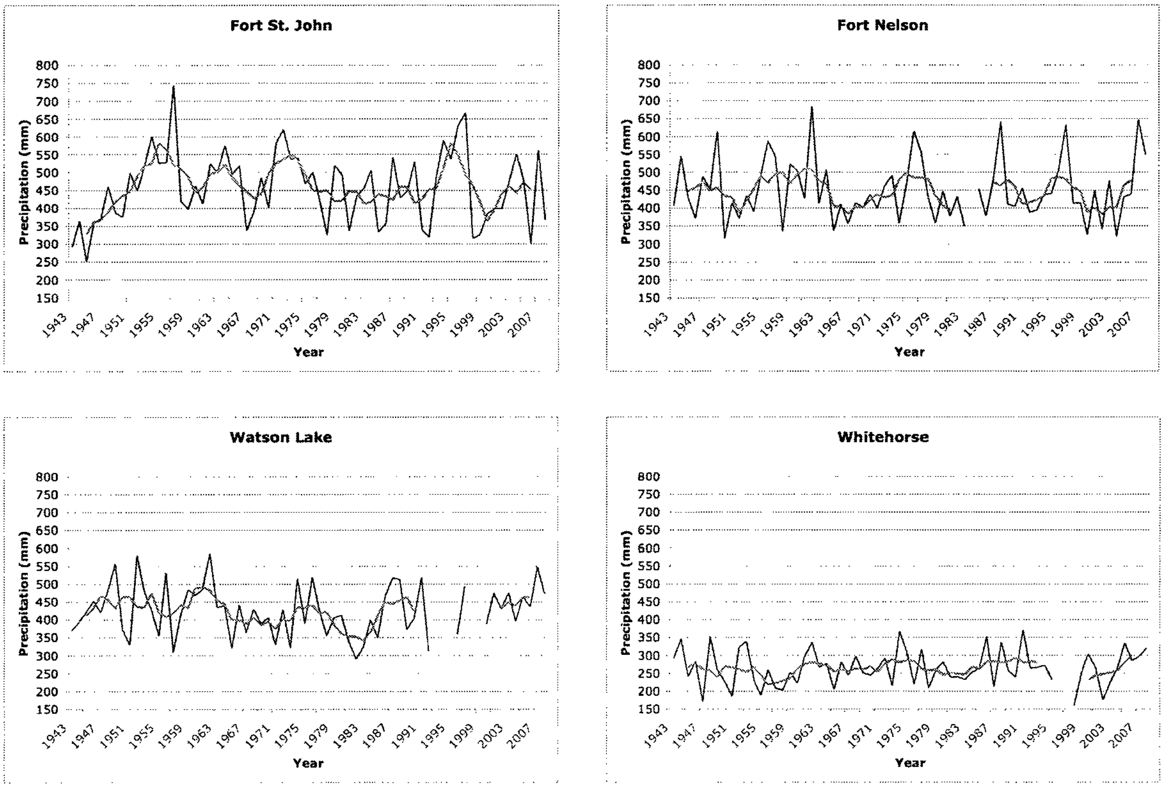


Figure 48. Total annual precipitation (mm) from 1943 to 2008 at Environment Canada weather stations in the study area (Environment Canada, 2008). The thin black line is the annual precipitation; the grey line is a 5-year running mean. The figure also allows comparison of spatial annual precipitation patterns along the studied part of the Alaska Highway, with slightly decreasing precipitation from Fort St. John to Fort Nelson, and further declining precipitation to Whitehorse. Up to five years of missing data in the 1980s and 1990s at each weather station may have affected the results. Watson Lake should be the most affected.

Whitehorse, though it certainly had interannual variability, was the most consistent across time in terms of total annual precipitation (Figure 48). There was noticeably lower precipitation in the mid-1950s, and it appears as though a low may also have occurred in the late-1990s, although there is data missing. The year of 2007 was a drier year than 1964 at all stations.

None of the climate stations showed statistically significant changes in annual precipitation levels between 1943 and 2008 when the period was examined as a whole (Table 17). When 1943 to 1964 was analyzed separately, Fort St. John showed a statistically significant increase in precipitation, while none of the other stations did (Table 17). Precipitation at Fort St. John showed an average increase of 100 mm/decade, for a total increase of roughly 220 mm from 1943 to 1964. The 1965 to 2008 analysis showed a statistically significant increase in precipitation at Watson Lake, while none of the other stations show statistically significant results (Table 17). Precipitation at Watson Lake showed an average increase of 18 mm/decade, for a total increase of roughly 80 mm from 1965 to 2008.

The data show that, over the 21 years prior to Brown' investigations, there was little significant change in the climatic parameters examined. There was a significant increase in precipitation at Fort St. John and a decline in the number of TDDs at Fort Nelson, which may have had modest impacts on permafrost conditions. In the absence of significant air temperature warming or snowfall increases, it is likely that permafrost conditions in at the time of Brown's (1967) investigations were similar to those that existed in 1943. In contrast, significant increases in MAATs and declines in FDDs at all four stations from 1965-2008 (Table 17) make it likely that permafrost degraded during that period, in between the investigations done by Brown (1967) and the 2007-2008 investigations.

5.0 Discussion

5.1 Characteristics of Permafrost in the Study Area

Since the study area falls into the sporadic discontinuous and isolated patches zones of permafrost, it was not surprising to find both thin, warm permafrost and highly localized variation in depth to permafrost and permafrost thickness (Brown and Péwé, 1973; French, 1996; Heginbottom *et al.*, 1995). EM31 surveys of selected study sites indicate that the base of near-surface permafrost is often less than 6 m below the ground surface, and that within several metres it is possible to have variation from zero permafrost to permafrost that has a maximum depth of greater than 6 m (see Figure 21). DC resistivity investigations at selected study sites in 2008 revealed similar discontinuity in permafrost, and found permafrost inferred to be as deep as 15 m at MP 788.5 and 10 m at MP 825.2 (A. Lewkowicz, personal communication, 2009). Burn (1998a) found permafrost extended to depths of up to 18.5 m in the Takhini area, west of Whitehorse. Temperatures in boreholes at two study sites (and Figure 18), one of which was at MP 825.2, were found to have TTOP values that were a small fraction of a degree below zero at each site. Study sites with permafrost had mean thaw depths of 63 cm, but thaw depths at individual sites had a spread of between 18 cm and 90 cm, with a mean range across all permafrost sites of 57 cm. At most sites, investigative probing also found unfrozen ground.

5.2 Climate Change in the Study Area

Data from Environment Canada weather stations show that there was no significant change in MAATs between 1943 and 1964, up to the time of Brown's survey, but that from 1965 to 2008 there were statistically significant temperature increases of

0.4°C/decade (Fort Nelson) to 0.5°C/decade (Fort St. John, Watson Lake, Whitehorse). Increases of this magnitude from 1965-2008 would result in average MAAT increases of about 2°C in the study area since Brown (1967) investigated. This warming trend coincides with an average Arctic warming of 0.4°C/decade from 1966 to 2003 (ACIA, 2005). Most of the warming from 1965 to 2008 took place in winter, as indicated by the declining FDDs at a rate of 140 to 159 FDDs/decade at all weather station sites (Table 17). From 1966 to 2003, average warming across the Arctic also occurred more in winter and spring than in summer (ACIA, 2005). From 1965 to 2008, statistically significant warming during the thawing season was only evident at Watson Lake and Whitehorse, with increases of 37 to 44 TDDs, respectively, per decade. The lack of a significant increase in TDDs at other sites demonstrates that winter warming drove the increase in MAAT.

There were small increases in rainfall of roughly 10 mm/decade at Fort St. John and Watson Lake from 1943-2008. The weather station sites were quite consistent with one another for air temperature trends, but trends in rainfall were more variable between sites. Snowfall exhibited statistically significant increases at all sites from 1943 to 1964 (Table 17), which could have led to permafrost diminishing in extent prior to Brown's survey. However, no significant changes occurred from 1965 to 2008 (Table 17). As a whole, there was little evidence of change in precipitation from 1943-2008. The two sites that had statistically significant precipitation results were Fort St. John, and Watson Lake. Fort St. John showed a substantial increase in total annual precipitation by an average of 100 mm/decade from 1943 to 1964. Watson Lake showed a more modest increase of 18 mm/decade from 1965-2008, after Brown's study.

The data show that atmospheric warming in the study area is likely the dominant climatic factor contributing to changes in near-surface permafrost in the study area from the time of Brown's investigations to the 2007-2008 investigations. Near Fort St. John, the increase in precipitation from 1943 to 1965 may also have affected Brown's measurements. Any other changes in precipitation have been modest.

5.3 Forest Fire

Forest fire may be a confounding variable when trying to determine where permafrost has degraded due to climate warming between 1965 and 2007-2008. The dependence of the warm permafrost in the study area on favourable surface conditions makes it vulnerable to thaw due to forest fire (Burn, 2004, Yoshikawa et al., 2002). Forest fire can cause an increase in soil temperature and active layer thickness, and permafrost degradation (Burn, 1998; Burn, 2004; Mackay, 1995; Yoshikawa et al., 2002)

Fire is an important disturbance regime in the boreal forest, where it plays a large role in determining the physiognomy of the region, as it is critical to the life cycles of many boreal plant species (Burn, 2004; Stocks *et al.*, 2002). The effects of forest fire on permafrost vary according to the type (crown, surface, or ground) and severity of the fire (Stocks *et al.*, 2002). While the conduction of heat to the permafrost during the fire is not significant, ground temperatures usually increase after a fire due to surface disturbance (Burn, 2004; Yoshikawa, 2002). Fire causing the removal of vegetation reduces shade and evaporation, raising the ground surface temperature (Burn, 2004; Mackay, 1995). The destruction of canopy cover also brings about increased snow depth (Burn, 2004; Mackay, 1995). Furthermore, the surface albedo is lowered by up to 50% for a number of years due to burning of the organic cover (Yoshikawa et al., 2002). The thickness of the remaining organic layer strongly influences the impacts of forest fire on permafrost (Yoshikawa *et al.*, 2002). If there is adequate organic material remaining, there may be little to no thermal disturbance to permafrost (Brown and Péwé, 1975; Yoshikawa *et al.*, 2002)

Fire could also have led to some permafrost loss at the study sites. Signs of fire, such as burn scars on tree trunks and charred material in the organic layer, were observed at some study sites, during the 2007-2008 investigations. Brown also observed some sites as being 'burned over' although his methods for deciding what sites were classified in that way are unknown. Forest fire data from British Columbia (1940-2008) and the Yukon (1946-2008) were obtained in order to examine whether or not forest fire was likely responsible for permafrost disappearance at any of the study sites (Figure 49).

The forest fire data was collected in a variety of ways, from walking the perimeter with a GPS, to flying around the fire with one, to satellite imagery. Older data, from the 1940s to 1960s, should be considered incomplete, because fire detection capabilities, particularly in the Yukon, were not fully developed and some fires were not detected or poorly mapped. Table 18 shows the sites affected by or likely affected by fire in the study area.

Burned sites could fall into five categories in terms of potential influence on permafrost existence at the study sites:

Type 1

A site was burned prior to Brown's investigation, and although he found permafrost, the

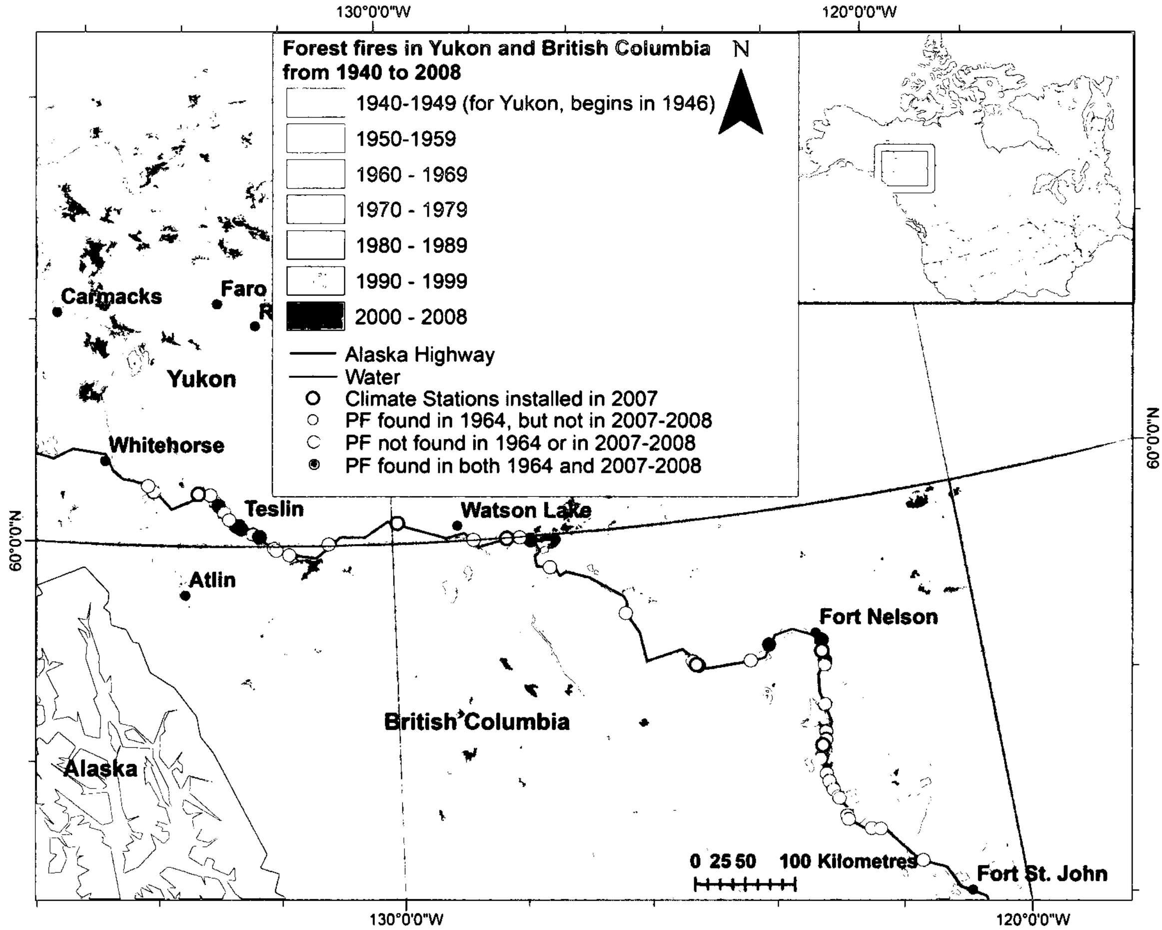


Figure 49. Forest fires in Yukon and British Columbia. Data from Yukon covers the period of 1946-2008, while data from British Columbia covers the period 1940-2008. Fire records, particularly those from the 1940s to 1960s, may be incomplete or poorly mapped (Wildfire Management Branch, Government of British Columbia, 2009; Wildlands and Fire Management Branch, Government of Yukon, 2008).

Table 18. Study sites affected or possible affected by forest fire. For permafrost status, 'Y' denotes sites where permafrost was found during both investigations; 'C' denotes where it appears to have disappeared since 1964, and 'N' denotes sites where permafrost was not found during either investigation. The 'Signs of fire noted' column indicates whether Brown (B), James (J) or both noted signs of fire at a site. Sources: (GeoBC, 2008; Geomatics Yukon, 2008)

Sites where signs of fire observed	Permafrost status	Signs of fire noted	Year of fire
MP 844.1	Y	J	pre 1946?
MP 579.1	Y	J	pre 1946?
MP 208.5	Y	B, J	1944
MP 882	C	J	pre 1946?
MP 219.6	C	B, J	1958
MP 204.6	C	J	1944
MP 199.9	C	J	1944
MP 197.9	C	J	1944
MP 187.2	C	J	1942
MP 173	C	J	1944
MP 762.5	N	B, J	1950
MP 627	N	J	pre 1946?
MP 169.2	N	J	1944
MP 153.8	N	J	1944
MP 151.4	N	J	1970
MP 134.3	N	J	1983
MP 90.1	N	J	pre 1940?
Sites where no signs of fire observed, but appear in or very close to fire polygons			
MP 819.1	C		1958?
MP 794.8	C		1950
MP 788.5	Y		1950
MP 587.6	N		1982
MP 546.5	N		1965 and 1982
MP 182.9	N		1950
MP 178	Y		1950

site was in sufficient disequilibrium due to fire that the permafrost subsequently degraded to beyond 2 m depth or disappeared.

Type 2

There was fire at a site in between the 1964 and 2007-2008 investigations, causing the permafrost present in 1964 to thaw, so that it was not detectable within 2 m of the ground surface in 2007-2008.

Type 3

A fire occurred at a site in between the 1964 and 2007-2008 investigations, causing gradual warming of the permafrost, but the disequilibrium has not yet caused its degradation to beyond 2 m depth.

Type 4

A site was burned prior to or after Brown's investigations, but not severely enough to cause significant impact on the underlying permafrost.

Type 5

A site was burned prior to Brown's investigation, so that he found no permafrost, but perennially frozen ground has since reformed due to vegetation succession.

Ten of the 24 sites that were likely burned since 1940 had no permafrost found during either investigation. These sites burned from possibly prior to 1944 to 1983. While vegetation succession and the regeneration of the organic layer can lead to permafrost re-forming where it has been degraded by fire (Yoshikawa *et al.*, 2002), this has not happened at any of Brown's non-permafrost sites that were burned.

Five of the sites where permafrost was found in both 1964 and 2007-2008 were or were likely to have been burned since 1940 (Table 18). All of these were burned from 14 to more than 20 years prior to Brown's investigation, likely making them Type 4 sites, where the fire was not severe enough to significantly impact the organic layer and its underlying permafrost. Alternatively, they could have already recovered prior to the 1964 survey.

The nine sites of the most interest to this study are those that had permafrost in 1964, were burned at some point, and had no permafrost in 2007-2008. Seven of the sites were burned in 1950 or earlier, with at least five burned in 1944 or earlier. Two sites apparently burned in 1958, although whether one of them actually burned is questionable (see below). None of the sites burned between the two surveys, so any influence of fire would have to be a lagged response. All nine sites, therefore, could fall into the Type 1 fire influence category. In 1964, Brown found active layers at these sites ranging from 41 cm to 61 cm, and organic layers ranging from 30 cm to 162 cm thick. It is possible that the organic layers were impacted little by fire, as moist, low-lying areas of permafrost often escape with little damage to surface vegetation or organic layers (Swanson, 1996). This leads to a much lower impact on active layers than if the organic horizon is destroyed (Swanson, 1996). Also, Brown noted that maximum spruce heights at these sites were between 6 m and 20 m, so the vegetation canopy was likely largely intact, and did not contribute greatly to fire-induced permafrost warming. In fact, Brown did not note any of the seven sites that burned in 1950 or before to be 'burned over'. This reinforces the probability that the fires were likely minor in severity. Finally, the relatively shallow active layers 14 to 20 or more years after being burned make it unlikely that it was fire that caused permafrost loss at these sites.

Of the two sites that appear to have burned in 1958, one may not have actually been subject to fire. There was a small alignment problem with the Yukon fire polygon data, and while MP 819.1 appears to be within a fire polygon, there were no signs of fire noted at the site, and it is quite likely that the polygon and the site do not actually intersect. The other site, MP 219.6, Brown described as burned over, with a 53 cm active layer and a 100 cm organic layer (Brown, 1967). Brown described the permafrost thickness at this site as being 53 cm thick (Brown, 1967). There were 9 m spruce at the site, as well as jack pine and poplar (Brown, 1967). Although the permafrost is very thin, the existence of a relatively shallow active layer, a canopy cover and a thick organic mat make it unlikely the permafrost at this site was greatly impacted by fire.

Forest fire can profoundly impact permafrost, and thawing of permafrost as a result of forest fire can occur for years to decades after the fire takes place (Burn, 1998). However, model studies based on the boreal forests of Interior Alaska suggest that if an organic layer of even 7 cm to 12 cm remains after a fire, the thermal impacts to permafrost are minimal (Yoshikawa *et al.*, 2002). Given the site conditions at burned sites where permafrost was found in 1964, but not in 2007-2008, it appears unlikely that forest fire contributed greatly to permafrost disappearance at the sites. Instead, it is likely that rising MAATs caused the disappearance of permafrost from the seven sites that were burned (or possibly burned) prior to the 1964 survey.

5.4 Persistence of Permafrost

Mean annual temperatures at the study sites with climate stations demonstrate that if the sites are in thermal equilibrium with the climate, it is the ground thermal conductivity ratio, via the thermal offset that is the most critical factor in allowing permafrost to persist in the study area. The presence of permafrost at five of the six climate station sites appears to be dependent on the thermal offset to keep mean annual ground temperatures below 0°C (Table 7 and Figure 16). However, if the sites are in disequilibrium with surface temperatures, the permafrost may be present due to the lag effect associated with the high latent heat of the frozen soil. Because the positive heat flow into the ground is relatively low, it may take several decades for the latent heat of the permafrost to be satisfied and for thaw to occur (Romanosky and Nicolsky, 2009. However, long-term monitoring in the future is the only way to tell whether permafrost is in equilibrium or not.

Numerous studies refer to the critical role of the thermal offset in determining the southernmost extent of discontinuous permafrost, (Shur and Jorgenson, 2007; Smith and Riseborough, 1998; Smith and Riseborough, 2002). At its southernmost limit, permafrost most often exists in peatlands (Brown; 1967; Brown and Péwé, 1975; Shur and Jorgenson, 2007; Zoltai, 1971). The seasonal variation of ground thermal conductivities in organic soils (due to the ground materials being frozen or unfrozen, and due to moisture variation between seasons) promotes heat loss during the winter, and minimizes the ground heat flux in summer, thereby facilitating the existence of permafrost (Beilman, 2008; Brown, 1967; Halsey *et al.*, 1995; Smith and Riseborough, 2002). Study sites where permafrost persisted had much thicker organic soil than those where it appears to have disappeared since 1964 or was not present in 1964. Permafrost-persistent sites also had higher moisture contents (on the day sampled) than sites with no permafrost. Because wet organic soil has a thermal conductivity ratio twice as large as wet silt, and eight times greater than dry gravel, it contributes to a large thermal offset that fosters the continued existence of permafrost (Shur and Jorgenson, 2007; Beilman *et al.*, 2008; Vitt *et al.*, 1994).

Based on the classifications of Shur and Jorgenson (2007) some permafrost sites in the study area are likely ecosystem-driven, while others, specifically those at the southernmost margin of permafrost existence, are ecosystem-protected. At sites such as MP 681.1, where the MAAT was -3.8°C in 2007-2008, permafrost may be able to re-aggrade after a surface disturbance (Shur and Jorgenson, 2007). At sites with MAATs above -2°C, reaggradation after surface disturbance is unlikely to occur (Shur and Jorgenson, 2007). Ecosystem-protected permafrost sites are likely underlain by permafrost that dates from at least the Little Ice Age that is in disequilibrium with the current climate and requires high thermal offsets in order to persist (Camill and Clark, 1998; Halsey *et al.*, 1995; Shur and Jorgenson, 2007; Beilman *et al.*, 2001; Vitt *et al.*, 1994). French and Egorov (1998) have suggested that highly localized permafrost may be even younger, and caused by just a small number of cold or low snowfall winters, but this appears unlikely of permafrost which is 5 m or more thick, as is the case at a number of sites.

In addition to the thermal offset, patterns of snowfall and air temperature can offer possibilities of why permafrost is able to persist at some sites in the study area, and not others. The Environment Canada stations at Fort St. John, Fort Nelson, Watson Lake and Whitehorse, none of which are underlain by permafrost, were used for comparison for these factors.

All of the project sites were colder than their proximate Environment Canada station in 2007-2008 (Table 12). The three southernmost project climate stations, MPs

400.5, 286 and 208.5, had MAATs of -1.8°C, -1.2°C, and -2.2°C, respectively, while their proximate station, Fort Nelson had a MAAT of -0.5°C. The higher MAAT at Fort Nelson makes it less likely to host permafrost than the three project climate sites, but in addition to warmer temperatures, it also had more snow depth days than MP 400.5, 286 or 208.5 (Table 13 and Figures 35 to 37). Fort St. John also had more SDDs than its nearest project site, MP 208.5, while also having a MAAT 4.4°C higher (Tables 12 and 13). The warm temperatures at the two Environment Canada stations, coupled with the strong insulating capabilities of snow, likely preclude permafrost (Smith and Riseborough, 2002; Stieglitz *et al.*, 2003).

The three project climate stations further north along the highway, MPs 597.5, 681.1 and 844.1, had lower MAATs than their proximate Environment Canada stations in 2007-2008 (Table 12). However, unlike the three southernmost project stations, they had more snow than the nearby Environment Canada stations. It is likely, then, that MP 597.5 and MP 844.1 can support permafrost due to their thermal offsets (if the permafrost is in equilibrium with surface temperatures), which are likely larger than those beneath the Environment Canada stations. MP 681.1 had the most snow of any of the climate stations, yet is still cold enough to host permafrost in spite of that.

Analysis of air temperature data indicate that significant air temperature inversions due to cold air drainage or pooling likely occur at MP 208.5, MP 286 and the Environment Canada Fort Nelson station. This makes the locations of these sites more favourable for permafrost development than sites without this climatic phenomenon, but it appears that even with the cold air pooling, Fort Nelson does not have low enough temperatures or a large enough thermal offset to support permafrost.

Air temperature inversions have been documented as impacting discontinuous permafrost distribution and thickness in the past. Taylor et al. (1998) examined atmospheric temperature inversions along a slope in the Norman Wells, NWT area and found that inversions 300 to 1500 m above the valley floor occurred frequently, especially in winter. Mean annual surface temperatures at the mountain summit were found to be about 1°C higher than those in the valley bottom, 969 m below (Taylor *et al.*, 1998). The temperature inversions were greater between 100 m and 500 m above the valley bottom, and this resulted in permafrost thicknesses at these elevations being up to 12 m less than those in the valley bottom (Taylor *et al.*, 1998).

In this project's study area, Harris (1982) found evidence of atmospheric temperature inversions in valleys near Summit Lake, to the west of Fort Nelson, on the eastern slopes of the Rocky Mountains. Attributing some of the difference to cold air drainage due to the large topographic relief, Harris found temperature differences of up to 33°C between sites at elevations of 751 m and 1524 m on cold January nights, with the lower elevation being colder (Harris, 1982). Harris suspected that cold air drainage exerted some control on permafrost distribution in the region (Harris, 1982, 1986).

In order to determine whether cold air drainage was contributing to the atmospheric temperature inversions inferred at MP 208.5, MP 286 and Fort Nelson, it was necessary to ascertain whether the sites were at valley bottoms in areas of large topographic relief. Topographic position indices were calculated for neighbourhoods of 500, 750 and 1000 m (Jenness, 2006). The Topographic Position Index (TPI) is an extension for ESRI's ArcView GIS software. It allows the classification of landscape into slope and landform categories, by comparing the elevation of a point to the mean elevation of pixels surrounding it, within a set neighbourhood size (Jenness, 2006). Its usefulness is very scale dependent, and it was found that the neighbourhood sizes chosen (500, 750 and 1000 m) were too small to adequately represent the positions of the sites in relation to surrounding slopes. Neighbourhoods that size may work effectively in mountain permafrost, but not in broad valleys and lowlands. Unfortunately, larger neighbourhood sizes could not be attempted due to time and computing capacity constraints.

It is not known whether cold air pooling at the three stations is a result solely of radiative cooling due to a negative radiation balance over the ground surface or whether cold air drainage from slopes is contributing to the pooling. However, it is thought that the temperature inversion is a factor that may help explain the persistence of permafrost at some of the sites in the study area.

5.5 Permafrost Distribution as an Indicator of Climate Warming

During the 21st century, the southernmost extent of permafrost is expected to shift northward several hundred kilometres (ACIA, 2005). Some authors, such as Kwong and Gan (1994) have concluded that it has already done so in the 20th century. They found a shift of 120 km northward in northern Alberta and NWT that seems to have occurred over the course of less than 40 years (to 1994). Halsey *et al.* (1995) has also concluded that the zones are shifting northward, and that air temperature isotherms are moving faster than loss of permafrost, due to the permafrost's state of disequilibrium with the current climate.

It appears that since Brown's investigations in 1964, permafrost has disappeared from many of his sites, particularly those in the southern reaches of the study area and in the warmer section near Whitehorse. Consequently, the southern limit of the 'Isolated Patches' zone (0 to 10%) (Heginbottom and Radburn, 1992) may have shifted approximately 75 km northward since 1964. Because much of the permafrost in the study area exists at temperatures near 0°C, in isolated patches at the southern extremity of permafrost zonation, it is more sensitive to climate warming-induced thaw than colder, more continuous permafrost (ACIA, 2005; Kwong and Gan, 1994). Although there are lag times in change associated with the insulating properties of snow, peat and the latent heat of fusion (Smith and Burgess, 1999), very marginal permafrost is still likely to respond to change on the timescale of years to decades (Burn, 1998; Kwong and Gan, 1994).

Comparative permafrost distribution can be used effectively as a proxy indicator of climatic warming (Kwong and Gan, 1994). Permafrost existing in isolated patches at the southern fringe of discontinuous permafrost will thaw with a warming climate (ACIA, 2005; Camill, 2005; Halsey *et al.*, 1995). However, caution must be exercised when extrapolating atmospheric temperature trends to ground temperatures, because there are other factors, such as changes in precipitation, vegetation, changes to the organic layer due to fire, or changes in groundwater flow, that can cause changes in ground thermal conditions leading to permafrost thaw (Osterkamp, 2007; Smith and Riseborough, 1983). Thus, while permafrost thaw can indicate climate warming, change in permafrost does not automatically equate to climate warming (Burn, 1998b; Osterkamp, 2007). In order for permafrost to be used as an indicator of climate warming, earlier records of climate and permafrost distribution must be available for the study area (Kwong and Gan, 1994). These data enable the researcher to account for or eliminate from consideration some reasons why ground thermal conditions at a particular site may have experienced change, thereby clarifying the climate signal.

Because microclimatic, terrain and soil properties exercise so much control over permafrost conditions in the discontinuous zone, changes in permafrost attributable to climate should not likely be applied beyond a regional scale (Kwong and Gan, 1994).

5.6 Future Research

As climate stations and boreholes have been installed in the study area, and since there are now two temporally different datasets, further research into permafrost in the region is both practical and desirable. The installation of climate stations and ground temperature loggers at sites with only seasonally-frozen ground would be invaluable, as the current research was based only on data at permafrost sites. Further investigation of atmospheric temperature inversion, through temperature loggers and use of the Topographic Positioning Index (with larger neighbourhoods), could also be important in determining how large a role cold air pooling plays in the maintenance of permafrost in the region. Lastly, a study of thermal diffusivity of soil at sites where there are climate stations and ground temperature loggers would help improve the understanding of the ground thermal response of permafrost and seasonally-frozen sites in the study area.

6.0 Conclusions

This study demonstrates that: (1) significant degradation of permafrost has occurred over the past four decades, especially in the southernmost part of the route where 67% of the permafrost sites in 1964 no longer exhibit perennially frozen conditions and to a lesser extent immediately to the east of Whitehorse; (2) the mapped southern limit of discontinuous permafrost (Heginbottom *et al.*, 1995) appears to have shifted roughly 75 km northward; (3) most of the permafrost still present in the study area is in peat or under thick organic mats, which probably relates to a large thermal offset or to the latent heat requirements of thawing permafrost; and (4) that where permafrost has persisted, it is very thin, discontinuous, at temperatures just below 0°C, and its location may relate in part to the existence of atmospheric temperature inversions in the region.

Changes in permafrost are attributed to significant climatic warming that has occurred in the area, at a rate of 0.4°C to 0.5°C per decade from 1965 to 2008 (based on data from Environment Canada weather stations). The majority of the warming trend occurred during winter. Active layer thicknesses are too variable and Brown's methods too unknown to conclusively demonstrate that thickening has occurred at the sites where permafrost is extant, but average thicknesses exceed those recorded by Brown. Electromagnetic induction surveys revealed permafrost in the area to be highly locally discontinuous and variable in thickness. Data from temperature cables installed in shallow boreholes confirmed that permafrost persists at only a fraction of a degree below 0°C.

This study is a step towards filling a research void to provide evidence of loss of permafrost at a multi-decadal scale. Careful archiving of information about the research sites should allow repetition of the survey by future generations of permafrost researchers, thus contributing to the legacy of the International Polar Year.

Appendix A: Metadata for Appendices B-G

App B: Extrapolation of Ground Thermal Profiles

Sites were investigated as described in Methods. At some sites, only one profile was measured due to terrain or other difficulties. Discarding the first measurement, and using the rest, the measurements at each depth were fitted with a linear trend line, and this line was forecasted to a time of 30 minutes. The temperature at 30 minutes (for each depth) was used as the equilibrium temperature.

Once a set of equilibrium temperatures had been achieved for a site, the temperatures were plotted on a line chart and a linear trendline was fitted to allow forecasting to below 0°C. It could then be seen whether the trendline predicted temperatures of 0° C or less at a depth 2 m below surface or shallower, and decisions could be made regarding the extrapolation result (see Appendix D).

App. C: Site Locations and Dates of Investigation

Site Name

R.J.E. Brown named his sites by the mileage they were away from the beginning of the Alaska Highway (in miles). His precision was to 0.1 of a mile, but there is no way of knowing how accurate he was. The same site names were kept in order to facilitate comparison between the 1964 and 2007-2008 permafrost studies.

UTM Coordinates

The Zone, Easting and Northing fields make up the UTM coordinates of the sites we investigated. They are in the WGS 84 datum. The UTM Coordinates were taken with a Garmin eTrex Vista Cx. The accuracy of this device, according to manufacturer specifications, ranges from ± 3 m to ± 15 m (Garmin, 2006). It should be noted, however, that forest cover causes significant difficulty in satellite signals reaching the handheld GPS unit, so the upper end of the accuracy range should be considered as very likely. Since waypoints were taken in 2007 and then returned to in 2008, and since the forest covered inhibited satellite communication with the device, sites investigated in 2008 could be up to 15 m away from those investigated in 2007. The coordinates listed are those taken in 2007.

Date of Investigation

The dates of investigation are the dates site investigations took place in 2007 and 2008, in the format of m/dd/yy. When more than one date is listed, often the second date is when a site was returned to in order to do an EM31 transect, take a soil sample, water-jet drill or measure a thermal profile. Sites that were not visited in one or both of the years of investigation are marked as such in the date of investigation field.

App. D: Permafrost Conditions

Permafrost Encountered (to 2 m)

A 'Y' in this field means a frost table was encountered within 1.5 m of the ground surface in 2007. An 'N' in this field means no frost table was encountered within 2 m of the ground surface, either upon initial investigation in 2007 or during investigation of 'indeterminate' sites in 2008. An 'I' in this field means the site was 'indeterminate', that it is not known whether or not there is permafrost within 2 m of the ground surface. An 'N*' denotes sites where it was impossible to penetrate to 2 m due to stones, but enough depth was reached to do a profile, as well as sites penetrated beyond 2 m.

Permafrost Predicted (to 2 m)

A 'Y' in this field means permafrost was predicted to within 2 m of the ground surface using extrapolated thermal profiles. These were not investigated in 2008. A 'N' means that extrapolated thermal profiles did not definitively predict permafrost within 2 m of the ground surface, and these were not investigated in 2008. An 'I' means that thermal profile extrapolations were inconclusive, and these sites were further investigated in 2008.

Permafrost Classification with respect to Brown's (1967) Results

A 'Y' in this field denotes that permafrost was found in both 1964 and 2007-2008. A 'C' denotes that permafrost was found in 1964, but not in 2007-2008. A 'N' denotes permafrost was not found in either set of investigations.

Avg. Thaw Depth 2007, 2008 (cm)

At sites with frost tables, *n* thaw depths were measured and recorded in 2007. This is their average value.

n for Avg. Thaw Depth 2007, 2008

This is the number of thawed layer measurements that are included in the calculation of 2007's average thaw depth. This number varies mostly due to rocks or roots preventing ground penetration for thaw depth measurement.

SD for Avg. Thaw Depth 2007, 2008 (cm)

This is the standard deviation for the average thaw depth of 2007.

App. E: Relief, Organic Layer, Vegetation and Surface Terrain Features, and App G: Electromagnetic Induction Results

Relief

This is a qualitative observation that denotes whether or not a site was on a noticeable slope. 'S' denotes slope without noting a slope direction, while a subscript of 'e', 'w', 'n' or 's' denotes whether a slope faces east, west, north or south, respectively. 'L' means the site was low-lying with no significant slope.

Median Organic Layer Thickness (cm)

This is the median organic layer thickness measured at a site, using both 2007 and 2008 measurements. The median is given because there are too many measurements where only a minimum, and not actual, thickness value is known. Some sites have so many minimum thickness values that a median was impossible to calculate, and so is absent.

Range of Organic Layer Thicknesses (cm)

This is the minimum and maximum of the range of measured organic layer thicknesses, using both 2007 and 2008 measurements.

n for Organic Layer Thicknesses

This is the number of measurements used in the organic layer thickness calculations. 'n' varies because more were taken at permafrost sites than non-permafrost sites (typically 10 per year as opposed to 5 per year), EM31 sites have more measurements and a few sites have fewer measurements because they were only visited in 2007

Tree Types

This group of fields denotes what tree types were present at a site. The types are mostly only as specific as genus, with jack pine being the only species-specific type listed. The trees are ordered in fields labeled 1-4 in order of abundance (field 1 being the most abundant). 'S' is spruce, 'J' is jack pine, 'T' is tamarack, 'P' is poplar, 'A' is alder, 'As' is aspen, 'W' is willow.

Max Tree Height (m) (visual estimate)

This group of fields shows an estimate for maximum tree height at a site. These are just visual estimates, so accuracy is likely quite low, but the numbers give a general idea. Smaller trees are likely more accurate, and so have been given more precise numbers (to 0.5 m instead of 1 m). The field number corresponds to tree type number, so a spruce in the tree type field '1' corresponds to the height listed in the max tree height field '1'. Not all tree types have a max height noted.

Surface Terrain Features

This group of fields covers microtopography and low vegetation cover. Vegetation is in order of abundance generally, but this was derived from only a visual appraisal. Microtopography is typically listed early because it is a dominant feature. The fields are arranged with '1' being most abundant and '8' least abundant. 'H' means hummocky, 'p' means peat plateau, 'M' means non-sphagnum mosses, 'Sph' means sphagnum mosses, 'Ln' means lichens, 'Lt' means Labrador tea, 'B' means ground birch, 'G' means grasses, 'Se' means sedges and 'Ht' means horsetail.

Electromagnetic Induction

These results use the symbols as Appendix E for vegetation and surface terrain features. In addition, the EM-31 results use ‘r’ to denote rocks and roots that prevented ground penetration, and ‘d’ and ‘h’ to indicate whether a specific point of measurement was in a depression or on a hummock, respectively.

App. F: Soil Conditions

Soil Field Description

This is a qualitative soil description that was done in the field by sight and touch. There are no naming conventions. This field may be particularly useful for sites without soil samples, such as sites with deep organic mats.

Sample Names

This field shows the names of soil samples. It is done in a format of yy/mm/dd-order sample taken that day. So, for example, the first sample taken on 08-08-16 is 08-08-16-01, while the second is 08-08-16-02.

Sample Depths (cm below ground surface)

This is the range of cm below ground surface from which a sample was taken. Each sample covers a range of depth of 10 to 20 cm.

Soil Moisture (%)

This is the percentage of weight that is attributable to soil moisture in the whole sample.

Organic Content (%)

This is the percentage of a subsample that was found to be organic based on the method of Loss on Ignition (LOI).

Mineral Soil Description (lab)

This field is a description of the mineral soil of a subsample based on the parameters laid out in Appendix 1 (Field Identification of Soils) in the Forest Road Engineering Guidebook (2nd ed.) of the Forest Practices Code of British Columbia.

Gravel %, Sand %, Silt %, Clay %

These fields are the percentage of the granulometry subsamples that are made up of each respective grain size class.

Mean particle size (phi), Kurtosis (phi), SD (phi), Skewness (phi)

These fields are statistical parameters for the granulometry subsamples. SD means standard deviation, while the other parameters are written out in full in the database field title.

Appendix B: Ground Thermal Profiles (2007)

Site	Depth below surface (cm)	Organic layer (cm)	Depth to frost table at time of investigation (cm)	Ground temperatures (°C) at one minute intervals									
				0	1	2	3	4	5	6	7	8	9
MP 90.1	140	15		6.57	6.28	6.17	6.02	5.99	5.95				
	120			6.06	6.28	6.28	6.28	6.24	6.24				
	100			6.35	M	6.72	6.75	6.75	6.75				
	80			6.79	7.05	7.09	7.09	7.09	7.09				
	60			7.32	7.28	7.28	7.28	7.28	7.28				
MP 90.1	140	15		6.87	6.64	6.50	6.42	6.39	6.35				
	120			6.42	6.53	6.53	6.53	6.53	6.53				
	100			6.57	6.75	6.79	6.79	6.79	6.79				
	80			6.87	7.02	7.05	7.05	7.05	7.05				
	60			7.17	7.32	7.39	7.39	7.43	7.43				
MP 128.1	140	20		5.45	5.45	5.45	5.45	5.45	5.45				
	120			5.91	5.95	5.88	5.88	5.88	5.88				
	100			6.13	6.53	6.61	6.61	6.64	6.64				
	80			6.87	7.13	7.13	7.17	7.17	7.17				
	60			7.32	7.47	7.51	7.51	7.51	7.51				
MP 128.1	130	30		6.79	6.64	6.57	6.53	6.46	6.42				
	110			6.72	6.94	6.94	6.94	6.94	6.94				
	90			7.05	7.36	7.39	7.39	7.39	7.39				
	70			7.55	7.78	7.78	7.78	7.78	7.78				
	50			7.85	8.09	8.13	8.17	8.17	8.17				
MP 134.3	145	40		6.20	5.73	5.56	5.49	5.42	5.38				
	125			5.56	M	5.84	5.81	5.77	5.77				
	105			5.81	6.09	6.09	6.06	6.06	6.06				

Site	Depth below surface (cm)	Organic layer (cm)	Depth to frost table at time of investigation (cm)	Ground temperatures (°C) at one minute intervals									
				0	1	2	3	4	5	6	7	8	9
	85			6.24	M	6.39	6.39	6.39	6.39				
	65			6.61	6.72	6.72	6.72	6.72	6.72				
MP 134.3	145	51		7.02	6.72	6.50	6.46	6.35	6.28				
	130			6.35	6.35	6.31	6.31	6.28	6.24				
	110			6.35	6.53	6.50	6.50	6.46	6.46				
	90			6.72	6.72	6.68	6.68	6.68	6.64				
	70			6.79	6.94	6.94	6.90	M	6.87				
MP 151.4	150	60		3.91	3.91	3.84	3.81	3.78	3.75				
	130			3.98	4.18	4.18	4.18	4.18	4.18				
	110			4.24	4.45	4.45	4.45	4.45	4.45				
	90			4.55	4.69	4.69	4.69	4.69	4.69				
	70			4.93	5.10	5.20	5.20	5.20	5.20				
MP 151.4	150	53		5.81	6.17	6.06	5.95	5.81	5.73				
	130			5.95	5.95	5.91	5.88	5.84	5.81				
	110			5.95	6.02	5.99	5.91	5.91	5.88				
	90			6.13	6.24	6.20	6.17	6.13	6.13				
	70			6.31	6.42	6.39	6.39	6.35	6.35				
MP 153	150	52		2.65	2.72	2.75	2.72	2.72	2.72				
	130			3.23	3.26	3.23	3.19	3.19	3.19				
	110			3.26	3.68	3.61	3.58	3.58	3.55				
	90			3.98	4.18	4.11	4.11	4.08	4.08				
	70			4.18	4.48	4.48	4.48	4.45	4.45				
MP 153	150	55		4.48	3.81	3.55	3.42	3.32	3.26				
	130			3.35	3.58	3.58	3.58	3.58	3.58				
	110			3.65	3.88	3.94	3.94	3.98	3.98				

Site	Depth below surface (cm)	Organic layer (cm)	Depth to frost table at time of investigation (cm)	Ground temperatures (°C) at one minute intervals									
				0	1	2	3	4	5	6	7	8	9
	90			4.14	4.31	4.31	4.31	4.31	4.31				
	70			4.45	4.65	4.65	4.65	4.65	4.65				
MP 153.8	150	40		3.55	3.71	3.68	M	3.61	3.58				
	130			3.98	4.21	4.18	4.18	4.18	4.14				
	110			4.31	4.48	4.48	4.48	4.48	4.45				
	90			4.75	4.93	4.89	4.86	4.86	4.86				
	70			5.20	5.49	5.49	5.45	5.42	5.42				
MP 153.8	150	50		4.93	4.72	4.58	4.51	4.45	4.41				
	130			4.51	4.62	4.62	4.62	4.58	4.58				
	110			4.82	4.89	4.89	4.86	4.86	4.86				
	90			4.96	5.17	5.17	5.13	5.13	5.10				
	70			5.17	5.31	5.17	5.13	5.13	5.13				
MP 154.7	150	67		3.94	3.98	3.98	3.94	3.94	3.91				
	130			4.48	4.48	4.45	4.41	4.41	4.41				
	110			4.45	4.65	4.69	4.69	4.69	4.69				
	90			4.79	5.13	5.20	5.20	5.20	5.20				
	70			5.27	5.84	5.95	5.99	5.99	5.99				
MP 154.7	150	50		4.65	4.31	4.11	4.01	3.94	3.91				
	130			3.98	4.14	4.14	4.11	4.11	4.11				
	110			4.14	4.35	4.38	4.38	4.38	4.38				
	90			4.48	4.72	4.75	4.75	4.75	4.75				
	70			4.82	5.00	5.03	5.00	5.00	5.00				
MP 169.2	150	35		5.27	5.56	5.45	5.34	5.27	5.24				
	130			5.73	5.84	5.84	5.81	5.77	5.73				
	110			5.84	6.24	6.24	6.24	6.20	6.20				

Site	Depth below surface (cm)	Organic layer (cm)	Depth to frost table at time of investigation (cm)	Ground temperatures (°C) at one minute intervals									
				0	1	2	3	4	5	6	7	8	9
	90			6.35	6.57	6.57	6.53	6.53	6.53				
	70			6.57	6.79	6.87	6.90	6.87	6.87				
MP 169.2	145	35		5.91	5.52	5.34	5.20	5.10	5.03				
	130			5.17	5.34	5.34	5.34	5.34	5.34				
	110			5.63	5.73	5.73	5.73	5.70	5.70				
	90			5.81	5.95	6.02	6.02	6.02	6.02				
	70			6.13	6.24	6.28	6.28	6.28	6.28				
MP 170.4	150	18		3.29	3.45	M	3.42	3.42	3.39				
	130			4.35	M	M	3.91	M	3.88				
	110			4.04	4.18	4.18	4.21	4.21	4.21				
	90			4.24	4.41	4.45	4.45	4.41	4.41				
	70			4.51	4.75	4.82	4.86	4.89	4.89				
MP 170.4	150	18		4.89	4.51	4.28	4.14	4.08	4.01				
	130			4.14	4.28	4.28	4.28	4.28	4.28				
	110			4.38	4.51	4.55	4.55	4.55	4.55				
	90			4.65	4.89	4.96	4.96	4.96	4.96				
	70			5.06	5.17	5.20	5.20	5.20	5.20				
MP 173	150	95		1.72	1.63	1.54	1.46	1.43	1.40				
	130			1.43	1.54	1.57	1.57	1.57	1.54				
	110			1.57	1.89	2.01	2.01	2.01	2.01				
	90			2.10	2.91	3.03	3.06	3.10	3.10				
	70			3.26	4.08	4.21	4.21	4.24	4.24				
MP 173	150	110		2.01	1.78	1.69	1.63	1.60	1.57				
	130			1.72	1.80	1.78	1.78	1.78	1.75				
	110			1.86	2.07	2.10	2.10	2.07	2.07				

Site	Depth below surface (cm)	Organic layer (cm)	Depth to frost table at time of investigation (cm)	Ground temperatures (ºC) at one minute intervals									
				0	1	2	3	4	5	6	7	8	9
	90			2.31	2.62	2.65	2.65	2.65	2.65				
	70			3.19	M	3.68	3.71	3.71	3.75				
MP 176.1	150	30		3.91	3.91	3.84	3.78	3.78	3.75				
	130			3.91	4.21	4.21	4.21	4.21	4.21				
	110			4.28	4.62	4.65	4.69	4.69	4.69				
	90			4.75	5.10	5.13	5.13	5.13	5.13				
	70			5.34	M	4.89	4.82	4.79	4.79				
MP 176.1	145	30		5.00	4.48	4.21	4.01	3.91	3.81				
	125			3.91	4.14	4.18	4.18	4.14	3.81				
	105			4.21	4.38	4.38	4.38	4.38	4.35				
	85			4.45	4.65	4.69	4.69	4.69	4.69				
	65			4.96	5.20	5.24	5.24	5.24	5.24				
MP 178	90	> 90	90	M	M	M	M	M	0.01				
	70			0.31	M	0.45	0.45	0.45	0.45				
	50			0.86	M	1.54	1.57	1.63	1.66				
	30			1.72	3.45	M	4.75	5.10	5.27	M	5.81		
	20			6.68	6.79	6.83	6.87	6.90	6.94				
MP 178	80	> 80	80	M	M	M	M	M	-0.01				
	70			0.01	-0.01	-0.01	-0.04	-0.01	-0.01				
	60			-0.01	-0.01	-0.04	-0.04	-0.04	-0.04				
	50			0.04	0.01	-0.01	-0.01	-0.01	-0.01				
	40			0.07	0.39	0.50	0.56	0.58	0.61				
	30			0.86	2.07	2.50	2.75	2.94	3.06	3.16			
	20			3.94	4.72	5.17	5.49	5.77	5.95	6.09			
MP 182.9	145	35		3.75	M	M	M	3.84	3.84	3.84			

Site	Depth below surface (cm)	Organic layer (cm)	Depth to frost table at time of investigation (cm)	Ground temperatures (ºC) at one minute intervals									
				0	1	2	3	4	5	6	7	8	9
	125			4.45	4.31	4.28	4.24	4.21	4.21				
	105			4.48	4.51	4.48	4.45	4.45	4.45				
	85			5.10	5.00	5.00	5.00	5.00	5.00				
	65			5.06	M	5.84	5.91	5.91	5.91	5.91			
MP 182.9	155	43		6.28	6.17	6.06	5.91	5.84	5.77				
	130			5.73	5.66	5.63	5.59	5.56	5.52				
	110			5.59	5.70	5.70	5.70	5.66	5.66				
	90			5.70	5.99	6.02	6.02	6.02	6.02				
	70			6.31	6.46	6.46	6.46	6.46	6.46				
MP 187.2	150	unsure		1.43	1.43	1.43	1.43	1.43	1.43				
	130			2.22	M	2.10	2.07	2.04	2.01				
	110			2.10	2.40	2.53	2.56	2.59	2.59				
	90			2.59	M	M	M	3.06	3.10	3.10			
	70			3.10	3.39	3.55	3.68	3.75	3.78				
MP 187.2	125	25		4.28	4.08	3.98	3.91	3.84	3.81				
	110			3.98	4.04	4.04	4.04	4.01	4.01				
	90			4.14	4.28	4.28	4.28	4.28	4.28				
	70			4.51	4.75	4.75	4.75	4.75	4.72				
	50			4.93	5.17	5.17	5.17	5.17	5.17				
MP 197.9	150	86		4.11	4.11	M	3.78	3.68	3.61				
	130			3.88	4.18	4.18	4.14	4.11	4.11				
	110			4.14	4.65	M	4.69	4.69	4.69				
	90			4.89	6.13	6.24	6.28	6.28	6.28				
	70			6.98	6.13	6.13	5.99	5.91	5.88				
MP 197.9	150	unsure		3.88	3.84	3.81	3.78	3.78	3.78				

Site	Depth below surface (cm)	Organic layer (cm)	Depth to frost table at time of investigation (cm)	Ground temperatures (ºC) at one minute intervals									
				0	1	2	3	4	5	6	7	8	9
	130			3.98	4.18	4.18	4.18	4.18	4.18				
	110			4.28	4.38	4.38	4.38	4.38	4.38				
	90			4.62	4.79	4.79	4.79	4.79	4.79				
	70			5.17	5.70	5.77	5.81	5.81	5.81				
MP 199.9	145	56		4.75	4.69	4.65	4.62	4.58	4.55				
	130			4.79	4.82	4.82	4.86	4.86	4.86				
	110			4.82	5.00	5.06	5.10	5.10	5.10				
	90			5.20	5.38	5.42	5.45	5.45	5.45				
	70			5.59	5.81	5.84	5.88	5.88	5.84				
MP 204.6	140	105		1.34	1.34	1.31	1.31	1.31	1.31				
	120			1.57	1.51	1.51	1.51	1.48	1.48				
	100			1.66	1.89	2.01	2.04	2.04	2.04				
	80			2.53	2.56	2.59	2.59	2.59	2.59				
	60			3.06	3.65	3.81	3.88	3.91	3.94				
MP 204.6	150	100		1.60	1.54	1.48	1.48	1.46	1.46				
	130			1.75	1.80	1.80	1.78	1.78	1.78				
	110			2.04	2.16	2.16	2.16	2.16	2.13				
	90			2.34	2.50	2.50	2.50	2.50	2.50				
	70			2.87	3.32	3.39	3.39	3.42	3.42				
MP 207.5	150	54		4.69	4.89	4.75	M	4.65	4.62				
	130			4.62	M	5.00	5.03	5.03	5.03				
	110			5.34	5.52	5.63	5.70	5.70	5.73				
	90			5.81	6.09	6.20	6.24	6.28	6.28				
	70			6.64	6.90	6.94	6.98	6.94	6.87				
MP 207.5	150	53		5.45	5.56	5.6	5.63	5.65	5.66				

Site	Depth below surface (cm)	Organic layer (cm)	Depth to frost table at time of investigation (cm)	Ground temperatures (ºC) at one minute intervals									
				0	1	2	3	4	5	6	7	8	9
	130			5.6	5.53	5.54	5.55	5.55	5.56				
	110			5.5	5.42	5.43	5.44	5.44	5.45				
	90			5.37	5.32	5.33	5.34	5.34	5.34				
	70			5.26	5.23	5.24	5.24	5.25	5.25				
MP 208.5	47	> 47	47	M	M	M	M	M	-0.04	-0.04	-0.04		
	40			0.07	1.03	1.11	M	1.20	1.17				
	30			1.43	2.40	2.59	2.69	M	2.81				
	20			2.91	4.08	M	5.00	M	5.49	M	M	6.02	6.17
	10			6.35	7.13	7.55	7.89	8.17	8.40	8.52			
MP 208.5	58	> 58	58	M	M	M	M	M	0.25	0.25	0.25		
	50			0.56	1.46	1.51	1.51	1.51	1.51				
	40			1.69	2.44	2.59	2.65	2.69	2.69				
	30			2.94	4.04	4.51	4.72	4.86	4.96				
	20			5.70	6.35	6.68	6.94	7.13	7.28				
MP 214.1	150	> 150		5.81	M	4.18	3.98	3.88	3.84				
	130			4.41	4.69	4.72	4.72	4.72	4.72				
	110			4.79	M	5.49	5.52	5.52	5.49				
	90			5.63	6.46	6.57	6.57	6.57	6.57				
	70			6.72	7.43	7.55	7.58	7.58	7.58				
MP 214.1	140	> 155		4.28	4.14	4.01	3.94	3.88	3.84				
	120			4.04	4.24	4.28	4.28	4.24	4.24				
	100			4.41	4.79	4.86	4.86	4.86	4.86				
	80			5.24	5.77	5.88	5.91	5.91	5.91				
	60			6.46	6.83	6.94	6.98	6.98	6.98				
MP 219.6	150	50		5.24	M	5.24	5.20	5.20	5.17				

Site	Depth below surface (cm)	Organic layer (cm)	Depth to frost table at time of investigation (cm)	Ground temperatures (ºC) at one minute intervals									
				0	1	2	3	4	5	6	7	8	9
	130			5.45	5.66	5.66	5.66	5.66					
	110			5.81	M	6.13	6.13	6.13	6.13				
	90			6.31	6.50	6.50	6.50	6.50	6.50				
	70			6.75	6.90	7.05	7.05	7.05	7.05				
MP 219.6	150	50		5.63	5.49	5.45	5.42	5.42	5.38				
	130			5.66	5.84	5.84	5.84	5.84	5.84				
	110			5.99	6.24	6.28	6.28	6.28	6.28				
	90			6.46	6.64	6.68	6.68	6.68	6.68				
	70			6.79	7.09	7.13	7.13	7.13	7.13				
MP 241.3	150	77		2.87	M	2.81	2.78	2.78	2.78				
	130			3.23	M	3.35	3.32	3.32	3.29				
	110			3.39	3.75	3.78	3.81	3.81	3.84				
	90			3.91	4.45	4.55	4.58	4.62	4.62				
	70			4.89	5.49	5.56	5.59	5.63	5.63				
MP 241.3	150	102		2.78	2.62	2.56	2.50	2.50	2.47				
	130			2.62	2.81	2.81	M	2.81	2.81				
	110			3.00	3.48	3.55	3.58	3.58	3.58				
	90			3.75	4.38	4.48	4.51	4.55	4.55				
	70			4.89	5.45	5.52	5.59	5.59	5.59				
MP 274.8	160	60		3.03	2.97	2.91	2.87	2.87	2.84				
	140			3.06	3.29	3.26	3.26	3.23	3.23				
	120			3.45	3.61	3.61	3.61	3.58	3.58				
	100			3.94	4.01	3.98	3.98	3.94	3.94				
	80			4.28	4.72	4.72	4.72	4.72	4.69				
MP 274.8	140	67		3.13	2.97	2.91	2.84	2.81	2.81				

Site	Depth below surface (cm)	Organic layer (cm)	Depth to frost table at time of investigation (cm)	Ground temperatures (°C) at one minute intervals									
				0	1	2	3	4	5	6	7	8	9
	120			3.23	3.42	3.39	3.35	3.35	3.32				
	100			3.48	3.75	3.78	3.75	M	3.75				
	80			4.24	4.24	M	M	M	4.24				
	60			4.65	5.49	5.59	5.63	5.52	5.49				
MP 277.9	66	> 66	66	M	M	M	M	M	0.39				
	50			1.31	M	2.10	2.19	2.25	2.25				
	40			2.47	3.32	3.58	3.71	3.78	3.81				
	30			4.21	4.89	5.10	5.20	5.27	5.31				
	20			6.50	7.74	8.09	8.44	8.56	8.76				
	10			9.32	10.36	11.04	11.47	11.82	12.00				
MP 277.9	50	> 50	50	M	M	M	M	M	-0.01				
	40			0.47	1.31	1.43	1.51	1.54	1.57				
	30			1.80	M	3.45	M	3.91	4.01	4.21	4.28		
	20			4.65	5.77	6.28	6.57	6.75	6.87				
	10			7.70	8.84	9.53	9.94	10.27	10.53				
MP 286	64	> 64	63	M	M	M	M	M	0.34				
	50			0.86	2.31	2.69	2.81	2.91	2.94				
	40			3.10	4.18	4.65	4.93	5.10	5.20				
	30			5.34	6.50	7.02	7.32	7.55	7.70				
	20			7.93	8.72	9.12	9.40	9.61	9.77				
MP 286	100	> 100	100	M	M	M	M	M	-0.01	-0.01	-0.01		
	80			0.89	0.75	0.72	0.69	0.69	0.67				
	60			1.09	2.04	2.16	2.22	2.25	2.28				
	40			2.87	M	4.96	5.52	M	6.31	6.64	6.87	7.09	7.28
	20			7.82	9.28	10.11	10.74	11.25	M	M	12.18		

Site	Depth below surface (cm)	Organic layer (cm)	Depth to frost table at time of investigation (cm)	Ground temperatures (ºC) at one minute intervals									
				0	1	2	3	4	5	6	7	8	9
MP 295	102	> 102	102	M	M	M	M	M	-0.01				
	80			0.92	1.54	1.66	M	1.72	1.75				
	60			2.07	M	2.94	3.10	3.16	3.23				
	40			3.35	3.84	4.11	4.24	4.35	4.45				
	20			4.75	5.73	6.31	6.64	6.94	7.17				
MP 295	74	> 74	74	M	M	M	M	M	-0.04				
	60			0.15	1.17	1.63	1.86	2.07	2.10				
	50			2.44	3.35	3.65	3.78	3.88	3.91				
	40			4.28	5.03	5.45	5.66	M	5.99				
	30			6.28	7.28	7.89	8.40	8.68	8.96				
	20			9.49	10.78	11.56	12.04	12.40	12.67				
MP 341.3	52	> 52	52	M	M	M	M	M	0.20				
	40			1.17	2.25	2.47	2.53	2.56	2.59				
	30			2.87	3.71	3.94	4.08	4.14	4.18				
	20			4.35	5.42	5.66	5.84	5.99	6.09				
	10			8.09	9.77	10.61	11.13	11.47	11.73				
MP 341.3	52	> 52	52	M	M	M	M	-0.01	-0.01				
	40			0.09	0.86	0.86	0.83	0.80	0.78				
	30			0.97	1.48	1.60	1.63	1.66	1.66				
	20			1.78	2.56	3.26	3.68	3.94	4.04				
	10			4.04	6.09	6.79	7.02	6.98	6.72				
MP 359.9	145	unsure		5.81	5.73	5.66	5.59	5.59	5.56				
	130			5.81	6.02	6.02	6.02	6.02	6.02				
	110			6.68	M	6.79	6.75	6.75	6.75				
	90			6.87	7.20	7.28	7.28	7.28	7.28				
	70			7.51	M	7.74	7.78	7.78	7.78				

Site	Depth below surface (cm)	Organic layer (cm)	Depth to frost table at time of investigation (cm)	Ground temperatures (ºC) at one minute intervals									
				0	1	2	3	4	5	6	7	8	9
MP 359.9	150	18		7.09	6.72	6.53	6.42	6.35	6.31				
	130			6.50	6.75	6.79	6.79	6.75	6.75				
	110			6.98	7.36	7.36	7.32	7.32	7.32				
	90			7.55	7.85	7.85	7.82	7.82	7.82				
	70			7.93	8.09	8.13	8.13	8.13	8.13				
MP 398.4	58	> 58	58	M	M	M	M	-0.01	-0.01				
	50			0.01	0.28	0.36	0.42	0.42	0.45				
	40			0.47	1.75	1.83	M	2.04	2.04				
	30			2.16	M	3.00	3.06	3.13	M	3.16			
	20			3.26	3.94	4.21	4.35	4.45	4.48				
MP 398.4	150	73	150	M	M	M	M	0.01	0.01				
	130			0.04	M	0.15	0.09	0.09	0.09				
	110			0.23	0.39	0.39	0.39	0.39	0.39				
	90			0.45	0.56	0.58	0.58	0.56	0.56				
	70			0.64	1.37	1.60	1.69	1.75	1.80				
MP 400.5	50	> 50	50	M	M	M	M	M	M	M	M	M	-0.04
	40			0.56	0.94	1.06	1.14	1.14	1.14				
	30			1.23	M	1.89	2.04	2.07	2.07				
	20			2.16	2.72	2.87	2.91	2.97	3.00				
	10			3.06	3.52	3.65	3.78	3.84	3.91				
MP 400.5	89	> 80	80	M	M	M	M	-0.04	-0.04				
	70			0.34	0.50	0.50	0.47	0.45	0.42				
	60			0.80	1.83	2.13	2.16	2.19	2.22				
	50			2.40	3.16	3.26	3.32	3.35	3.35				
	40			3.61	4.18	4.28	4.35	4.38	4.41				

Site	Depth below surface (cm)	Organic layer (cm)	Depth to frost table at time of investigation (cm)	Ground temperatures (°C) at one minute intervals									
				0	1	2	3	4	5	6	7	8	9
	30			4.93	5.45	5.59	5.63	5.66	5.70				
MP 403.8	145	50		1.54	1.54	1.54	1.51	1.51	1.51				
	125			1.72	1.75	1.75	1.75	1.72	1.72				
	105			1.86	2.07	2.07	2.07	2.07	2.07				
	85			2.37	2.44	2.44	2.44	2.44	2.44				
	65			2.62	2.65	2.69	2.69	2.69	2.72				
MP 403.8	150	35		4.79	3.42	M	2.53	2.40	2.31				
	130			2.34	2.47	2.56	2.56	2.53	2.50				
	110			2.56	2.78	2.87	2.91	2.91	2.91				
	90			2.94	3.13	3.23	3.26	3.29	3.29				
	70			3.32	3.55	3.81	3.98	4.14	4.24				
MP 478.1	145	43		3.52	3.71	3.68	3.65	3.65	3.61				
	130			3.68	3.88	3.91	3.91	3.91	3.88				
	110			3.91	M	4.11	4.14	4.14	4.14				
	90			4.18	4.31	4.35	4.38	4.38	4.38				
	70			4.41	4.55	4.51	4.48	4.48	4.45				
MP 478.1	145	35		5.45	4.89	4.55	4.35	4.21	4.11				
	125			4.41	4.45	4.38	4.31	4.28	4.24				
	105			4.35	4.38	4.38	4.38	4.35	4.35				
	85			4.45	4.58	4.62	4.62	4.65	4.62				
	65			4.72	4.79	4.82	4.82	4.82	4.82				
MP 546.5	155	45		3.32	3.48	3.48	3.48	3.48	3.48				
	130			3.71	4.01	4.01	4.01	4.01	4.01				
	110			4.11	4.45	4.48	4.48	4.48	4.48				
	90			4.58	4.96	5.03	5.03	5.06	5.06				

Site	Depth below surface (cm)	Organic layer (cm)	Depth to frost table at time of investigation (cm)	Ground temperatures (°C) at one minute intervals									
				0	1	2	3	4	5	6	7	8	9
	70			5.10	5.66	5.81	5.91	5.99	6.02				
MP 546.5	155	30		3.91	3.68	3.58	3.55	3.52	3.48				
	130			3.65	3.91	3.91	3.91	3.91	3.91				
	110			4.04	4.24	4.28	4.28	4.28	4.28				
	90			4.38	4.51	4.55	4.55	4.58	4.58				
	70			4.69	4.79	4.86	4.86	4.89	4.89				
MP 579.1	86	30	86	M	M	M	M	M	M	M	0.31		
	70			0.34	0.45	0.53	0.53	0.56	0.56				
	60			0.58	0.75	0.78	0.83	0.86	0.86				
	50			0.92	1.14	1.28	1.37	1.46	1.48				
	30			1.57	2.75	3.42	3.88	4.18	M	4.55	4.65		
MP 579.1	150	46	unsure	0.56	0.39	0.34	0.31	0.31	0.28				
	130			0.39	0.53	0.50	0.50	0.47	0.47				
	110			0.47	0.56	0.53	0.53	0.53	0.50				
	90			0.56	0.58	0.58	0.58	0.58	0.58				
	70			0.64	0.72	0.72	0.72	0.72	0.69				
	50			0.86	1.17	1.17	1.17	1.17	1.11				
MP 587.6	150	46		2.53	2.65	2.65	2.65	2.65	2.65				
	130			2.72	2.94	2.97	2.97	2.94	2.94				
	110			2.97	M	3.32	3.32	3.32	3.29				
	90			3.42	3.68	3.71	3.75	3.75	3.75				
	70			3.78	3.81	3.88	3.88	3.88	3.88				
MP 587.6	150	40		6.17	4.89	4.45	4.14	3.94	3.81	3.68			

Site	Depth below surface (cm)	Organic layer (cm)	Depth to frost table at time of investigation (cm)	Ground temperatures (ºC) at one minute intervals									
				0	1	2	3	4	5	6	7	8	9
	130			3.71	3.84	3.84	3.84	3.84	3.81	3.78			
	110			3.78	3.84	3.84	3.84	3.84	3.84	3.81			
	90			3.94	4.01	4.01	4.01	4.01	4.01	4.01			
	70			4.04	4.14	4.21	4.24	4.24	4.24	4.24			
MP 597.5	50	> 50	50	M	M	M	M	M	M	M	0.09		
	40			0.17	0.92	1.11	1.23	1.26	1.28				
	30			1.57	1.66	1.72	1.72	1.75	1.78				
	20			2.10	3.00	3.45	3.52	3.58	3.61				
	10			3.65	4.14	4.48	4.72	4.93	5.06				
MP 597.5	60	> 75	75	0.39	0.31	0.23	0.17	0.15	0.12				
	50			0.15	0.20	0.23	0.25	0.25	0.25				
	40			0.42	0.97	1.09	1.11	1.14	1.14				
	30			1.37	2.22	2.53	2.69	2.78	2.84				
	20			3.65	4.41	4.75	4.96	5.10	5.17				
MP 627	135	20		7.93	7.32	6.87	6.61	6.39	6.20	6.09			
	90			7.58	7.36	7.17	7.05	6.98	6.90	6.87	6.83	6.79	6.75
	70			6.75	6.87	6.94	6.98	6.98	6.98				
MP 681.1	58	> 58	58	0.01	0.01	0.01	0.01	0.01	0.01				
	50			0.09	0.50	0.75	0.83	0.92	0.94				
	40			1.00	1.20	1.28	1.34	M	1.43				
	30			1.48	2.25	2.72	3.13	3.26					
	20			3.39	M	4.58	4.82	M	5.17				
	10			6.90	7.47	7.93	8.20	8.44	8.60				
MP 681.1	150	unsure		3.32	M	1.86	1.75	1.69	1.63				
	130			1.80	2.04	2.04	2.04	2.01	2.01				

Site	Depth below surface (cm)	Organic layer (cm)	Depth to frost table at time of investigation (cm)	Ground temperatures (°C) at one minute intervals									
				0	1	2	3	4	5	6	7	8	9
	110			2.07	2.37	2.40	2.40	2.40	2.40				
	90			2.44	2.97	3.03	3.06	3.10	3.10				
	70			3.39	3.84	4.01	4.08	4.11	4.14				
MP 681.1	150	unsure		3.88	3.68	3.55	3.48	3.42	3.39				
	130			3.78	3.91	3.94	3.94	3.94	3.94				
	110			4.11	4.51	4.62	4.62	4.65	4.65				
	90			4.75	5.24	5.38	5.42	5.42	5.45				
	70			5.63	6.06	6.17	6.24	6.28	6.28				
MP 731	150	> 150		5.31	5.31	5.31	5.24	5.20	5.17				
	130			5.38	5.84	5.88	5.88	5.88	5.88				
	110			6.02	6.50	6.53	6.57	6.57	6.57				
	90			6.68	7.17	7.20	7.24	7.28	7.28				
	70			7.55	8.24	8.32	8.36	8.40	8.40				
MP 731	150	> 150		5.52	5.45	5.42	5.38	5.34	5.34				
	130			5.77	6.02	6.06	6.09	6.09	6.09				
	110			6.24	6.61	6.68	6.72	6.72	6.75				
	90			6.87	7.39	7.47	7.55	7.55	7.58				
	70			7.82	8.28	8.36	8.44	8.44	8.48				
MP 762.4	100	45		5.59	5.88	5.84	5.81	5.77	5.77				
	80			5.81	6.17	6.17	6.17	6.17	6.17				
	60			6.31	M	6.64	6.64	6.64	6.64				
MP 762.4	115	57		5.95	5.52	5.38	5.31	5.24	5.20				
	95			5.31	5.56	5.56	5.56	5.56	5.52				
	75			5.49	5.88	5.91	5.95	5.95	5.95				

				Ground temperatures (ºC) at one minute intervals									
Site	Depth below surface (cm)	Organic layer (cm)	Depth to frost table at time of investigation (cm)	0	1	2	3	4	5	6	7	8	9
MP 771.6	90	25		5.99	6.50	5.66	5.63	5.59	5.56				
	70			5.63	5.77	5.81	5.77	5.77	5.77				
MP 774	132	21		4.48	4.38	4.31	4.28	4.28	4.24				
	110			4.41	4.58	4.58	4.58	4.58	4.58				
	90			4.82	4.89	4.89	4.89	4.89	4.89				
	70			5.00	5.10	5.10	5.10	5.10	5.10				
MP 788.5	110	unsure	91	-0.04	-0.04	-0.04	-0.04	-0.04	-0.04				
	90			0.20	0.36	M	0.39	0.39	0.39				
	70			0.58	M	1.48	1.48	1.48	1.48				
	50			2.10	2.65	2.72	2.75	2.78	2.78				
	30			3.91	4.58	4.86	5.03	5.13	5.38				
MP 788.5	40	unsure	40	0.07	0.07	0.07	0.07	0.07	0.07				
	30			0.15	1.11	1.51	1.34	1.17	0.92				
	20			1.00	2.40	3.00	3.13	3.03	2.84				
	10			4.48	6.90	8.13	8.76	9.08	9.24				
MP 788.5	130	unsure		4.48	4.04	3.98	3.94						
	110			5.45	4.93	4.86	4.82						
	90			6.31	5.91	5.84	5.81						
	70			7.74	7.05	6.94	6.90						
	50			8.80	8.17	8.09	8.01	8.01					
	30			10.02	9.65	9.57	9.53	9.53					
MP 794.8	150	40		3.42	2.65	2.44	2.34	2.28	2.25				
	130			2.50	2.87	2.91	2.87	2.84	2.84				
	110			2.97	3.26	3.29	3.32	3.29	3.29	3.78			
	90			3.78	3.94	3.98	3.98	3.98	3.98				

Site	Depth below surface (cm)	Organic layer (cm)	Depth to frost table at time of investigation (cm)	Ground temperatures (°C) at one minute intervals									
				0	1	2	3	4	5	6	7	8	9
	70			4.45	4.65	4.65	4.65	4.65	4.65				
MP 794.8	148	38		1.89	1.83	1.83	1.80	M	1.78				
	128			2.19	2.22	2.22	2.22	2.22	2.22				
	108			2.53	2.78	2.78	2.78	2.78	2.78				
	88			3.03	3.29	3.29	3.32	3.32	3.32				
	68			3.48	3.75	3.81	3.84	3.84	3.84				
MP 803.3	72	> 72	72	0.78	0.31	0.20	0.15	0.09	0.09				
	52			0.58	1.14	1.20	1.17	1.14	1.11				
	32			2.34	2.91	3.16	3.26	3.32	3.29				
MP 803.3	130	> 52	52	1.00	0.34	0.09	0.01	-0.01	-0.04	-0.04			
	120			1.48	0.25	0.01	-0.04	-0.07	-0.07				
	85			-0.04	-0.04	-0.04	-0.04	-0.04	-0.04	-0.04			
	65			-0.01	0.04	0.07	0.04	0.04	0.04				
	45			0.20	0.39	0.50	0.58	0.64	0.67				
	25			9.03	8.13	7.87	7.72	7.69	7.65				
MP 807.3	83	43	83	M	M	M	M	M	M	M	M	M	0.12
	60			0.25	0.47	0.50	0.50	0.50	0.50				
	40			0.64	0.94	1.00	1.00	1.03	1.03				
	20			1.66	2.31	2.72	2.72	2.84	2.97				
MP 807.3	150	unsure		0.83	0.42	0.28	0.23	0.20	0.17				
	130			0.23	0.23	0.23	0.20	0.20	0.20				
	110			0.23	0.23	0.23	0.23	0.23	0.23				
	90			0.28	0.34	0.34	0.34	0.34	0.34				
	70			0.86	0.97	1.00	1.00	1.00	1.00				
MP 814	150	37		5.38	4.65	4.51	4.41	4.41	4.38				

Site	Depth below surface (cm)	Organic layer (cm)	Depth to frost table at time of investigation (cm)	Ground temperatures (ºC) at one minute intervals									
				0	1	2	3	4	5	6	7	8	9
	130			4.38	4.62	4.65	4.65	4.65	4.65				
	110			4.65	4.82	4.86	4.86	4.89	4.89				
	90			4.89	5.10	5.13	5.17	5.17	5.17				
	70			5.20	5.38	5.45	5.45	5.49	5.49				
MP 814	150	37		4.24	4.14	4.08	4.01	4.01	3.98				
	130			4.14	4.24	4.24	4.21	4.21	4.21				
	110			4.31	4.38	4.38	4.38	4.38	4.38				
	90			4.41	4.58	4.62	4.65	4.65	4.65				
	70			4.69	4.79	4.82	4.82	4.82	4.82				
MP 819.1	150	50		1.80	1.43	1.26	1.20	1.14	1.11				
	130			1.23	1.31	1.31	1.28	1.28	1.26				
	110			1.37	1.37	1.37	1.37	1.34	1.34				
	90			1.40	1.48	1.48	1.46	1.40	1.31				
	70			1.34	1.31	1.63	1.92	1.83	1.86	1.86			
MP 819.1	150	63		3.94	3.48	3.19	3.10	3.03	M				
	130			3.35	3.42	3.42	3.39	3.35	3.35				
	110			3.68	3.68	3.68	3.68	3.65	3.65				
	90			3.88	3.98	3.98	3.98	3.98	3.98				
	70			4.18	4.31	4.51	4.58	4.62	4.62				
MP 828.8	150	25		2.84	2.25	2.01	1.83	1.75	1.69				
	130			2.01	2.34	2.37	2.37	2.37	2.37				
	110			2.62	2.78	2.81	2.81	2.81	2.81				
	90			3.16	3.42	3.45	3.48	3.48	3.48				
	70			3.68	3.98	4.11	4.14	4.18	4.18				

Site	Depth below surface (cm)	Organic layer (cm)	Depth to frost table at time of investigation (cm)	Ground temperatures (°C) at one minute intervals									
				0	1	2	3	4	5	6	7	8	9
MP 828.8	150	25		3.39	2.69	2.37	M	2.19	2.13	2.10			
	130			2.37	2.56	2.56	M	2.50	2.50	2.47			
	110			3.03	3.03	3.00	3.00	3.00	2.97				
	90			3.13	3.48	3.61	3.65	3.65	3.65				
	70			3.98	4.18	4.21	4.24	4.24	4.28				
MP 834	150	17		2.72	2.47	2.25	2.13	2.04	1.98				
	130			2.04	M	2.40	2.44	2.44	2.44				
	110			2.56	2.84	3.00	3.06	3.06	3.10				
	90			3.19	3.35	3.42	3.42	3.42	3.42				
	70			3.52	4.01	4.11	4.18	4.18	4.18				
MP 834	150	9		5.49	4.89	4.58	4.38	4.28	4.18	4.11			
	130			4.31	4.41	4.41	4.45	4.41	4.41				
	110			4.55	4.82	4.89	4.93	4.96	4.96				
	90			5.17	5.38	5.49	5.52	5.56	5.56				
	70			5.63	5.84	5.95	5.99	6.02	6.06				
MP 882	150	25		2.01	M	1.37	1.28	1.23	1.20				
	130			1.34	1.34	1.34	1.34	1.31	1.31				
	110			1.66	1.69	M	1.69	1.69	1.69				
	90			1.80	2.16	2.16	2.19	2.19	2.19				
	70			2.37	2.59	2.62	2.65	2.65	2.65				
MP 886.5	145	18		3.65	3.55	3.45	3.42	3.39	3.35				
	130			3.75	3.81	3.78	3.78	3.78	3.78				
	110			3.88	M	4.28	4.31	4.31	4.31				
	90			4.35	4.72	4.72	4.75	4.79	4.79				
	70			4.89	4.93	4.93	4.93	4.93	4.93				

Site	Depth below surface (cm)	Organic layer (cm)	Depth to frost table at time of investigation (cm)	Ground temperatures (ºC) at one minute intervals									
				0	1	2	3	4	5	6	7	8	9
MP 886.5	150	22		4.62	4.38	4.14	4.04	3.94	3.91				
	130			4.08	4.24	4.24	4.24	4.21	4.18				
	110			4.38	4.62	4.65	4.62	4.62	4.62				
	90			4.72	5.00	5.06	5.06	5.06	5.06				
	70			5.20	5.56	5.59	5.63	5.59	5.59				
MP 891.5	150	58		0.39	0.45	0.42	0.39	0.39	0.39	M	0.34		
	130			0.80	0.45	0.42	0.36	0.34	0.34				
	110			0.39	0.39	0.36	0.36	0.36	0.36				
	90			0.39	0.42	0.42	0.42	0.42	0.42				
	70			0.47	0.58	0.58	0.61	0.61	0.61				
MP 891.5	150	62		1.60	1.51	1.46	1.43	1.37	1.34				
	130			1.75	1.57	1.51	1.46	1.46	1.43				
	110			1.72	2.04	2.07	2.07	2.07	2.07				
	90			2.50	2.62	2.65	2.69	2.69	2.69				
	70			2.87	3.06	3.10	3.10	3.10					

Appendix C: Site Locations and Dates of Investigation

	UTM Coordinates			Dates of investigation (m/dd/yy)	
Site name	Zone	Easting	Northing	Dates of investigation 2007	Dates of investigation 2008
MP 90.1	10 V	585763	6277733	8/19/07	not visited
MP 128.1	10 V	549137	6315792	8/20/07	8/16/08
MP 134.3	10 V	540304	6317765	8/20/07	8/16/08
MP 151.4	10 V	519124	6330186	8/21/07	8/17/08
MP 153	10 V	518657	6332901	8/19/07	8/16/08
MP 153.8	10 V	518484	6334058	8/21/07	8/17/08
MP 154.7	10 V	518240	6335694	8/19/07	not visited
MP 169.2	10 V	513317	6352602	8/21/07	8/17/08
MP 170.4	10 V	512654	6354076	8/21/07	8/17/08
MP 173	10 V	510445	6356698	8/19/07	8/18/08
MP 176.1	10 V	508906	6361892	8/21/07	8/17/08
MP 178	10 V	508054	6364769	8/17/07	8/15/2008, 8/18/2008
MP 182.9	10 V	506004	6371321	8/22/07	not visited
MP 187.2	10 V	504564	6378884	8/18/07	8/19/08
MP 197.9	10 V	501125	6394828	8/18/07	not visited
MP 199.9	10 V	502570	6397764	8/18/07	8/15/08
MP 204.6	10 V	506617	6403108	8/18/07	8/15/08
MP 207.5	10 V	505716	6407343	8/22/07	not visited
MP 208.5	10 V	505261	6407896	8/17/07	8/14/2008, 8/19/2008
MP 214.1	10 V	508889	6413458	8/16/07	8/14/08
MP 219.6	10 V	510187	6421557	8/16/07	not visited
MP 241.3	10 V	513144	6448902	8/16/07	8/14/08
MP 274.8	10 V	518583	6488396	8/15/07	not visited
MP 277.9	10 V	519520	6492726	8/15/07	8/13/08
MP 286	10 V	517789	6502605	8/15/07	8/12/08
MP 295	10 V	519024	6513814	8/14/07	8/12/08
MP 341.3	10 V	466762	6516720	8/14/07	8/21/08
MP 359.9	10 V	446431	6503454	8/23/07	8/21/08
MP 398.4	10 V	394452	6505984	8/13/07	8/11/08
MP 400.5	10 V	392325	6507177	8/13/07	8/11/08
MP 403.8	10 V	389012	6511194	8/12/07	8/11/08
MP 478.1	10 V	330031	6569160	8/24/07	not visited
MP 546.5	09 V	599571	6619922	8/24/07	8/22/08
MP 579.1	09 V	581978	6648353	8/12/07	8/10/08
MP 587.6	09 V	571307	6651856	8/25/07	8/10/08
MP 597.5	09 V	558329	6651396	8/11/07	8/10/08
MP 627	09 V	525188	6651846	8/26/07	8/9/08
MP 681.1	09 V	450151	6672771	8/11/07	8/9/08
MP 731	09 V	380559	6655188	8/26/07	8/23/08
MP 762.4	09 V	340904	6646276	8/27/07	8/9/08
MP 771.6	08 V	663195	6650998	8/27/07	8/9/2008, 08/24/08
MP 774	08 V	661131	6653111	8/27/07	8/8/2008, 08/24/08

	UTM Coordinates			Dates of investigation (m/dd/yy)	
Site name	Zone	Easting	Northing	Dates of investigation 2007	Dates of investigation 2008
MP 788.5	08 V	646362	6664453	8/10/07	8/8/08
MP 794.8	08 V	639181	6666596	8/10/07	8/7/08
MP 803.3	08 V	627597	6671450	8/10/07	8/6/08
MP 807.3	08 V	622385	6674164	8/10/07	8/6/08
MP 814	08 V	615147	6680583	8/27/07	8/26/08
MP 819.1	08 V	610301	6687140	8/10/07	not visited
MP 825.2	08 V	604319	6694120	8/9/07	8/26/08
MP 828.8	08 V	600647	6698087	8/9/07	8/26/08
MP 834	08 V	595515	6704802	8/28/07	8/5/2008, 08/26/08
MP 844.1	08 V	583330	6705438	8/8/07	8/26/08
MP 882	08 V	539286	6705701	8/8/07	8/4/08
MP 886.5	08 V	533170	6711853	8/28/07	8/27/08
MP 891.5	08 V	526041	6714063	8/29/07	8/4/2008, 08/27/08

Appendix D: Permafrost Conditions

Site name	Permafrost encountered (to 2 m)	Permafrost Predicted (to 2 m)	Permafrost class. with respect to Brown's results	Avg. Thaw Depth 2007 (cm)	n for Avg. Thaw Depth 2007	SD for Avg. Thaw Depth 2007 (cm)	Avg. Thaw Depth 2008 (cm)	n for Avg. Thaw Depth 2008	SD for Avg. Thaw Depth 2008 (cm)
MP 90.1		N	N						
MP 128.1		N	N						
MP 134.3		N	N						
MP 151.4		N	N						
MP 153	N	I	N						
MP 153.8		N	N						
MP 154.7		N	C						
MP 169.2		N	N						
MP 170.4		N	N						
MP 173	N	I	C						
MP 176.1		N	N						
MP 178	Y		Y	69.8	9	19.8	66.2	13	24.5
MP 182.9		N	N						
MP 187.2	I	I	C						
MP 197.9		N	C						
MP 199.9	N*	I	C						
MP 204.6	N	I	C						
MP 207.5		N	N						
MP 208.5	Y		Y	47.5	10	5.4	46.8	8	5.4
MP 214.1	N	I	C						
MP 219.6		N	C						
MP 241.3	N	I	C						
MP 274.8		N	C						
MP 277.9	Y		Y	55.6	10	7.5	52.2	10	4.4
MP 286	Y		Y	59.2	10	16.7	78.8	14	26.7
MP 295	Y		Y	77.4	10	23.6	93.6	9	23.4
MP 341.3	Y		Y	5.6	9	5.6	74.2	5	26
MP 359.9		N	N						

Site name	Permafrost encountered (to 2 m)	Permafrost Predicted (to 2 m)	Permafrost class. with respect to Brown's results	Avg. Thaw Depth 2007 (cm)	n for Avg. Thaw Depth 2007	SD for Avg. Thaw Depth 2007 (cm)	Avg. Thaw Depth 2008 (cm)	n for Avg. Thaw Depth 2008	SD for Avg. Thaw Depth 2008 (cm)
MP 398.4	Y		Y	84	9	26.5	74.3	10	10.1
MP 400.5	Y		Y	55.6	10	12.4	78.8	15	24
MP 403.8	N	I	C						
MP 478.1		N	N						
MP 546.5		N	N						
MP 579.1	Y		Y	77.4	8	12.3	56	3	6.2
MP 587.6	N*	I	N						
MP 597.5	Y		Y	54.9	9.5	9.5	51.4	20	8.9
MP 627	N	I	N						
MP 681.1	Y		Y	52.1	9	7.8	45.3	9	9.1
MP 731		N	N						
MP 762.4	N	I	N						
MP 771.6	N*	I	N						
MP 774	N*	I	N						
MP 788.5	Y		Y	80.7	10	32.5	71.3	4	32
MP 794.8	N*	I	C						
MP 803.3	Y		Y	52.9	8	11.6	44.6	10	6.6
MP 807.3	Y		Y	62.3	10	11.9	52.9	10	7.7
MP 814		N	N						
MP 819.1	N	N	C						
MP 825.2	Y		Y	63.1	9	20.1	67.2	6	28.7
MP 828.8	N	N	C						
MP 834	N	I	N						
MP 844.1	Y		Y	54.3	3	18.3	66	5	8.5
MP 882	N	N	C						
MP 886.5	N	I	N						
MP 891.5	N*	I	N						

Appendix E: Relief, Organic Layer, Vegetation and Surface Terrain Features

		Organic layer			**Tree types**				**Max. tree height (m)**		**Surface terrain features**							
Site Name	**Relief**	Median organic layer thickness (cm)	Range of organic layer thicknesses (cm)	n for organic layer thickness	1	2	3	4	1	2	1	2	3	4	5	6	7	8
MP 90.1	L	15	10 to 20	5	S	J			9		M	Lt	G					
MP 128.1	L	22.5	10 to 30	10	S	W			4.5	1	H	M	Ln	G	B			
MP 134.3	L	36.5	20 to 62	10	S	J			9		H	M	Sph	Lt	Ln	Ht		
MP 151.4	L	47	25 to 70	10	S	W			6	1	H	M	Sph	Lt	Ln	G		
MP 153	L	48.5	20 to 67	10	S	W			4.5	1	H	M	Sph	B	G	Se	Ln	Lt
MP 153.8	L	31	17 to 50	10	S	W			6	1	B	H	M	G	Se	Ln	Lt	
MP 154.7	L	50	43 to 57	5	S				9		H	M	Lt	Ln	G	B		
MP 169.2	L	28.5	13 to 59	10	S	J	P		6		H	M	Lt	Ln	G			
MP 170.4	S_n	24	18 to 39	10	S	J			12		H	M	Ln	Lt	G			
MP 173	L	85	50 to 110	10	S				6		H	M	Lt	Ln	B	G		
MP 176.1	S_n	30	20 to 64	10	S				6		H	M	Lt	G	Ht	B		
MP 178	L		> 35 to > 135	30	S				9		H	M	Lt	Ln				
MP 182.9	L	40	35 to 45	5	S	W			9	1.5	H	M	Lt	Ln	B	G		
MP 187.2	L	40.5	25 to 97	10	S				7.5		H	Sph	M	Lt	Ln	Ht	B	
MP 197.9	L	86	62 to 89	5	S				7.5		M	Sph	Lt	Ln	G	Se		
MP 199.9	S_n	34	26 to 70	10	S	W			12		H	Lt	M	Ht	Ln			
MP 204.6	L	101	71 to 112	10	S				6		H	M	Sph	Lt	Ln	G	Se	Ht
MP 207.5	L	53	26 to 57	5	S	T			6		H	M	Lt	Ln				
MP 208.5	L		> 40 to 82	30	S				3		H	M	Sph	Lt	Ln			
MP 214.1	L		> 135 to > 155	10	S	P			6		H	M	Sph	Lt				
MP 219.6	L	55	50 to 60	5	S	J	P		9		H	M	Sph	Lt				
MP 241.3	L	120	77 to 130	10	S				4.5		H	M	Sph	Ln	Lt			
MP 274.8	L	53	48 to 74	5	S	W			7.5	0.7	H	M	Sph	Lt	Ln			
MP 277.9	L		>46 to > 67	20	S				3.5		H	M	Sph	Lt	Ln			
MP 286	L		> 47 to 114	20	S	T			7.5		(p)	H	M	Sph	Lt	Ln		
MP 295	L	50	35 to 94	10	S	A	T	P	7.5		H	M	Lt	Ln				
MP 341.3	L		> 42 to 82	20	S	T			4.5		H	M	Ln	Sph	Lt	B		
MP 359.9	S_w	27	15 to 38	10	S	P			12		M	Lt	Ln	Ht				

Site Name	Relief	Organic layer Median organic layer thickness (cm)	Range of organic layer thicknesses (cm)	n for organic layer thickness	Tree types 1	2	3	4	Max. tree height (m) 1	2	Surface terrain features 1	2	3	4	5	6	7	8
MP 398.4	S_s	46	34 to > 98	20	S	W			9		H	M	Lt	Ln	G			
MP 400.5	L		36 to > 109	30	S	W			6	0.7	(p)	H	M	G	Ln	Lt	Se	B
MP 403.8	L	32.5	15 to 50	10	S	W			12	0.7	(p)	H	M	Ht				
MP 478.1	S_n	37	35 to 46	5	S				12		H	M	Lt	Ht				
MP 546.5	L	37	28 to 52	10	S	T	W	A	15		H	M	Ln	Lt				
MP 579.1	L	46	30 to 125	20	S				12		H	M	Lt	Sph	Ln			
MP 587.6	L	43	28 to 56	9	S	W			12	1	H	M	Lt	Ln	Ht			
MP 597.5	L		39 to > 75	30	S	T			13.5		(p)	Ln	Lt	Sph	M			
MP 627	S_{sw}	29.5	20 to 37	10	S	W			18	2	M	Lt	Ln	Ht				
MP 681.1	L	24	12 to 31	10	S	T	W		15		H	M	Sph	Ln	Lt	B		
MP 731	L	> 150	> 150 to > 150	5	S				12		M	Sph	G	Se	B			
MP 762.4	L	45	30 to 57	5	S						H	M	Sph	Lt	G	Se		
MP 771.6	L	22	15 to 36	20	S	J			15		H	M	Ln	Lt				
MP 774	L	20	9 to 44	14	S	J	W		12		H	M	Ln	Lt				
MP 788.5	L	67	32 to > 132	9	S				12		(p)	H	M	Sph	Ln	Lt		
MP 794.8	L	30	21 to 47	10	S				15		M	Ln	G					
MP 803.3	L	22.5	15 to 38	10	S	W			12		M	Ln	Lt	G	Ht			
MP 807.3	L	29.5	17 to 47	20	S				15		H	M	Lt	Ht				
MP 814	S_s	33.5	19 to 55	10	S	W			9		H	M	Lt	Ln				
MP 819.1	L	49	40 to 63	5	S				15		M	Lt	Ln					
MP 825.2	L	33	18 to 56	20	S				15		H	M	Ln	Lt				
MP 828.8	S	31	26 to 47	6	S	W	A		9	2	Lt	M						
MP 834	L	15	9 to 25	7	S	J			15		M	Ln	Lt					
MP 844.1	L	34	21 to > 100	8	S	W			9	2	M	Lt						
MP 882	S	25	25 to 25	1	S				12		H	M						
MP 886.5	L	17.5	5 to 26	10	S	As			15		H	M	Lt	Ln				
MP 891.5	L	53.5	20 to 63	10	S	W			12		H	M	G	Se	Lt			

Appendix F: Soil Conditions

Note: Some sites have more than one soil sample, as samples at multiple depths were collected where the depth to frost table, water table, or stony layer permitted.

Site name	Soil Field Description	Sample depths (cm below ground surface)	Soil moisture (%)	Organic content (%)	Mineral soil description (lab)	Gravel (%)	Sand (%)	Silt (%)	Clay (%)	Mean particle size (phi)	Kurtosis (phi)	SD (phi)	Skewness (phi)
MP 90.1	Silt and sand. Very dense, quite dry, and not very cohesive. Gravelly layer at approximately 15 cm depth.												
MP 128.1		10-20	50%	21%									
MP 128.1		40-50	20%	6%	clayey SILT, some sand, trace gravel	1%	11%	57%	31%	6.76	1.02	2.34	-0.08
MP 134.3	Mineral soil a dark silt with organics to 45cm depth, then there is a layer of gravel, and then clay.	20-30	64%	32%									
MP 134.3		40-50	41.1%	14%	silty sand, some gravel and clay	14%	41%	34%	11%	3.24	0.91	3.74	0.08
MP 151.4	Heavily organic silty clay turning into highly cohesive clay at approximately 45	28-38	64%	45%									

Site name	Soil Field Description	Sample depths (cm below ground surface)	Soil moisture (%)	Organic content (%)	Mineral soil description (lab)	Gravel (%)	Sand (%)	Silt (%)	Clay (%)	Mean particle size (phi)	Kurtosis (phi)	SD (phi)	Skewness (phi)
	cm.												
MP 151.4		50-60	21%	7%	clayey SILT, some sand	0%	14%	51%	35%	6.82	1.06	2.57	-0.19
MP 153	Silty, moderately cohesive clay that is wet at depth.	20-30	66%	32%									
MP 153		45-55	50%	21%	sandy, clayey silt	0%	25%	52%	22%	6.02	1.04	2.96	0.31
MP 153		70-80	55.3%	27%									
MP 153.8	Loamy clay with more silt at lesser depths. Highly cohesive clay with some gravel at depth.	17-27	53%	27%	sandy SILT, some clay	0%	20%	61%	19%	5.87	0.93	2.28	0.1
MP 153.8		50-60	27%	11%	clayey SILT, some sand, trace gravel	1%	15%	59%	25%	6.35	0.97	2.35	-0.02
MP 154.7	moderately cohesive silty clay. Hit gravel at 1.25 m depth.												
MP 169.2	Slightly cohesive sandy clay.	17-27	31%	11%	silt and sand, some clay, trace gravel	1%	39%	49%	11%	4.64	1.07	2.47	0.12

Site name	Soil Field Description	Sample depths (cm below ground surface)	Soil moisture (%)	Organic content (%)	Mineral soil description (lab)	Gravel (%)	Sand (%)	Silt (%)	Clay (%)	Mean particle size (phi)	Kurtosis (phi)	SD (phi)	Skewness (phi)
MP 169.2		50-60	18%	5%	clayey silt, some sand, trace gravel	4%	10%	49%	37%	6.96	1.4	2.95	-0.27
MP 170.4	Highly cohesive clay with a gravel layer at approximately 30 cm.	20-30	20%	5%	clayey SILT, some sand, trace gravel	2%	16%	53%	29%	6.41	1	2.6	-0.2
MP 170.4		50-60	18%	5%	SILT and clay, some sand, trace gravel	7%	14%	50%	30%	6.27	1.29	3.3	-0.26
MP 173	moderately cohesive silty clay underlain by highly cohesive light brown clay.	70-75	27.4%	10%	sandy SILT, some clay	0%	20%	61%	18%	5.8	0.96	2.27	0.11
MP 176.1	Silty and organic with some clay and gravel.	20-30	83%	78%									
MP 176.1		40-50	67%	49%									
MP 178		34-44	79%	88%									
MP 182.9	Very wet silty clay with gravel layers.												
MP 187.2	Wet, silty clay. Very gradual transition from organic to mineral. Gravel layer.												
MP 197.9	Silty clay.												

Site name	Soil Field Description	Sample depths (cm below ground surface)	Soil moisture (%)	Organic content (%)	Mineral soil description (lab)	Gravel (%)	Sand (%)	Silt (%)	Clay (%)	Mean particle size (phi)	Kurtosis (phi)	SD (phi)	Skewness (phi)
MP 199.9	Highly cohesive and dense silty clay. Very difficult to probe through. Brown silty layer with lots of roots after living organic.	30-40	17%	4%	SILT and clay, some sand, trace gravel	3%	18%	58%	22%	5.95	1.09	2.68	-0.16
MP 199.9		60-70	19%	5%	clayey SILT, trace sand and gravel	1%	9%	55%	35%	7.07	1.13	2.38	-0.11
MP 204.6	Highly cohesive brown clay with small gravel, and small silty layer between organic and clay layers.	70-80	32%	11%	clayey SILT, trace sand and gravel	1%	5%	65%	29%	7.05	1.25	1.94	-0.06
MP 207.5	Wet, moderately cohesive silty clay.												
MP 208.5	Did not get past organic.												
MP 214.1	Did not get past organic.												
MP 219.6	Gradual transition from organic to mineral. Mineral soil slightly cohesive silt and clay.												

Site name	Soil Field Description	Sample depths (cm below ground surface)	Soil moisture (%)	Organic content (%)	Mineral soil description (lab)	Gravel (%)	Sand (%)	Silt (%)	Clay (%)	Mean particle size (phi)	Kurtosis (phi)	SD (phi)	Skewness (phi)
MP 241.3	Very gradual transition between organic and mineral. Mineral soil a silty clay. Water table reached at 55 cm depth.												
MP 274.8	Highly cohesive clay with a small amount of silt and fine sand												
MP 277.9	Below organic layer is silt with high organic content												
MP 286													
MP 295		unknown	41%	8%	SAND, trace silt	0%	94%	5%	0%	1.96	1.28	1.04	0.1
MP 341.3	Seems to be all organic to the frost table												
MP 359.9	Wet silty clay with gravelly layers	15-25	44%	19%	clayey, sandy SILT	0%	24%	50%	26%	6.01	0.88	2.74	0
MP 359.9		40-50	37%	12%	sandy silt, some clay, trace gravel	8%	29%	43%	21%	5.29	1.04	3.5	-0.14
MP 398.4	Slightly cohesive. Mostly silt with some fine sand and gravel.	46-56	68%	63%									
MP 398.4		62-72	35%	14%									

Site name	Soil Field Description	Sample depths (cm below ground surface)	Soil moisture (%)	Organic content (%)	Mineral soil description (lab)	Gravel (%)	Sand (%)	Silt (%)	Clay (%)	Mean particle size (phi)	Kurtosis (phi)	SD (phi)	Skewness (phi)
MP 400.5	Peaty. Highly cohesive clay reached at 1.13 m in one probe												
MP 403.8	Peaty	15-25	38%	12%									
MP 403.8		45-55	40%	15%									
MP 403.8		85-95	25%	6%									
MP 478.1	Moderately cohesive silty clay with scattered stones.												
MP 546.5	Silty soil high in organics. Gradual transition from organic to mineral soil.	45-55	70%	43%									
MP 546.5		60-70	39%	20%									
MP 579.1	Peaty, but not with a really thick organic mat. Sandy silt with many scattered stones. Moderately cohesive.												
MP 587.6	Organic-heavy silt; at depth there is highly cohesive clay	30-40	11%	2%	silty SAND, trace clay	0%	66%	31%	2%	3.53	1.07	1.71	0.47
MP 587.6		60-70	18%	2%	SAND and silt, trace clay	0%	62%	37%	1%	3.79	1.11	1.24	0.21

Site name	Soil Field Description	Sample depths (cm below ground surface)	Soil moisture (%)	Organic content (%)	Mineral soil description (lab)	Gravel (%)	Sand (%)	Silt (%)	Clay (%)	Mean particle size (phi)	Kurtosis (phi)	SD (phi)	Skewness (phi)
MP 587.6		100-110	19%	2%	SILT and SAND	0%	48%	52%	0%	4.06	1.1	1	0.03
MP 597.5	organic with coarse sand, more sand and silt with depth (but still mostly organic) and scattered stones												
MP 627	Sandy. After 125 cm, sandy clay followed by alternating layers of sand and clay. Possibly alternating lakebed vs. shoreline?	28-48	24%	5%									
MP 627		58-78	17%	3%	SAND, some silt, trace clay	0%	81%	17%	2%	2.37	1.21	1.94	0.44
MP 627		125-145	14%	1%	SAND, some silt	0%	82%	18%	0%	2.76	1.04	1.36	0.27
MP 681.1	wet, moderately cohesive, silty, organic-rich	19-39	80%	81%									
MP 681.1		40-60	75%	81%									
MP 731	Very wet; a lot of standing water.												
MP 762.4	Many scattered stones and very wet (standing water).												

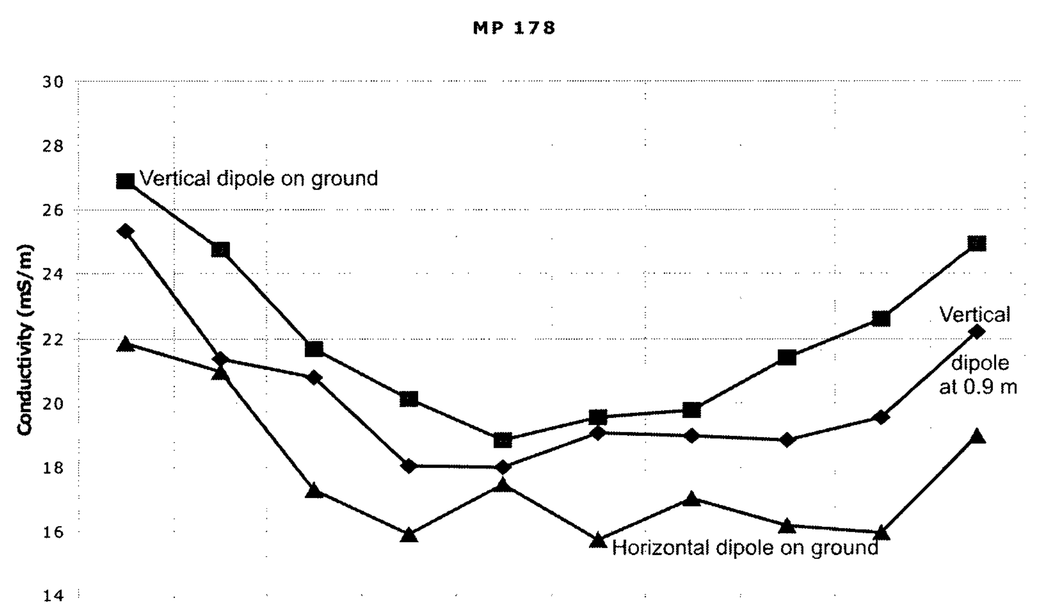
Site name	Soil Field Description	Sample depths (cm below ground surface)	Soil moisture (%)	Organic content (%)	Mineral soil description (lab)	Gravel (%)	Sand (%)	Silt (%)	Clay (%)	Mean particle size (phi)	Kurtosis (phi)	SD (phi)	Skewness (phi)
MP 771.6	Sand with silt and gravel. Slightly cohesive.	22-32	10%	4%	gravelly, silty sand trace clay	28%	42%	25%	5%	1.81	0.69	3.74	0.23
MP 774	Silty, gravelly sand with scattered stones.	15-25	15%	4%	silty sand, some gravel, trace clay	19%	45%	32%	3%	2.31	0.8	3.45	-0.01
MP 774		45-55	9%	1%	silty, gravelly sand, trace clay	21%	41%	33%	5%	2.48	0.72	3.47	0.03
MP 788.5		67-79	77%	80%									
MP 788.5		95-115	85%	86%									
MP 794.8	clay with some silt and fine sand	30-50	26%	10%	clayey sand and silt	0%	35%	44%	21%	5.44	0.74	2.7	0.11
MP 794.8		50-70	19%	4%	silty SAND, some clay	0%	51%	35%	15%	4.74	0.78	2.48	0.45
MP 794.8		70-90	22%	4%	clayey SILT, some sand	0%	16%	57%	26%	6.49	0.98	2.37	-0.19
MP 803.3	peaty, deep organic layer	27-47	71%	82%									
MP 807.3	gravelly sand at depth	30-50	31%	11%	SAND, some gravel, trace silt and clay	13%	75%	10%	3%	1.13	1.68	2.24	0.09
MP 814		20-30	13%	4%	silty SAND, some gravel, trace clay	17%	52%	26%	4%	2.32	0.94	3.35	0.03

Site name	Soil Field Description	Sample depths (cm below ground surface)	Soil moisture (%)	Organic content (%)	Mineral soil description (lab)	Gravel (%)	Sand (%)	Silt (%)	Clay (%)	Mean particle size (phi)	Kurtosis (phi)	SD (phi)	Skewness (phi)
MP 814		50-60	12%	2%	sandy SILT, some clay, some gravel	11%	20%	55%	14%	4.82	0.97	3.52	-0.44
MP 819.1	very wet silty sands and sandy silts with clay. Gravelly layers.												
MP 825.2	cohesive silt with sand and scattered stones	25-35	46%	23%									
MP 825.2		60-70	21%	5%	silty SAND, some clay, trace gravel	3%	52%	33%	12%	4.22	0.85	2.8	0.33
MP 828.8	gravelly	27-37	11%	3%	sandy, gravelly silt, trace clay	26%	33%	35%	6%	2.41	0.65	3.84	-0.04
MP 828.8		70-80	16%	2%	SILT, some clay, trace sand, trace gravel	1%	10%	74%	14%	6.26	1.31	1.86	-0.1
MP 834	Slightly cohesive silt, with some fine sand in the upper layers.	17-27	22%	3%	SILT, trace sand and clay	0%	9%	86%	5%	5.66	1.15	1.32	0
MP 834		50-60	17%	2%	SILT, some clay, trace sand	0%	4%	82%	14%	6.61	1.13	1.37	0.02
MP 844.1	silty soil with rocks and gravel	21-31	58%	40%									
MP 844.1		35-45	61%	65%									
MP 882	light grey sandy silt. Wet at depth.												

Site name	Soil Field Description	Sample depths (cm below ground surface)	Soil moisture (%)	Organic content (%)	Mineral soil description (lab)	Gravel (%)	Sand (%)	Silt (%)	Clay (%)	Mean particle size (phi)	Kurtosis (phi)	SD (phi)	Skewness (phi)
MP 886.5	Clayey silt with some sand, moderately cohesive. Quite wet in 2007, but dry in 2008.	5-15	14%	6%	SAND, some gravel, trace silt and clay	14%	74%	6%	6%	1	2.51	2.5	0.17
MP 886.5		60-70	19%	5%	CLAY, some silt and sand	0%	11%	17%	72%	8.3	1.22	2.69	-0.49
MP 891.5	Very wet (some standing water), mineral soil is clayey silt that becomes highly cohesive with depth (and becomes clay) (wetter and looser above). Some gravel layers, including a hard one consistently at 75 cm depth. Gravel layer separates the silt and clay	20-30	84%	63%									

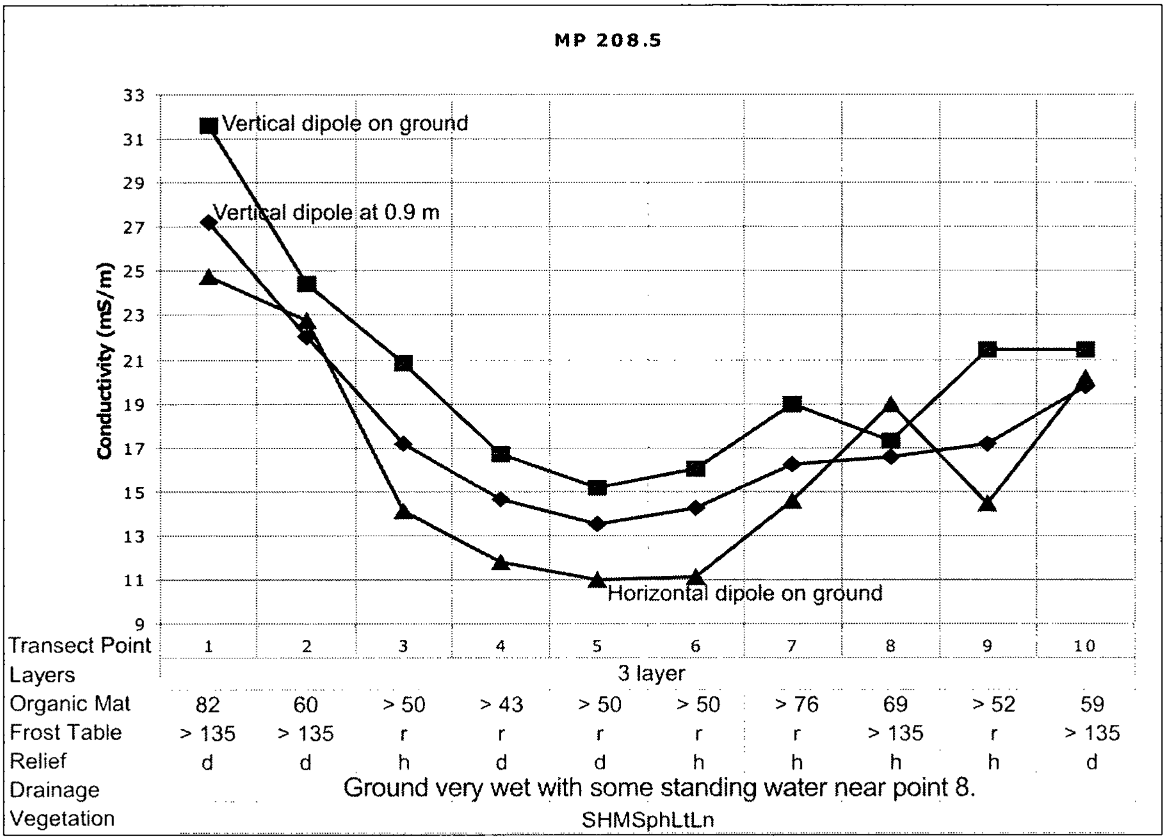
Appendix G: Electromagnetic Induction Results

The following figures show the results of the eight EM31 surveys not displayed in Results.



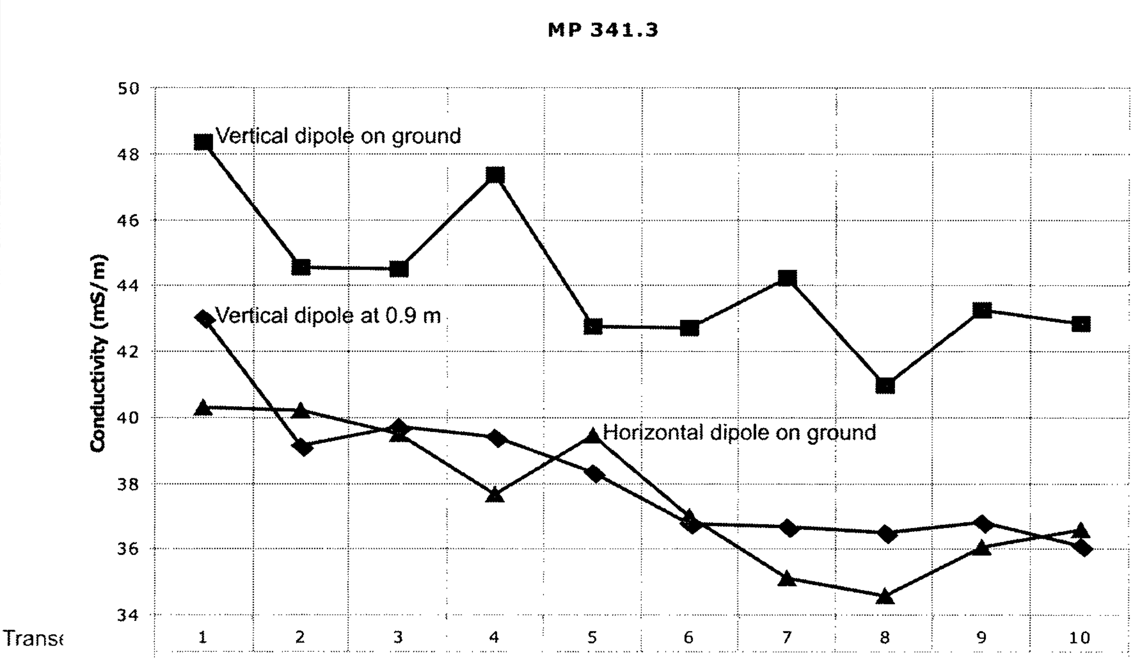
Transe	1	2	3	4	5	6	7	8	9	10
Layers	3 layer									
Organic Mat	66	54	51	44	53	> 35	> 40	50	> 38	> 41
Frost Table	> 150	> 150	119	87	86	r	r	r	r	r
Relief	Small hummocks. Transect begins on higher ground and goes progressively downslope.									
Drainage	Wettest at points 1 and 2, though no standing water. Quite dry until point 8. Points 9 and 10 moist.									
Vegetation	SG	SMGLn	SMLnLtG	SMLnB	SMLnB	SMLnB	SMLn	SMLnB	SMSph	SMSphLn

MP 178, showing 3 layered terrain as inferred through interpretation of EM31 readings.



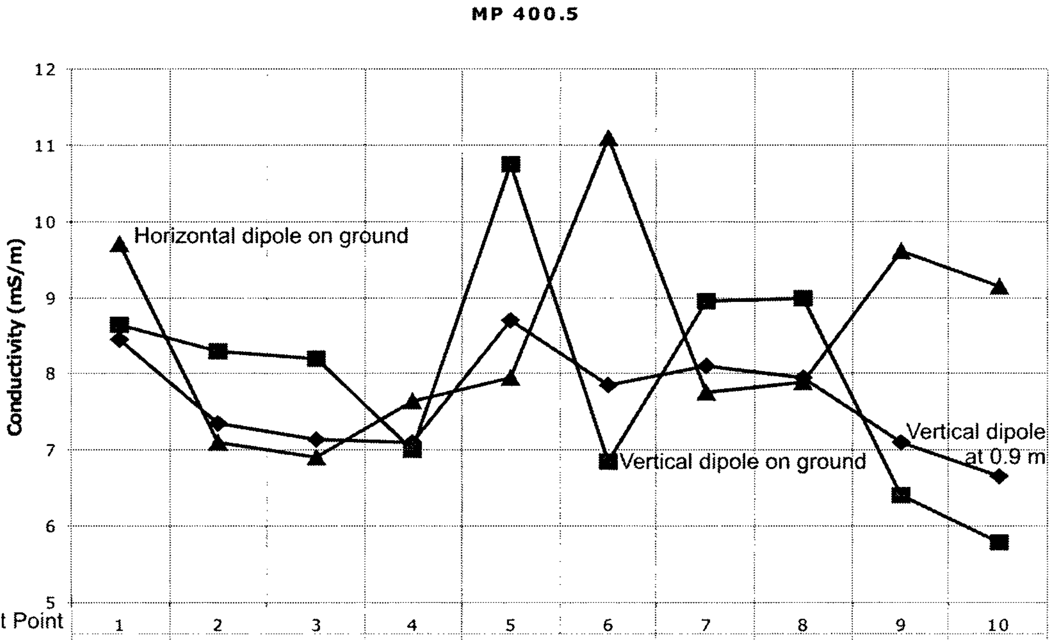
Transect Point	1	2	3	4	5	6	7	8	9	10
Layers	3 layer									
Organic Mat	82	60	> 50	> 43	> 50	> 50	> 76	69	> 52	59
Frost Table	> 135	> 135	r	r	r	r	r	> 135	r	> 135
Relief	d	d	h	d	d	h	h	h	h	d
Drainage	Ground very wet with some standing water near point 8.									
Vegetation	SHMSphLtLn									

MP 208.5, showing 3 layered terrain as inferred through interpretation of EM31 readings.



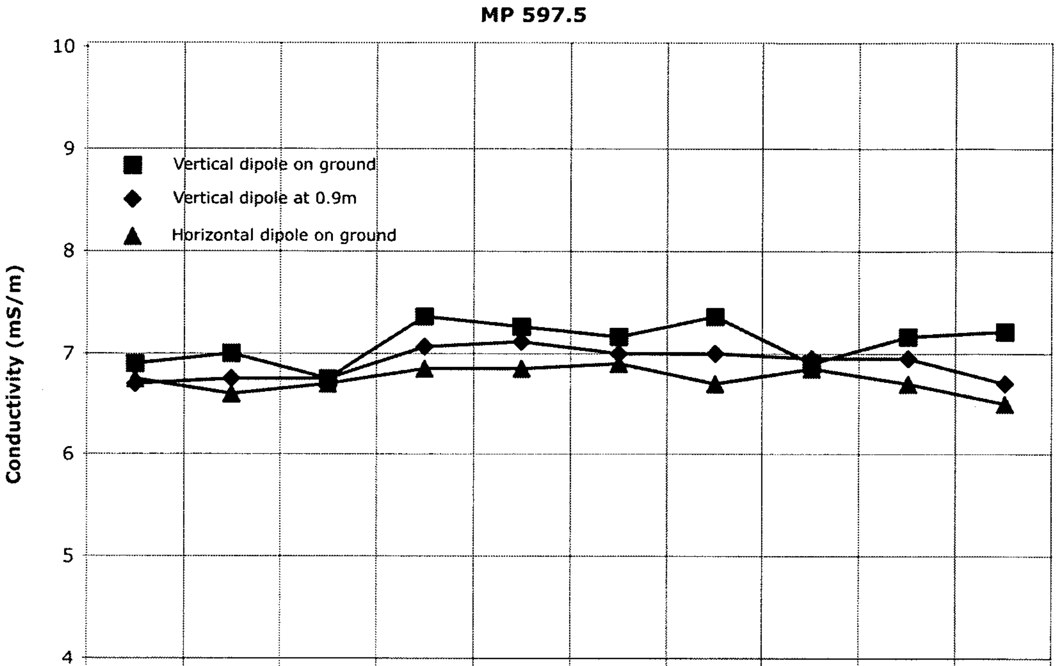
Transe	1	2	3	4	5	6	7	8	9	10
Layers	3 layer									
Organic Mat	64	56	82	> 57	63	51	52	75	> 58	51
Frost Table	> 135	> 56	> 135	57	> 135	> 102	105	100	58	51
Relief	h	h	h	h	d	d	d	h	d	h
Drainage	Ground moist, but not saturated and no standing water.									
Vegetation	STMLnSphLtB									

MP 341.1, showing 3 layered terrain as inferred through interpretation of EM31 readings.



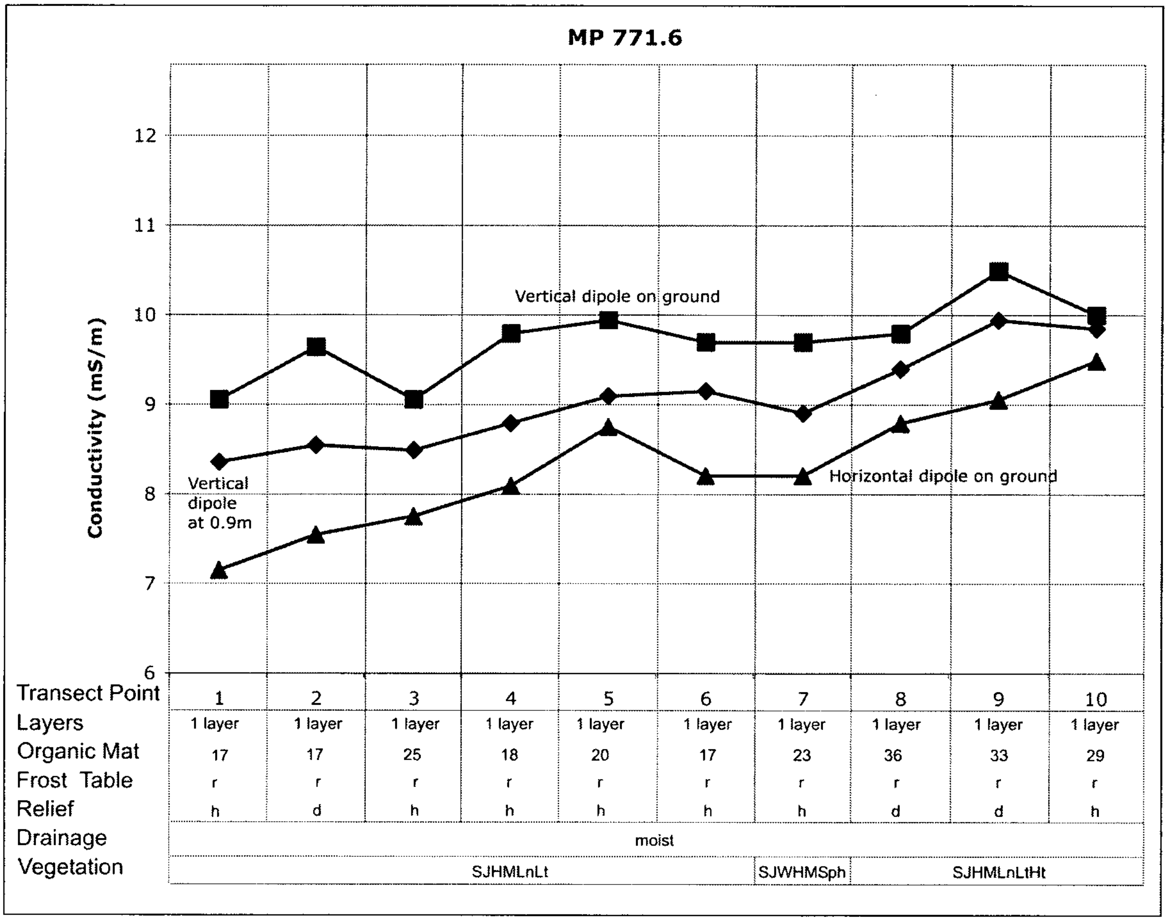
Transect Point	1	2	3	4	5	6	7	8	9	10
Layers	2 layer	3 layer	3 layer	2 layer	3 layer	2 layer	3 layer	3 layer	2 layer	2 layer
Organic Mat	36	> 41	> 41	> 45	> 48	55	> 46	> 46	60	76
Frost Table	105	r	r	45	r	115	r	r	78	92
Relief	d	h	h	d	h	d	h	h	d	h
Drainage	Ground moist, but not saturated and no standing water.									
Vegetation	SW(p)HMGLnLtSeB									

MP 400.5, showing 2 and 3 layered terrain as inferred through interpretation of EM31 readings.



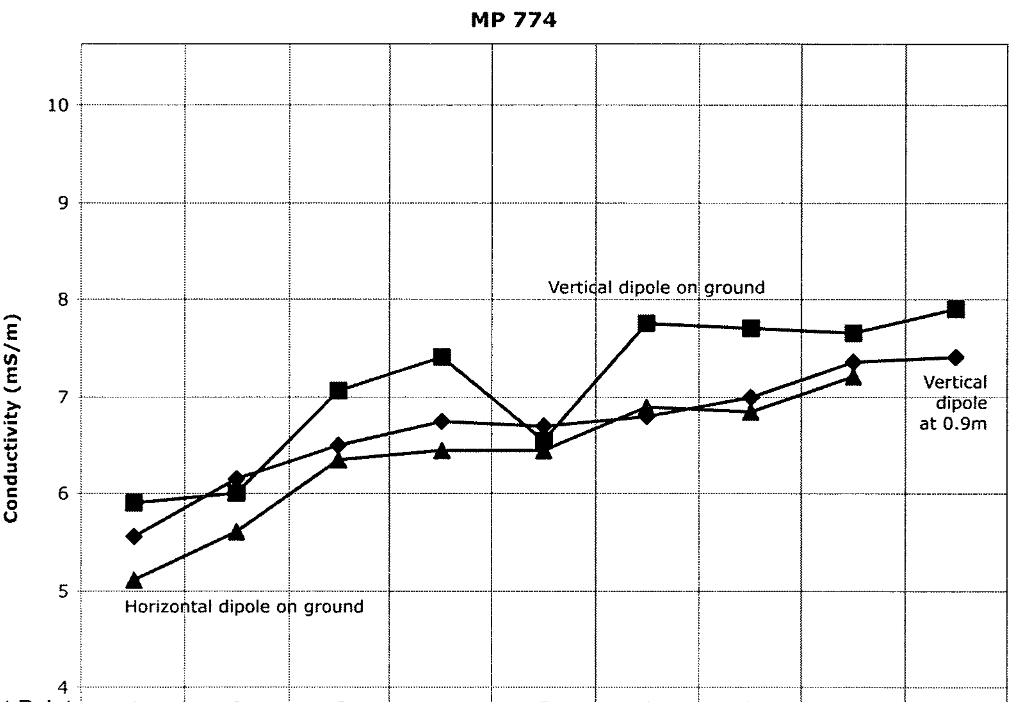
Transect Point	1	2	3	4	5	6	7	8	9	10
Layers	3 layer	3 layer	3 layer	3 layer	3 layer	3 layer	3 layer	3 layer	3 layer	3 layer
Organic Mat	>47	>44	>42	>37	>45	>50	>51	>48	39	>46
Frost Table	47	44	42	37	45	50	51	48	45	46
Relief	h	h	h	d	h	h	h	h	d	h
Drainage	Ground wet at point 1, less wet at points 2 to 8, then wetter again at points 9 and 10. No standing water.									
Vegetation	STW(p)HG LtSphM	STW(p)H SphMLt	STW(p)HS phMLtLnB	ST(p)H LnLtMSph	ST(p)HM SphLtLn	ST(p)H MSphLtLn	STW(p)HM SphLtLn	STW(p)HM SphLtLn	STW(p)HM SphLtLnG	STW(p)HM SphLtLnG

MP 597.5, showing 3 layered terrain as inferred through interpretation of EM31 readings.



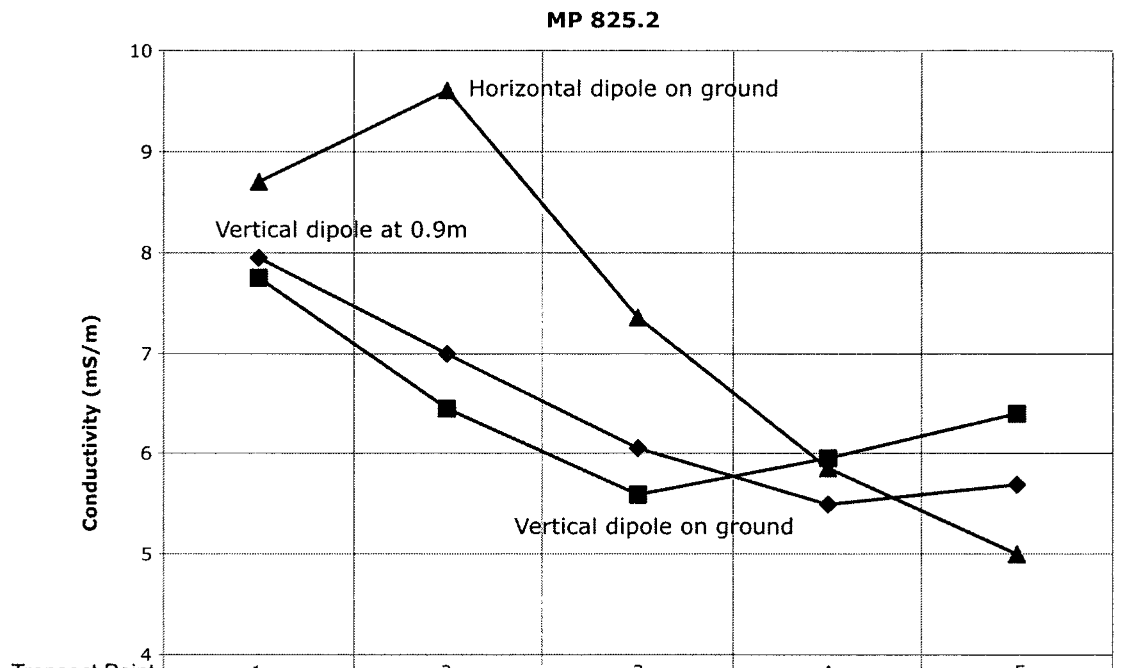
Transect Point	1	2	3	4	5	6	7	8	9	10
Layers	1 layer	1 layer	1 layer	1 layer	1 layer	1 layer	1 layer	1 layer	1 layer	1 layer
Organic Mat	17	17	25	18	20	17	23	36	33	29
Frost Table	r	r	r	r	r	r	r	r	r	r
Relief	h	d	h	h	h	h	h	d	d	h
Drainage	moist									
Vegetation	SJHMLnLt						SJWHMSph	SJHMLnLtHt		

MP 771.6, showing 1 layered terrain as inferred through interpretation of EM31 readings.



Transect Point	1	2	3	4	5	6	7	8	9
Layers	1 layer	1 layer	1 layer	1 layer	1 layer	1 layer	1 layer	1 layer	1 layer
Organic Mat	9	18	19	14	19	19	29	17	23
Frost Table	r	r	r	r	r	r	r	r	r
Relief	d	h	h	h	d	h	h	d	h
Drainage	moist								
Vegetation	SJHMLnLt	SJHMLnLt	SJHMLn	SJMLn	SJWH MLnGLt	SJWHM SphLn	SJWH MSph	SJWHM LnLtG	SJWHM LnLtG

MP 774, showing 1 layered terrain as inferred through interpretation of EM31 readings.



Transect Point	1	2	3	4	5
Layers	1 layer	2 layer	2 layer	3 layer	3 layer
Organic Mat	50	40	56	32	32
Frost Table	>135	46	>135	60	60
Relief	h	h	h	h	h
Drainage	Ground moist at point and gets progressively drier to point 5				
Vegetation	SHMG	SHMGLn	SHMG	SHMGLn	SHMGLn

MP 825.2, showing 1, 2 and 3 layered terrain as inferred through interpretation of EM31 readings.

Appendix H: Statistical Testing of Long-term Climate Data

Significance test results for MAATs from 1943 to 2008 at Environment Canada weather stations in the study area (confidence limit of 95%) (Environment Canada, 2008).

Station	Record	n	Slope Coefficient	F prob.	Std. error of slope	R^2	Intercept prob.	Slope prob.
Fort St. John	1943-2008	66	0.023	0.006	0.008	0.114	0.008	0.006
Fort Nelson	1943-2008	66	0.021	0.001	0.006	0.150	0.001	0.001
Watson Lake	1943-1992, 1996-1997, 2000-2008	61	0.008	0.253	0.007	0.022	0.181	0.253
Whitehorse	1943-1995, 1998-2008	64	0.015	0.050	0.008	0.061	0.045	0.045

Significance test results for MAATs from 1943 to 1964 at Environment Canada weather stations in the study area (confidence limit of 95%) (Environment Canada, 2008).

Station	Record	n	Slope Coefficient	F prob.	Std. error of slope	R^2	Intercept prob.	Slope prob.
Fort St. John	1943-1964	22	-0.018	0.659	0.040	0.010	0.647	0.659
Fort Nelson	1943-1964	22	-0.052	0.124	0.032	0.114	0.129	0.124
Watson Lake	1943-1964	22	-0.037	0.299	0.034	0.054	0.317	0.299
Whitehorse	1943-1964	22	-0.036	0.350	0.038	0.044	0.355	0.350

Significance test results for MAATs from 1965 to 2008 at Environment Canada weather stations in the study area (confidence limit of 95%) (Environment Canada, 2008).

Station	Record	n	Slope Coefficient	F prob.	Std. error of slope	R^2	Intercept prob.	Slope prob.
Fort St. John	1965-2008	44	0.053	0.001	0.014	0.252	0.001	0.001
Fort Nelson	1965-2008	44	0.040	0.001	0.011	0.252	0.000	0.001
Watson Lake	1965-1992, 1996-1997, 2000-2008	39	0.051	0.000	0.011	0.374	0.000	0.000
Whitehorse	1965-1995, 1998-2008	42	0.051	0.000	0.013	0.280	0.000	0.000

Significance test results for FDDs from 1944 to 2008 at Environment Canada weather stations in the study area (confidence limit of 95%) (Environment Canada, 2008).

Station	Record	n	Slope Coefficient	F prob.	Std. error of slope	R^2	Intercept prob.	Slope prob.
Fort St. John	1943-1992, 1994-2008	63	-7.293	0.007	2.617	0.113	0.003	0.007
Fort Nelson	1943-1995, 1998-2008	62	-8.014	0.002	2.538	0.142	0.001	0.002
Watson Lake	1943-1992, 1995-2008	62	-4.286	0.125	2.756	0.039	0.042	0.125
Whitehorse	1943-1994, 1998-2008	62	-5.445	0.082	3.074	0.050	0.040	0.082

Significance test results for FDDs from 1944-1964 at Environment Canada weather stations in the study area (confidence limit of 95%) (Environment Canada, 2008).

Station	Record	n	Slope Coefficient	F prob.	Std. error of slope	R^2	Intercept prob.	Slope prob.
Fort St. John	1943-1964	21	-2.326	0.881	15.299	0.001	0.835	0.881
Fort Nelson	1943-1964	21	12.070	0.359	12.848	0.044	0.414	0.359
Watson Lake	1943-1964	21	7.110	0.652	15.519	0.011	0.719	0.652
Whitehorse	1943-1964	21	9.557	0.577	16.842	0.017	0.619	0.577

Significance test results for FDDs from 1965-2008 at Environment Canada weather stations in the study area (confidence limit of 95%) (Environment Canada, 2008).

Station	Record	n	Slope Coefficient	F prob.	Std. error of slope	R^2	Intercept prob.	Slope prob.
Fort St. John	1965-1992, 1994-2008	42	-14.025	0.003	4.396	0.203	0.002	0.003
Fort Nelson	1965-1995, 1998-2008	41	-14.879	0.002	4.447	0.223	0.001	0.002
Watson Lake	1965-1992, 1995-2008	41	-15.622	0.001	4.353	0.248	0.000	0.001
Whitehorse	1965-1994, 1998-2008	41	-15.927	0.003	5.113	0.199	0.002	0.003

Significance test results for TDDs from 1943 to 2008 at Environment Canada weather stations in the study area (confidence limit of 95%) (Environment Canada, 2008).

Station	Record	n	Slope Coefficient	F prob.	Std. error of slope	R^2	Intercept prob.	Slope prob.
Fort St. John	1943-1991, 1994-2008	64	1.182	0.204	0.921	0.026	0.993	0.204
Fort Nelson	1943-1995, 1999-2008	63	0.726	0.407	0.870	0.011	0.659	0.407
Watson Lake	1943-1991, 1996-2008	62	0.007	0.993	0.797	0.000	0.251	0.993
Whitehorse	1943-1995, 1998-2008	64	0.245	0.796	0.943	0.001	0.489	0.796

Significance test results for TDDs from 1943 to 1964 at Environment Canada weather stations in the study area (confidence limit of 95%) (Environment Canada, 2008).

Station	Record	n	Slope Coefficient	F prob.	Std. error of slope	R^2	Intercept prob.	Slope prob.
Fort St. John	1943-1964	22	-4.602	0.314	4.460	0.051	0.209	0.314
Fort Nelson	1943-1964	22	-7.182	0.040	3.277	0.194	0.020	0.040
Watson Lake	1943-1964	22	-4.578	0.225	3.654	0.073	0.145	0.225
Whitehorse	1943-1964	22	-2.471	0.557	4.133	0.018	0.421	0.557

Significance test results for TDDs from 1965 to 2008 at Environment Canada weather stations in the study area (confidence limit of 95%) (Environment Canada, 2008).

Station	Record	n	Slope Coefficient	F prob.	Std. error of slope	R^2	Intercept prob.	Slope prob.
Fort St. John	1965-1991, 1994-2008	42	3.188	0.068	1.702	0.081	0.243	0.068
Fort Nelson	1965-1995, 1999-2008	41	1.951	0.265	1.725	0.032	0.628	0.265
Watson Lake	1965-1991, 1996-2008	40	4.437	0.001	1.273	0.242	0.009	0.001
Whitehorse	1965-1995, 1998-2008	42	3.723	0.040	1.754	0.101	0.114	0.040

Significance test results for annual rainfall from 1943 to 2008 at Environment Canada weather stations in the study area (confidence limit of 95%) (Environment Canada, 2008).

Station	Record	n	Slope Coefficient	F prob.	Std. error of slope	R^2	Intercept prob.	Slope prob.
Fort St. John	1943-2008	66	1.067	0.049	0.531	0.059	0.087	0.049
Fort Nelson	1943-1983, 1985-2008	65	0.917	0.098	0.546	0.043	0.165	0.098
Watson Lake	1943-1987, 1989-1992, 1996-1997, 2000-2008	60	1.037	0.011	0.394	0.107	0.024	0.011
Whitehorse	1943-1995, 1998-2008	64	0.465	0.113	0.289	0.040	0.186	0.113

Significance test results for annual rainfall from 1943 to 1964 at Environment Canada weather stations in the study area (confidence limit of 95%) (Environment Canada, 2008).

Station	Record	n	Slope Coefficient	F prob.	Std. error of slope	R^2	Intercept prob.	Slope prob.
Fort St. John	1943-1964	22	3.965	0.158	2.702	0.097	0.171	0.158
Fort Nelson	1943-1964	22	3.533	0.261	3.051	0.063	0.280	0.261
Watson Lake	1943-1964	22	1.631	0.446	2.096	0.029	0.478	0.446
Whitehorse	1943-1964	22	-2.000	0.197	1.500	0.082	0.182	0.197

Significance test results for annual rainfall from 1965 to 2008 at Environment Canada weather stations in the study area (confidence limit of 95%) (Environment Canada, 2008).

Station	Record	n	Slope Coefficient	F prob.	Std. error of slope	R^2	Intercept prob.	Slope prob.
Fort St. John	1965-2008	44	0.130	0.896	0.984	0.000	0.984	0.896
Fort Nelson	1965-1983, 1985-2008	43	1.207	0.222	0.973	0.036	0.285	0.222
Watson Lake	1965-1987, 1989-1992, 1996-1997, 2000-2008	38	1.208	0.092	0.698	0.077	0.131	0.092
Whitehorse	1965-1995, 1998-2008	42	0.425	0.417	0.518	0.017	0.511	0.417

Significance test results for annual snowfall from 1943 to 2008 at Environment Canada weather stations in the study area (confidence limit of 95%) (Environment Canada, 2008).

Station	Record	n	Slope Coefficient	F prob.	Std. error of slope	R^2	Intercept prob.	Slope prob.
Fort St. John	1943-2008	65	-0.184	0.634	0.386	0.004	0.462	0.634
Fort Nelson	1943-1983, 1985-2008	64	-0.203	0.476	0.283	0.008	0.296	0.476
Watson Lake	1943-1987, 1989-1992, 1996-1997, 2000-2008	60	-0.506	0.079	0.283	0.052	0.034	0.079
Whitehorse	1943-1995, 1998-2008	63	0.290	0.255	0.253	0.021	0.384	0.255

Significance test results for annual snowfall from 1943 to 1964 at Environment Canada weather stations in the study area (confidence limit of 95%) (Environment Canada, 2008).

Station	Record	n	Slope Coefficient	F prob.	Std. error of slope	R^2	Intercept prob.	Slope prob.
Fort St. John	1943-1964	22	6.803	0.000	1.464	0.519	0.000	0.000
Fort Nelson	1943-1964	22	2.840	0.049	1.354	0.180	0.057	0.049
Watson Lake	1943-1964	22	3.740	0.015	1.405	0.262	0.018	0.015
Whitehorse	1943-1964	22	2.464	0.031	1.064	0.212	0.035	0.031

Significance test results for annual snowfall from 1965 to 2008 at Environment Canada weather stations in the study area (confidence limit of 95%) (Environment Canada, 2008).

Station	Record	n	Slope Coefficient	F prob.	Std. error of slope	R^2	Intercept prob.	Slope prob.
Fort St. John	1965-2008	44	-0.302	0.671	0.706	0.004	0.574	0.671
Fort Nelson	1965-1983, 1985-2008	43	0.246	0.638	0.519	0.005	0.769	0.638
Watson Lake	1965-1987, 1989-1992, 1996-1997, 2000-2008	39	-0.256	0.593	0.475	0.008	0.452	0.593
Whitehorse	1965-1995, 1998-2008	42	-0.194	0.684	0.472	0.004	0.579	0.684

Significance test results for total annual precipitation from 1943 to 2008 at Environment Canada weather stations in the study area (confidence limit of 95%) (Environment Canada, 2008).

Station	Record	n	Slope Coefficient	F prob.	Std. error of slope	R^2	Intercept prob.	Slope prob.
Fort St. John	1943-2008	66	0.191	0.771	0.653	0.001	0.951	0.771
Fort Nelson	1943-1983, 1985-2008	65	-0.054	0.923	0.562	0.000	0.619	0.923
Watson Lake	1943-1992, 1996-1997, 2000-2008	61	0.043	0.931	0.491	0.000	0.726	0.931
Whitehorse	1943-1995, 1998-2008	64	0.118	0.723	0.332	0.002	0.963	0.723

Significance test results for total annual precipitation from 1943 to 1964 at Environment Canada weather stations in the study area (confidence limit of 95%) (Environment Canada, 2008).

Station	Record	n	Slope Coefficient	F prob.	Std. error of slope	R^2	Intercept prob.	Slope prob.
Fort St. John	1943-1964	22	10.043	0.004	3.037	0.353	0.004	0.004
Fort Nelson	1943-1964	22	3.391	0.288	3.104	0.056	0.322	0.288
Watson Lake	1943-1964	22	2.655	0.306	2.530	0.052	0.349	0.306
Whitehorse	1943-1964	22	-0.647	0.737	1.898	0.006	0.685	0.737

Significance test results for total annual precipitation from 1965 to 2008 at Environment Canada weather stations in the study area (confidence limit of 95%) (Environment Canada, 2008).

Station	Record	n	Slope Coefficient	F prob.	Std. error of slope	R^2	Intercept prob.	Slope prob.
Fort St. John	1965-2008	44	-0.741	0.525	1.155	0.010	0.405	0.525
Fort Nelson	1965-1983, 1985-2008	43	1.131	0.253	0.975	0.032	0.357	0.253
Watson Lake	1965-1992, 1996-1997, 2000-2008	39	1.818	0.028	0.796	0.124	0.050	0.028
Whitehorse	1965-1995, 1998-2008	42	0.216	0.712	0.581	0.003	0.888	0.712

7.0 References

Aguado E and Burt JE. 2004. Understanding Weather and Climate. 3rd ed. Pearson Education, Inc.: New Jersey.

Anisimov OA, Nelson FE. 1997. Permafrost zonation and climate change: Results from transient general circulation models. *Climatic Change* **35**: 241-258.

Arctic Climate Impact Assessment (ACIA). 2005. *Impacts of a Warming Arctic: Arctic Climate Impact Assessment.* Cambridge University Press: Cambridge.

Bednarski J. 2008. Landform assemblages produced by the Laurentide Ice Sheet I northeastern British Columbia and adjacent Northwest Territories—constraints on glacial lakes and patterns of ice retreat. *Canadian Journal of Earth Sciences* **45**(5): 593-610.

Beilman DW, Vitt DH, Halsey LA. 2001. Localized permafrost peatlands in Western Canada: definition, distributions and degradation. *Arctic, Antarctic and Alpine Research* **33**(1): 70-77.

Brown RJE. 1964. Permafrost investigations on the Mackenzie Highway in Alberta and Mackenzie District. Technical Paper no. 175, Division of Building Research, National Research Council, Canada.

Bond, JD. 2004. Late Wisconsinan McConnell glaciation of the Whitehorse map area (105D), Yukon. In *Yukon Exploration and Geology 2003*, DS Emond and LL Lewis (eds.). Yukon Geological Survey: Whitehorse, Yukon; 73-88.

Brown RJE. 1967. *Permafrost Investigations in British Columbia and Yukon Territory.* Ottawa: NRC.

Brown, RJE. 1970. Occurrence of permafrost in Canadian peatlands. *Proceedings of 3rd International Peat Congress 1968.* Quebec, Canada: 174-181.

Brown, RJE, Péwé TL. 1973. Distribution of permafrost in North America and its relationship to the environment: A review, 1963-1973. In *Proceedings of the 2nd International Conference on Permafrost, Yakutsk, USSR*, North American contribution. National Academy of Science, Washington, DC; 71-100.

Burn CR. 1998a. The response (1958-1997) of permafrost and near-surface ground temperatures to forest fire, Takhini River valley, southern Yukon Territory. *Canadian Journal of Earth Sciences* **35**: 184-198.

Burn CR. 1998b. Field investigations of permafrost and climatic change in Northwest North America. In *Permafrost: Seventh International Conference, Yellowknife, Canada, Proceedings,* Lewkowicz AG, Allard M (eds). Universite′ Laval, Centre d'e′tudesnordiques: Quebec. Nordicana 55, 107-120.

Burn CR. 2000. The thermal regime of a retrogressive thaw slump near Mayo, Yukon Territory. *Canadian Journal of Earth Sciences* **37**: 967-981.

Burn CR. 2004. The Thermal Regime of Cryosols. In *Cryosols: permafrost-affected soils*, JM Kimble (ed.). Springer-Verlag Berlin Heidelberg: Berlin, Germany; 391-413.

Burn CR, Kokelj SV. 2009. The Environment and Permafrost of the Mackenzie Delta Area. *Permafrost and Periglacial Processes* **20**: 83-105.

Burn CR, Zhang Y. 2009. Permafrost and climate change at Herschel Island (Qikiqtaruq), Yukon Territory, Canada. *Journal of Geophysical Research* **114**: F02001, doi:10.1029/2008JF001087.

Camill P. 2005. Permafrost thaw accelerates in boreal peatlands during late-20th century climate warming. *Climatic Change* **68**: 135-152.

Camill P, Clark JS. 2000. Long-term perspectives on lagged ecosystem responses to climate change: Permafrost in boreal peatlands and the grassland/woodland boundary. *Ecosystems* **3**: 534-544.

Carey SK, Woo M. 1999. Hydrology of two slopes in subarctic Yukon. *Hydrological Processes* **13**: 2549-2562.

Denny, CS. 1952. Late quaternary geology and frost phenomena along Alaska Highway, Northern British Columbia and Southern Yukon. *Bulletin of the Geological Society of America* **63**: 883-922.

Dallas Semiconductor. 2008. DS1921G Thermochron iButton. http://www.datasheets.maxim-ic.com/en/ds/DS1921G.pdf [20 April 2008].

Data Weighing Systems, Inc., 2009. http://www.dataweigh.com/ [20 April 2008].

Environment Canada. 2005. Terrestrial *Ecozones of Canada.* http://www.ec.gc.ca/soer-ree/English/vignettes/Terrestrial/terr.cfm [10 July 2009].

Environment Canada. 2007a. *Canadian Climate Normals or Averages 1971-2000.* http://climate.weatheroffice.ec.gc.ca/climate_normals/index_e.html [3 October 2007].

Environment Canada 2007b. *Canadian Climate Normals or Averages 1961-1990.* http://www.climate.weatheroffice.ec.gc.ca/climate_normals/index_1961_1990_e.html [3 October 2007].

Environment Canada. 2008. *Canadian Climate Data.* http://climate.weatheroffice.ec.gc.ca/climateData/canada_e.html [10 February 2009].

Environment Canada, 2008. National Climate Data and Information Archive. http://www.climate.weatheroffice.ec.gc.ca/climateData/canada_e.html [15 December 2008].

Frauenfeld OW, Zhang T, Barry RG, Gilichinsky D. 2004. Interdecadal changes in seasonal freeze and thaw depths in Russia. *Journal of Geophysical Research* **109**: page numbers unavailable.

French HM, Egorov IE. 1998. 20th century variations in the southern limit of permafrost near Thompson, Northern Manitoba, Canada. In *Permafrost: Seventh International Conference, Yellowknife, Canada, Proceedings,* Lewkowicz AG, Allard M (eds). Universite′ Laval, Centre d'e′tudes nordiques: Quebec. Nordicana 55, 297-304.

French HM, and Slaymaker. 1993 Canada's Cold Land Mass, In *Canada's Cold Environments*, H. M. French and O Slaymaker (eds). Canada: McGill-Queen's University Press; 3-28.

Fulton, RJ. 1989. *Quaternary Geology of Canada and Greenland.* Ottawa: Geological Survey of Canada; 839 pp.

Garmin Ltd. 2006. ETrex Vista CX Owner's Manual. USA: Garmin, Ltd.

Geomatics Yukon. 2006. Digital Elevation Model (30 m) [Data File]. Whitehorse: Government of Yukon. Available download: http://www.geomaticsyukon.ca/data_download.html#elevation [15 October 2009].

Geonics Limited. 2005. *Geonics Limited.* http://www.geonics.com/ [12 April, 2008].

Geonics Limited. 1977. *Operating Manual for EM31 Non-Contacting Terrain Conductivity Meter*, Geonics Ltd.

Wildfire Management Branch, Government of British Columbia. 2009. *Historical Fire Perimeters* [Data File]. Ministry of Forests and Range, Government of British Columbia. Available download: http://apps.gov.bc.ca/pub/geometadata/metadataDetail.do?recordUID=57060&recordSet=ISO19115 [October 10 2009].

Government of Canada, 2002. *The State of Canada's Ecosystem in Maps.*[Data File]. http://geogratis.cgdi.gc.ca/Ecosystem/ecosystem.html [5 July 2009].

Wildland Fire Management Branch, Government of Yukon. 2008. *Fire History* [Data File]. Whitehorse: Government of Yukon. Available download: http://www.geomaticsyukon.ca/data_download.html [September 9, 2009].

Department of Public Works. 1966. *Alaska Highway Engineering Study.* Ottawa: Government of Canada.

Halsey LA, Vitt DH, Zoltai SC. 1995. Disequilibrium response of permafrost in boreal continental western Canada to climate change. *Climatic Change* **30**: 57-73.

Harris SA. 1982. Cold air drainage west of Fort Nelson, British Columbia. *Arctic* **35**(4): 537-541.

Harris SA. 1986. Permafrost distribution, zonation and stability along the eastern ridges of the Cordillera of North America. *Arctic* **39**(1): 29-36.

Hauck C, Vonder Mühll D. 1999. Detecting Alpine Permafrost using Electro-magnetic Methods. In *Advances in Cold Regions Thermal Engineering and Sciences*, Hutter K , Wang Y , Beer H . (eds). Springer: Heidelberg; 475-482.

Head KH. 1992. *Manual of soil laboratory, Volume 1: Soil classification and compaction tests.* London, UK: Pentech Press.

Heginbottom JR, Dubreuil MA, Harker PT. 1995. Canada Permafrost. (1:7,500,000 scale). In *The National Atlas of Canada*, 5th Edition, sheet MCR 4177. Ottawa: National Resources Canada.

Heginbottom JA and Radburn LK (compilers) 1992. *Permafrost and ground ice conditions of northwestern Canada; Geological Survey of Canada, Map 1691A, scale 1:1,000,000.* Digitized by S. Smith, Geological Survey of Canada. Boulder, CO: National Snow and Ice Data Center/World Data Center for Glaciology.

Hoekstra P, McNeill D. 1973. Electromagnetic probing of permafrost. In *2nd International Conference on Permafrost, Proceedings.* National Academy of Sciences - National Research Council Canada, Publication 2115: Washington, DC; 517-526.

Intergovernmental Panel on Climate Change (IPCC). 2007. *Climate Change 2007: Synthesis Report.* Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, Pachauri, R.K and Reisinger, A. (eds.)]. IPCC, Geneva, Switzerland: 104 pp.

Jorgenson MT, Racine CH, Walters JC, Osterkamp TE. 2001. Permafrost degradation and ecological changes associated with a warming climate in central Alaska. *Climatic Change* **48**(4): 551-579.

Jorgenson MT, Krieg RA. 1988. A model for mapping permafrost distribution based on landscape component maps and climatic variables. In *Proceedings of Fifth International Conference on Permafrost.* TAPIR Publishers: Trondheim; 1:176 182.

Jenness J. 2006. *Topographic Position Index (tpi_jen.avx) extension for ArcView 3.x, v.*1.3a. Jenness Enterprises. http://www.jennessent.com/arcview/tpi.htm [15 November 2008].

Karunaratne KC, Burn CR. 2004. Relations between air and surface temperature in discountinuous permafrost terrain near Mayo, Yukon Territory. *Canadian Journal of Earth Sciences* **41**: 1437-1451.

Kaufman DS, Ager TA, Anderson NJ, Anderson PM, Andrews JT, Bartlein PJ, Brubaker LB, Coats LL, Cwynar LC, Duvall ML, Dyke AS, Edwards ME, Eisner WR, Gajewski K, Geirsdóttir A, Hu FS, Jennings AE, Kaplan MR, Kerwin MW, Lozhkin AV, MacDonald GM, Miller GH, Mock CJ, Oswald WW, Otto-Bliesner BL, Porinchu DF, Rühland K, Smol JP, Steig EJ, Wolfe BB. 2004. Holocene thermal maximum in western Arctic (0-180°W). *Quaternary Science Reviews* **23**(5-6): 529-560.

Kershaw GP. 2003. Permafrost landform degradation over more than half a century, Macmillan/Caribou Pass region, NWT/Yukon, Canada. In *Permafrost: Proceedings of the 8th International Conference on Permafrost, Zurich, Switzerland, 21-25 July 2003.* Taylor & Francis: Zurich;543-548.

Klene AE, Nelson FE, Shiklomanov NI. 2001. The N-factor in natural landscapes: variability of air and soil-surface temperatures, Kuparuk River basin, Alaska, USA. *Arctic, Antarctic and Alpine Research* **33**: 140-148.

Kneisel C, Hauck C, Fortier R, Moorman B. 2008. Advances in geophysical methods for permafrost investigations. *Permafrost and Periglacial Processes* **19**: 157-178.

Kudryavtsev VA, Garagulya LS, Kondrat'yeva KA, Melamed VG. 1974. Fundamentals of Frost Forecasting in Geological Engineering Investigations. Cold Regions Reseach and Engineering Laboratory: Hanover, NH.

Kwong, YTJ, Gan, TY. 1994. Northward migration of permafrost along the Mackenzie Highway and climatic warming. *Climatic Change* **26**(4): 399-419.

Lachenbruch AH, Marshall BV. 1986. Changing climate: Geothermal evidence from permafrost in the Alaskan Arctic. *Science* **234**: 689–696.

Lewkowicz, AG. 2008. Evaluation of miniature temperature-loggers to monitor snowpack evolution at mountain permafrost sites, northwestern Canada. *Permafrost and Periglacial Processes* **19**: 323-331.

Lunardini, VJ. 1978. Theory of n-factors and correlation of data. In *Proceedings of the Third International Conference on Permafrost, Edmonton, Aberta. July 10-13, 1978.* National Research Council of Canada: Ottawa; 1:40-46.

Mackay JR. 1995. Active layer changes (1968–1993) following the forest-tundra fire near Inuvik, N.W.T. *Arctic and Alpine Research* **27**: 323–336.

Menounos B, Osborn G, Clague JJ, Luckman BH. 2009. Latest Pleistocene and Holocene glacier fluctuations in western Canada. *Quaternary Science Reviews* **28** (21-22): 2049-2074.

McNeill JD. 1980. Electromagnetic Terrain Conductivity Measurements at Low Induction Numbers. Technical Note TN-6, Geonics Ltd.

Measurement Specialties Inc., 2008. *44033RC Precision Epoxy NTC Thermistor.* http://www.meas-spec.com/WorkArea/showcontent.aspx?id=1708 [22 February 2008].

Microtrac, 2008. *S3500 Particle Analyzer.* http://www.microtrac.com/ProductsTechnology/MicrotracS3500ParticleSizeAnalyzer.aspx [22 February 2008].

Mikutta R, Kleber M, Kaiser K, Jahn R. 2005. Review: Organic matter removal from soils using hydrogen peroxide, sodium hypochlorite, and disodium peroxodisulfate. *Soil Science Society of America Journal* **69**: 120-136.

Ministry of Forests. 2002. *Forest Practices Code of British Columbia Forest Road Engineering Guidebook.* Government of British Columbia: 1-218.

Morris, ER. 2009. Height-above-ground effects on penetration depth and response of electromagnetic induction soil conductivity meters. *Computers and Electronics in Agriculture* **68**: 150-156.

Natural Resources Canada. 2007. Canadian Digital Elevation Data [Data File]. Sherbrooke: Government of Canada. Available download: http://www.geobase.ca/geobase/en/find.do;jsessionid=DEE052FAB41537536A6DECB385323049?produit=cded [12 October 2009].

Onset Computer Corporation. 2008. *Onset Computer Corporation.* http://www.onsetcomp.com/data-logger#outdoor [12 October 2008].

Osterkamp,TE. 2007. Causes of warming and thawing permafrost in Alaska. *Eos, Transactions, American Geophysical Union* **88**(44): 522-523.

Osterkamp TE, Romanovsky VE. 1999. Evidence for warming and thawing of discontinuous permafrost in Alaska. *Permafrost and Periglacial Processes* **10**: 17-37.

Pavlov, AV. 1994. Current changes of climate and permafrost in the arctic and sub-arctic of Russia. *Permafrost and Periglacial Processes* **5**: 101-110.

Pypker TG, Unsworth MH, Lamb B, Allwine E, Edburg S, Sulzman E, Mix AC, Bond BJ. 2007. Cold air drainage in a forested valley: Investigating the feasibility of monitoring ecosystem metabolism. *Agricultural and Forest Meteorology* **145**: 149-166.

RBR Ltd. 2009. *Multi Channel Data Loggers*. http://www.rbr-global.com/products/multi channel-data-loggers [10 January 2010].

Romanovsky VE, Gruber S, Instanes A, Jin H, Marchenko SS, Smith SL, Trombotto, Walter KM. 2007. Frozen Ground. In *Global Outlook for Ice and Snow.* Earthprint, UNEP/GRID: Arendal, Norway; 181-200.

Romanovsky VE,Nicolsky DJ, 2009. How Fast Can Permafrost Thaw? (Invited), *Eos Trans.* AGU, 90(52), Fall Meet. Suppl., Abstract C53A-01.

Sartorelli AN, French RB. 1982. Electromagnetic induction methods for mapping permafrost along northern pipeline corridors. In *Proceedings of the 4th Canadian Permafrost Conference, Nat. Res. Counc. Canada.* 283-298.

Sartorius Mechatronics, Germany. Sartorius L610 Laboratory Scale. http://www.sartorius-mechatronics.de/...sartoriusmechpdf/MAN-L610-0G2_L2200P-0G2-e.pdf [20 April 2008].

Shur Y, Hinkel KM, Nelson FE. 2005. The transient layer: Implications for geocryology and climate-change science. *Permafrost and Periglacial Processes* **16**: 5-17.

Shur YL, Jorgenson MT. 2007. Patterns of permafrost formation and degradation in relation to climate and ecosystems. *Permafrost and Periglacial Processes* **18**: 7 19.

Serreze MC, Walsh JE, Chapin III FS, Osterkamp T, Dyurgerov M, Romanovsky V, Oechel WC, Morison J, Zhang T, Barry RG. 2000. Observational evidence of recent change in the northern high-latitude environment. *Climatic Change* **46**: 159-207.

Smith SL, Burgess M. 1999. Mapping the sensitivity of Canadian permafrost to climate warming. In *Interactions between the cryosphere, climate and greenhouse gases, Birmingham, 18-30 July 1999.* International Association of Hydrological Sciences, Wallingford: UK; 71-78.

Smith SL, Burgess MM, Riseborough D, Nixon MF. 2005. Recent trends from Canadian permafrost thermal monitoring network sites. *Permafrost and Periglacial Processes* **16**: 19-30.

Smith MW, Riseborough DW. 1983. Permafrost sensitivity to climate change. *Permafrost: Fourth International Conference, Fairbanks, Alaska, Proceedings,* National Academy Press: Washington, DC; 1178-1183.

Smith MW, Riseborough, DW. 1996. Ground temperature monitoring and detection of climate change. *Permafrost and Periglacial Processes* **7**: 301-310.

Smith MW, Riseborough DW. 1998. Exploring the limits of permafrost. In *Permafrost: Seventh International Conference, Yellowknife, Canada, Proceedings*, Lewkowicz AG, Allard M (eds). Universite′ Laval, Centre d'e′tudes nordiques: Quebec. Nordicana 55, 935-941.

Smith MW, Riseborough DW. 2002. Climate and the limits of permafrost: a zonal analysis. *Permafrost and Periglacial Processes* **13**: 1-15.

Soil Classification Working Group. 1998. *The Canadian System of Soil Classification* (3rd ed). Research Branch, Agriculture and Agri-Food Canada, Ottawa, Publication 1646, 187 p.

Stendel M, Chistiansen JH. 2002. Impact of global warming on permafrost conditions in a coupled GCM. *Geophysical Research Letters* **29**(13): 10-1-10-4.

Stieglitz M, Dery SJ, Romanovsky VE, Oterkamp TE. 2003. The role of snowcover in the warming of arctic permafrost. *Geophysical Research Letters* **30**(13): 54-64.

Stocks BJ, Mason JA, Todd JB, Bosch EM, Wotton BM, Amiro BD, Flannigan MD, Hirsch KG, Logan KA, Martell DL, Skinner WR. 2002. Large forest fires in Canada, 1959-1997. *Journal of Geophysical Research* **107**: 8149, doi: 10.1029/2001JD000484.

Swanson DK. 1996. Susceptibility of permafrost soils to deep thaw after forest fires in interior Alaska, USA, and some ecologic implications. *Arctic and Alpine Research*, **28**(2): 217-227.

Taylor, AE. 1995. Field measurements of n-factors for natural forest areas, Mackenzie Valley, Northwest Territories. In *Current Research, Geological Survey of Canada* **1995-B**: 89-98.

Taylor A, Nixon M, Eley J, Burgess M and Egginton P. 1998: Effects of atmospheric temperature inversions on ground surface temperatures and discontinuous permafrost, Norman Wells, Mackenzie Valley, Canada. In A.G. Lewkowicz and M. Allard, (eds.) *Proceedings, Seventh International Conference on Permafrost, Yellowknife, June 23-27, 1998.* Nordicana, Centre d'etudes nordiques, Quebec City. 1043-1048.

Taylor B . 1997. The Climates of British Columbia and Yukon. In *Responding to global climate change in British Columbia and Yukon, Volume 1 of the Canada Country Study: Climate Impacts and Adaptation,* Taylor E and Taylor B (eds). Aquatic and Atmospheric Sciences Division, Environment Canada, Pacific and Yukon Region, and Air Resources Branch, British Columbia Ministry of the Environment, Lands and Parks, Canada: 3-1 to 3-15.

Vitt DH, Halsey LA, Zoltai SC. The bog landforms of continental western Canada in relation to climate and permafrost patterns. *Arctic and Alpine Research* **26**(1): 1 13.

Wahl HE, Fraser DB, Harvey RC, Maxwell JB. 1987. *Climate of Yukon.* Environment Canada, Ottawa; 1-321.

Yoshikawa K, Bolton WR, Romanovsky VE, Fukuda M, Hinzman LD. 2002. Impacts of wildfire on permafrost in the boreal forests of Interior Alaska. Journal of Geophysical Research **108**: 8148, doi:10.1029/2001JD000438.

Zoltai SC. 1971 Southern limit of permafrost features in peat landforms, Manitoba and Saskatchewan. Geological Association of Canada special paper, 9, 305310.