VARIATION OF MEAN ANNUAL GROUND TEMPERATURE IN SPRUCE FORESTS OF THE MACKENZIE DELTA, NORTHWEST TERRITORIES

by

Julian C.N. Kanigan, B.Sc.

A thesis submitted to
the Faculty of Graduate Studies
in partial fulfillment of
the requirements of the degree of

Master of Science

Carleton University
Ottawa, Ontario

Your file Votre référence
ISBN: 978-0-494-33701-1
Our file Notre référence
ISBN: 978-0-494-33701-1

ABSTRACT

Mean annual ground temperatures were measured at 28 spruce-forest sites in the Mackenzie Delta, to determine if differences in surface conditions between spruce-forest communities lead to differences in mean annual ground temperature. Surface conditions, including vegetation, organic-layer depth, and snow cover, were measured. Mean annual ground temperatures ranged from -0.6 to -2.9°C, and were negatively correlated with white spruce tree size, suggesting that canopy cover and the resulting interception of snow and radiation explain some of the variation. Ground temperature is also likely related to organic-layer depths and the presence of numerous water bodies. Spruce/alder-bearberry communities had thin organic layers, relatively open canopies, frequent flooding, and mean annual ground temperatures that were significantly higher than those of the other communities (-0.6 to -1.5°C). Mean annual ground temperatures at two sites in the central delta have increased by 0.3 and 0.9°C over the last 35 years in association with climate warming.

ACKNOWLEDGEMENTS

I gratefully acknowledge the advice and support of Dr. Chris Burn, and I am inspired by his commitment to northern research. Our conversations and fieldwork at Illisarvik will be well remembered. I am also thankful to Elyn Humphreys, and Michael Pisaric of Carleton University, and Mark Nixon, Larry Dyke, and Dan Riseborough of the Geological Survey of Canada for their helpful comments during the preparation of this thesis.

I am indebted to Dr. Steve Kokelj for my introduction to permafrost studies, and imparting his unwavering enthusiasm on the subject. His work ethic, especially with respect to fieldwork, is something to aspire to. Many thanks to the Water Resources Division of Indian and Northern Affairs Canada, and in particular, Dr. Kathleen Racher, for providing me with a productive work-space during my stays in Yellowknife. I am also grateful to Annette Hopkins of the Operations Directorate, Indian and Northern Affairs Canada for supporting my decision to pursue a Masters degree.

Financial support for this project was provided by the Natural Sciences and Engineering Research Council of Canada, the Northern Scientific Training Program of Indian and Northern Affairs Canada, the Water Resources Division of Indian and Northern Affairs Canada, the Aurora Research Institute, and an Ontario Graduate Scholarship.

There are many people to thank from Inuvik for their role in ensuring that the field work was a success. Larry Greenland provided field assistance, and his dedication, initiative and sense of humour made a long and busy field season seem short. William Hirst also provided field assistance. His calm approach and uncanny sense of direction in the delta were much appreciated. In addition to field work, Douglas Esagok provided us with access to his cabin on Napoiak Channel - a welcome luxury and refuge from the mosquitoes. His skill and ease with all aspects of living and working in the delta were admired and relied upon. Les Kutny provided thoughtful advice, meticulous field assistance, and a constant supply of provisions throughout the summer. Karen Heikkila was instrumental in ensuring that our research permits were issued in time.

I have appreciated the conversations and company of all of the students in the department with whom I have shared the experience of the past two years, including Pascale Roy-Levéillée, Peter Morse, Kumari Karunaratne, and Celina Duarte. In particular, I would like to thank Thai Nguyen-Nguyen for his positive outlook, and attention to detail, without which our summer field season would not have been a success. And I suspect that his outstanding culinary abilities were the glue that held our field camps together. Thanks to Adam Smith for our reassuring discussions on statistical methods, and to both Adam and Daisy for making me feel at home in Ottawa.

And finally, I am thankful to Heather for her patience and constant support through the past two years. You are truly my Number 1 fan.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER ONE

OVERVIEW AND OBJECTIVES

1.1 Introduction

The southern and central Mackenzie Delta, Northwest Territories (Fig. 1.1), is an area experiencing relatively rapid climate warming, where the ground thermal regime is currently little known (Serreze et al., 2000; Burn et al., 2004). It is characterized by forested land surfaces, with up to half of the area occupied by water bodies. This thesis provides mean annual ground temperatures measured at 20-m depth at 28 spruce-forest sites. Mean annual ground temperatures were analyzed in relation to their associated surface conditions, and sites were located away from water bodies to minimize the thermal influence of rivers and lakes. Several spruce-forest (*Picea*) communities with different physical characteristics have previously been identified in the delta, and ground temperatures were analyzed to determine their variation by spruce-forest community. Four regions based on flooding regime have been identified in the delta south of treeline. Mean annual ground temperatures were also analyzed to determine their variability by delta region. The thesis also provides an assessment of recent ground temperature change at two spruce-forest sites.

1.2 Research context

The few existing ground temperature measurements in spruce forests of the Mackenzie Delta indicate that mean annual ground temperatures are relatively warm (-2.5 to -4°C) (Johnston and Brown, 1961; Mackay, 1966; Smith, 1973; Mackay, 1974). Permafrost at temperatures close to 0°C is considered sensitive to environmental change because it requires less energy for thawing than colder permafrost (Smith and Burgess,

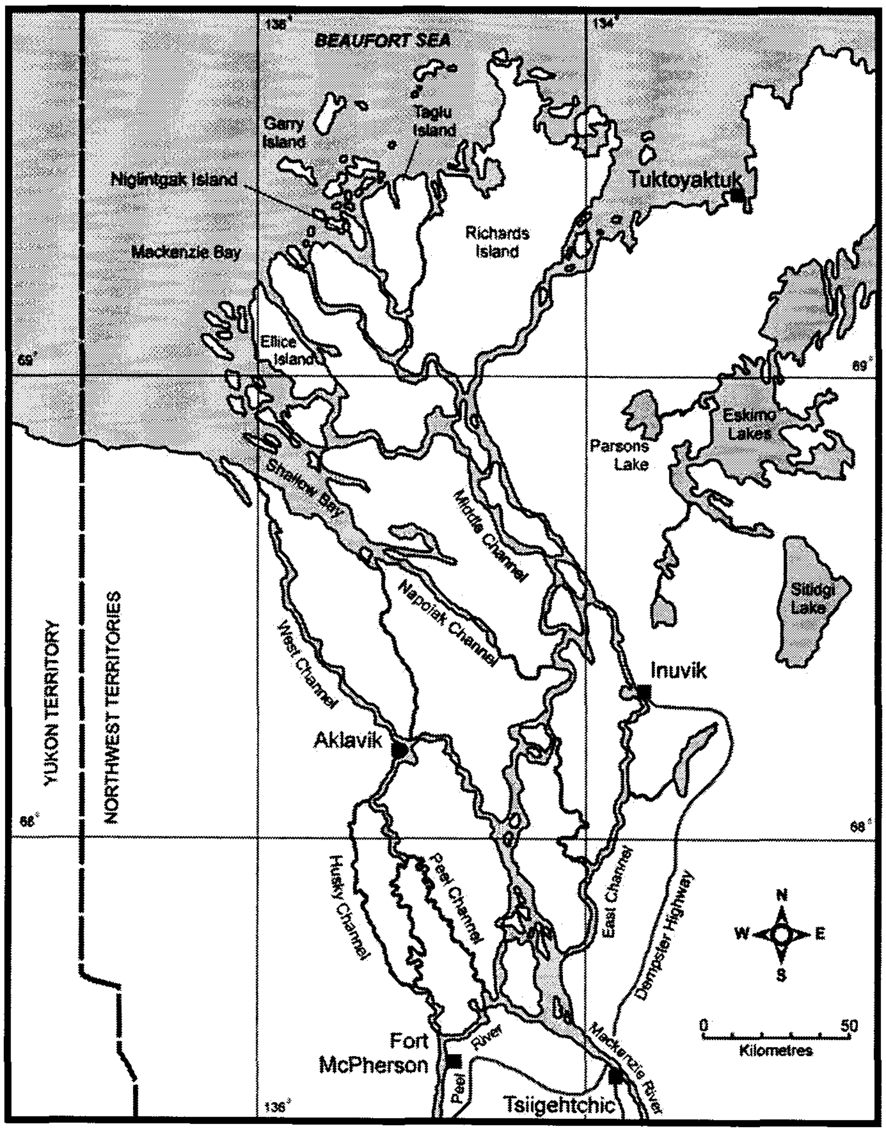

Figure 1.1 Mackenzie Delta region, Northwest Territories (modified from Kokelj and Burn, 2005a, Fig. 1).

2004). An understanding of ground temperatures is important in an area of near-surface, ice-rich permafrost close to 0°C, such as the Mackenzie Delta, because a small increase in temperature could lead to thawing of permafrost and terrain subsidence. Thawing of ice-rich permafrost can affect soil nutrient availability and soil moisture, and terrain subsidence can adversely impact engineered structures (Kokelj and Burn, 2005a). This is particularly relevant since the Mackenzie Delta region is a focus for energy resource development and the construction of associated infrastructure.

At a continental scale, ground temperatures are well correlated with climate, but at a regional scale, such as within the Mackenzie Delta, ground temperatures are buffered from air temperatures by local surface conditions such as vegetation, snow cover, water availability, and surficial materials (Luthin and Guymon, 1974; Smith and Riseborough, 1996). In permafrost terrain, water bodies cause the greatest deviation of ground temperatures from patterns otherwise determined by climate (Lachenbruch et al., 1962). Due to the high latent heat of fusion, only the upper meter or so of the water freezes in winter, and deeper water prevents the underlying sediment from freezing. Since the Mackenzie Delta is characterized by thousands of small lakes and channels, measurements must be made at sites that are located away from water bodies, to control for their warming influence.

1.3 Ground temperature measurement

Near surface ground temperatures fluctuate between summer maxima and winter minima over the year (Fig. 1.2). Differences between the maximum and minimum temperatures are large near the surface, and decrease with depth. This study focuses on the ground temperature at the depth of zero annual amplitude (Fig. 1.2). This is the depth

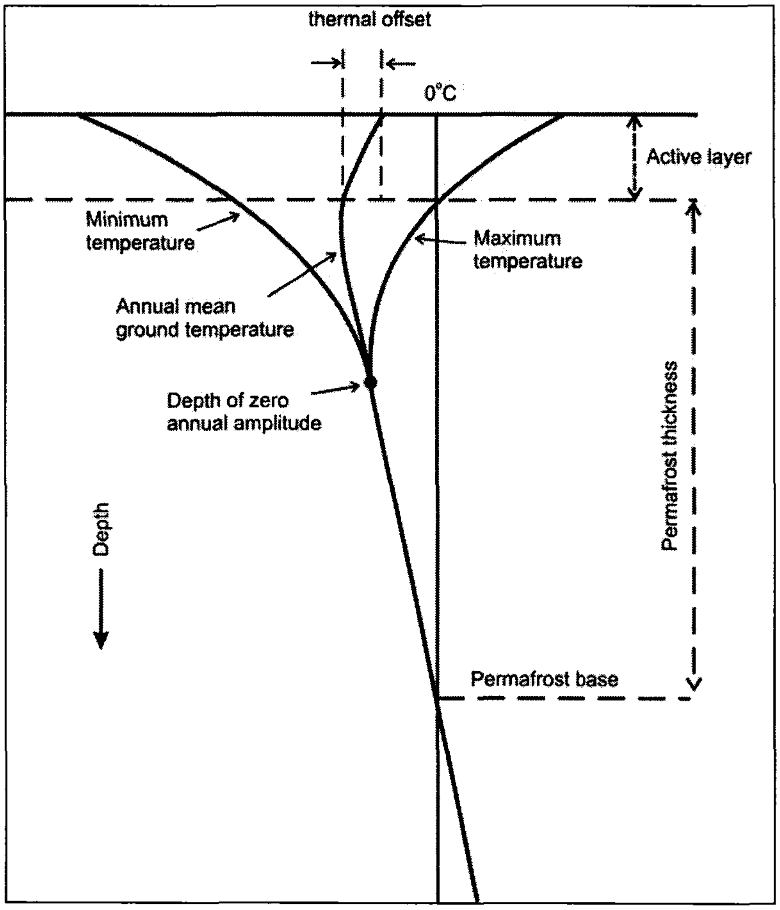

Figure 1.2 Typical ground temperature profile in permafrost (modified from Burn, 2004, Fig. 3.3.2).

at which the annual fluctuation in ground temperature is less than 0.1°C (van Everdingen, 2005), and the value approximates the mean annual ground temperature. The mean annual ground temperature is useful in the spatial or temporal comparison of ground temperatures because it is affected by long-term changes insurface temperature caused by changes in climate and surface conditions, and is not subject to seasonal influences (van Everdingen, 2005). Measurement of the temperature at the depth of zero annual amplitude is practical since relatively few measurements may be used to estimate the mean annual ground temperature (Mackay, 1974), whereas estimates from near-surface temperatures would require multiple measurements throughout the year. The depth of zero annual amplitude is characteristically located 10 to 20 m below the ground surface (van Everdingen, 2005). In this study, ground temperatures were measured between 15 and 20-m depth, based on previous permafrost studies in the Mackenzie Delta (Mackay, 1974; Smith, 1975).

1.4 The Mackenzie Delta

The Mackenzie Delta is Canada's largest delta, covering an area of approximately 13,000 km^2 (Burn, 2002a) (Fig. 1.1). The delta consists of alluvial materials deposited by the Mackenzie and Peel rivers (Mackay, 1963), and within the delta, the Middle Channel carries approximately 80% of the annual flow (Hirst et al., 1987). The delta contains a northward extension of treeline due to a relatively early snow-free season and consequent warm summer ground temperatures, and nutrient-rich soils caused by annual flooding (Burn, 2002a; Kokelj and Burn, 2005b). Ecological succession is associated with the flooding regime and sedimentation (Gill, 1972; Smith, 1975). Throughout the delta, a sequence of vegetation communities develops on aggrading point bars. Horsetail

(*Equisetum*) and willow (*Salix*) communities occupy areas adjacent to channels, and are subject to frequent flooding. Alder (*Alnus*) shrub communities occupy poorly drained depressions further away from the channel, and south of treeline, spruce-forest communities are located away from the channel, above the level of annual flooding. The dominant vegetation cover of the inner delta is white spruce forest, while the outer delta is vegetated by low shrubs and sedges.

A successional sequence of four spruce-forest communities have been identified in the central and southern Mackenzie Delta based on differences in flooding and sedimentation rates (Gill 1972; Pearce et al. 1988). The four communities, spruce/alder-bearberry, spruce/feathermoss, spruce/crowberry-lichen and spruce/tamarack-sphagnum, differ in terms of vegetative composition, and surface conditions, including canopy cover, snow depth and organic-layer thickness (Pearce et al., 1988; Kokelj and Burn, 2005a).

Four broad geographic regions have been identified in the Mackenzie Delta south of treeline based on elevation and related flooding regime (Cordes et al., 1985; Pearce, 1986). The regions are named for their position in the delta: west central delta, east central delta, southwestern delta, and southeastern delta (Fig. 1.3). Land surfaces in the central delta are at a lower elevation than in the southern delta, so flooding occurs more often in the central delta (Cordes et al., 1985). Based on the dominant vegetation associations and discharge levels, it appears that flooding is less frequent on the west side of the delta than on the east side (Pearce et al., 1988).

1.5 Research hypotheses

Given the scarcity of ground temperature data in the region, a basic objective of this thesis is to determine a range of mean annual ground temperatures of spruce forest

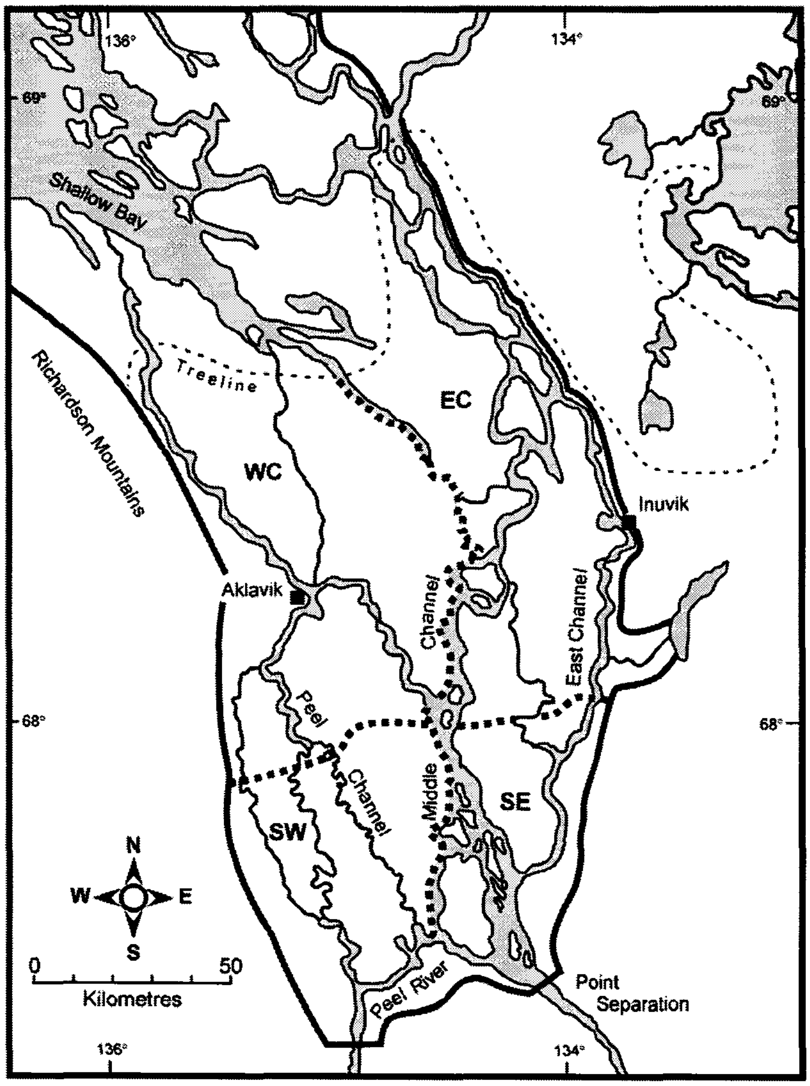

Figure 1.3 Central and southern Mackenzie Delta (modified from Kokelj and Burn, 2005a, Fig. 1). Ground temperatures were measured in four regions of the delta: WC-west central, EC-east central, SW-southwestern, SE-southeastern. Dotted lines represent approximate boundaries between delta regions from Pearce (1986). The solid line bounds the delta (Mackay, 1963). Treeline is from Mackay (1963).

sites in the central and southern Mackenzie Delta. Flooding and sedimentation regimes in the Mackenzie Delta associated with site elevation affect vegetation growth, and related surface conditions (Gill, 1972; Smith, 1975). These physical conditions also influence the development of near-surface ground ice so that vegetation type is closely related to near-surface ground ice characteristics (Kokelj and Burn, 2005a). An objective of the thesis is to determine if the variable surface conditions of the spruce-forest communities, such as canopy cover, snow depth and organic-layer thickness, also influence mean annual ground temperatures, so that mean annual ground temperatures differ between the communities. A further objective is to determine if mean annual ground temperatures differ between the four delta regions south of treeline.

Two ground temperature measurement sites in the east central delta, originally established over 35 years ago, were re-instrumented in 2005 at their original locations and depths (Johnston and Brown, 1964; Smith, 1973). A subsidiary objective of this thesis is to describe temporal change of mean annual ground temperatures at these sites by comparing historical and contemporary data.

1.6 Thesis structure

This thesis is composed of six chapters. The second chapter reviews current understanding of how surface conditions control the various fluxes of the surface energy balance, and factors influencing ground temperature. The third chapter describes the study area and methods used in the research, and presents the vegetation survey data. The fourth chapter describes the physical characteristics of the four spruce-forest communities, and relations between these characteristics. The fifth chapter presents mean annual ground temperatures and active-layer depths, and analyzes their relations with site physical characteristics. The temporal variation of ground temperatures at two sites is examined. The final chapter provides a summary of results and presents the conclusions of this thesis.

CHAPTER TWO

THEORETICAL CONSIDERATIONS

2.1 Introduction

Permafrost is ground that remains at or below 0°C for at least two consecutive years (van Everdingen, 2005). At a continental scale, climate is the main determinant of ground temperature, so that as mean annual air temperatures decrease, the proportion of the landscape underlain by permafrost increases (Burn and Nelson, 2006). The ground thermal regime is a function of the ground surface temperature, soil properties, and the heat flowing from the earth's core (Williams and Smith, 1989). The ground surface temperature is related to air temperature, but the relation varies with the physical characteristics of the landscape that affect the partitioning of the surface energy balance, such as slope, aspect, vegetation, snow cover, surficial materials, and soil moisture content (Smith and Burgess, 2004). Sites that are located in close proximity are affected by the same climate, but varying surface conditions lead to different ground surface temperatures, and consequently different ground thermal regimes. A review of controls on the ground thermal regime will demonstrate how site characteristics affect local variations in ground temperatures and active-layer depths.

2.2 Surface energy balance

The ground surface temperature is a product of the surface energy balance, which describes how the radiative surplus or deficit at the earth's surface is partitioned into the subsurface and the atmosphere (Oke, 1987). The surface energy balance is:

$$Q^* = Q_H + Q_L + Q_G \qquad [1]$$

Q^* (Wm^{-2}) represents the net radiation available at the ground surface. It is the sum of net short-wave (K^*) and net long-wave radiation (L^*), and is the basic supply of radiant energy. Q^* is primarily controlled by incoming ($K\downarrow$) and outgoing ($K\uparrow$) short-wave radiation, as the fluxes of long-wave radiation are dependent on the temperature of the atmosphere and the ground surface, which are influenced by $K\downarrow$ and $K\uparrow$. The amount of net radiation available at the surface boundary layer varies both spatially and temporally. At high latitudes in summer, Q^* is relatively high. $K\downarrow$ is large as the sun maintains a high position in the sky through the day, and $K\uparrow$ is small since the albedo of a snow-free, natural surface, such as a coniferous forest, is relatively low (0.05-0.15) (Oke, 1987). In winter, Q^* is relatively low. $K\downarrow$ is low as the sun maintains a low position in the sky, and $K\uparrow$ is proportionately high due to the high albedo of snow-covered surfaces (0.40-0.95).

Q_H (Wm^{-2}) is the flux of sensible heat between the surface and the atmosphere by convection. Q_L (Wm^{-2}) is the latent heat flux, and describes the flux of latent heat into or out of the atmosphere due to evapotranspiration, condensation, sublimation or snowmelt. Q_G (Wm^{-2}) is the ground heat flux, and describes the flux of heat through soil or rock by conduction and convection. For simplicity this equation omits the net energy storage change which results from the absorption or release of energy by a variety of energy sinks and sources, and the influence of advected horizontal heat loss or gain. However these are also important components of the surface energy balance at a site (Oke, 1997).

The partitioning of Q^* into the three fluxes determines the direction and amount of energy available for Q_G and the temperature of the ground surface. Variations in the ground surface temperature can be attributed to the response of the fluxes to changes in physical conditions of the soil and atmosphere. The ground thermal regime is driven by the ground surface temperature, but ground temperatures are influenced by the ground thermal properties of the soil that determine how heat flows through this medium.

2.3 Ground thermal properties

2.3.1 Heat conduction

Heat enters or leaves the ground via Q_G. Given a homogeneous medium in a steady-state, the amount of heat that flows by conduction is:

$$Q_G = -\lambda \, (dT/dz) \qquad [2]$$

where λ is the soil thermal conductivity ($Wm^{-1}K^{-1}$), T is the temperature (°C), z is the depth (m), and dT/dz is the vertical soil temperature gradient.

The thermal conductivity (λ) is defined as the quantity of heat that will flow through a unit area of a substance per unit time under a unit temperature gradient (Williams and Smith, 1989). In a composite material, such as soil, the thermal conductivity is dependent on the conductivities of the soil constituents given by the geometric mean:

$$\lambda = \lambda_m^{(1-p)} \cdot \lambda_w^{(p-q-r)} \cdot \lambda_a^{q} \cdot \lambda_i^{r} \qquad [3]$$

where λ, λ_m, λ_w, λ_a, and λ_i are the thermal conductivities of the ground, mineral materials, water, air and ice, respectively; p is the porosity; and q and r are the volumetric fractions of air and ice (Burn, 2004).

In dry soils, the thermal conductivity increases with an increase in the quartz content, and decreases with an increase in organic content, such as peat. The addition of moisture to a dry soil increases its conductivity mainly because water, which has a higher thermal conductivity, replaces air in the soil pore spaces (Oke, 1987). A substantial increase in thermal conductivity occurs as wet soil freezes, since the thermal conductivity of ice is about four times that of water.

Conductive heat flow is actually more complex than described by equation 2 because a steady-state is rarely achieved with changing surface temperatures, and soil thermal properties vary with depth and time as moisture content changes.

2.3.2 Heat capacity

The temperature change experienced by the soil as a result of the heat transfer described by equation 2 depends on the heat capacity, C_s ($Jm^{-3}{}^{\circ}C^{-1}$) of the soil. The specific heat capacity is the energy required to change the temperature of 1 g of soil by 1°C. Since soils are composite materials, C_s is calculated using a weighted average:

$$C_s = (1\text{-}p)C_m + (p\text{-}q\text{-}r)C_w + qC_a + rC_i \qquad [4]$$

where C_m, C_w, C_a, and C_i are the specific heat capacities of the soil, minerals, water, air and ice, respectively; p is the porosity; and q and r are the volumetric fractions of air and ice (Burn, 2004). For a given amount of heat supplied or removed, changes in temperature will be greater in a material with low heat capacity (Williams and Smith, 1989).

Dry soils have relatively low heat capacities. The addition of moisture to the pore spaces of a soil increases its heat capacity, since water has a higher heat capacity than air (Oke, 1987). During cooling of moist soils at temperatures just below 0°C, the heat capacity appears to increase due to the release of the latent heat of fusion as soil water freezes. The latent heat of fusion releases 3.34MJ per kilogram of water, which must be removed from the ground through the loss of heat to the atmosphere before further cooling can occur. However, there are several reasons why soil water freezes over a range of temperatures rather than at 0°C. Solutes excluded during the formation of pore ice increase the dissolved ion concentration in the remaining unfrozen water (Hallet, 1978), further depressing its freezing point (Banin and Anderson, 1974). Fine grained soils, such as clays, have a high specific surface area, and generally have higher unfrozen water content because water is adsorbed to the more numerous soil particles due to electrostatic interactions (Williams and Smith, 1989). Each soil has a characteristic unfrozen water content curve, and at a given temperature below 0°C, different soils will have different amounts of unfrozen water. The apparent heat capacity (C_a) accounts for both the heat capacity of the soil materials and the heat released by the latent heat of fusion (Williams and Smith, 1989).

$$C_a(T) = C_s(T) + L_f(d\theta_u/dT)_T \qquad [5]$$

As discussed, the specific heat capacity (C_s) of frozen soils varies with temperature due to the change in the fractions of ice and water. The effect of the latent heat of fusion (L_f) is obtained by taking the slope of the unfrozen water content curve ($d\theta_u/dT$) at temperature (T) (Williams and Smith, 1989).

2.3.3 Heat conduction equation

The change in ground temperature over time, in a homogenous medium with vertical conductive heat flow, can be calculated with the heat conduction equation (Williams and Smith, 1989)

$$C(dT/dt) = \lambda(d^2T/dz^2) \qquad [6]$$

where t represents time. Ground temperatures will change most rapidly at the depth where the curvature of the soil temperature profile is greatest.

2.4 Factors controlling ground temperatures

Site physical characteristics affect the partitioning of energy into the fluxes of the surface energy balance and lead to local variation of ground temperatures and active-layer depths.

2.4.1 Snow

Snow increases the effective depth below the surface of points within the ground, which affects the propagation of the surface temperature wave into the ground (Smith, 1975). As a result, the amplitude of the temperature wave at the ground surface is reduced, and in winter, ground temperatures at snow-covered sites are higher than at those without snow.

Snow is an effective insulator because its low thermal conductivity restricts Q_H. It impedes the loss of ground heat and buffers the ground from cold winter air temperatures, with the net effect of raising mean annual ground temperatures (Mackay and McKay, 1974). The effectiveness of snow as an insulator depends on the density and depth of the snow cover (Goodrich, 1982). For example, in the central Mackenzie Delta, windier sites on point bars are associated with low, dense snow, and relatively low ground surface temperatures (Smith, 1975). Field studies in the central Mackenzie Delta have also shown that ground temperatures increase with increasing snow depth, up to a depth of about 50 cm, above which further increases in snow depth have minimal additional influence on ground temperatures (Smith, 1975). In terms of ground surface temperatures, variations in snow cover are most critical at shallow snow depths, indicating that the timing of early-winter snow cover is also an important determinant of ground surface temperature.

Mean annual ground temperatures are influenced by both the timing of snow accumulation, and the maximum snow depth developed over the winter (Goodrich, 1982; Ling and Zhang, 2003). A thick, early snow cover will inhibit the loss of ground heat and frost penetration so that ground temperatures remain relatively warm through the winter. For example, in an open sub-arctic, coniferous forest near Churchill, Manitoba, active-layer freeze-back was delayed until late-December due to a deep, early snowpack (Rouse, 1984a).

The release of latent heat associated with the freezing of moist soils is also a factor in prolonging ground freezing and maintaining warm ground temperatures through the winter. Snow cover is related to the maintenance of moist soil conditions, since the melting of a deep snow pack provides soil moisture throughout the summer and into the period of ground freezing. Rouse (1984a) also observed that a large release of latent heat from moist forest soils contributed to the delay of active-layer freeze-back.

Snow increases the surface albedo, leading to a reduction in the amount of short-wave radiation absorbed at the snow surface, thereby decreasing Q*. The intensity of this effect fluctuates as the albedo of fresh snow is much higher than that of a mature melting snowpack in spring (Zhang, 2005).

2.4.2 Vegetation

In summer, one of the main effects of the vegetative canopy is to intercept radiation, which decreases at the ground surface (Brown and Péwé, 1973; Rouse, 1984a). As a result, summer net radiation at the ground surface, and daytime ground surface temperatures are lower in forested areas in comparison with open sites (Smith, 1975; Rouse, 1984b). The canopy acts as a buffer between the ground and the atmosphere, moving the active surface, where principal radiative exchanges occur, away from the ground surface and into the canopy layer (Oke, 1987, 1997).

Forest canopies have a high aerodynamic roughness that results in greater turbulent exchange with the atmosphere (Oke, 1987), thus greater rates of evapotranspiration occur in the canopy, increasing Q_L (Brown, 1966). In the boreal forest, however, evapotranspiration by coniferous trees is relatively minor due to small leaf surface areas and high stomatal resistance (Pomeroy and Goodison, 1997), resulting in a higher sensible heat flux (Eugester et al., 2000). Shrubs and mosses on the forest floor are more effective contributors to Q_L.

Below the canopy, in the trunk space, windspeed is greatly reduced (Oke, 1987). This leads to a lower Q_H, and reduces the loss of ground heat at times when Q_G is directed towards the atmosphere. For instance, at night the surface temperature remains high, and the ground temperature gradient is low (Brown, 1966). Long-wave cooling of the ground surface at night is reduced in vegetated areas since vegetation absorbs and re-emits long-wave radiation towards the ground surface (Smith, 1975).

An important effect of vegetation on ground temperatures in winter is in enhancing snow accumulation, particularly since snow cover is present for up to eight months in high latitude environments. The ability of vegetation to accumulate snow is positively related to vegetation height, stem diameter and density, and canopy density (Evans et al., 1989).

On point bars of the east central Mackenzie Delta, variation in snow cover, associated with bands of different vegetation structure, controls the distribution of permafrost (Smith, 1975). Tall willows adjacent to channels act as windbreaks and accumulate blowing snow, leading to warmer ground temperatures. In the northern Mackenzie Delta area, snow depth has increased where vegetation has grown in a previously unvegetated drained lake basin (Mackay and Burn, 2002). In response, the active layer has deepened and ground temperatures have gradually increased. In an open canopy, sub-arctic coniferous forest, Rouse (1984b) found much deeper snow than in the adjacent tundra due to the ability of the spruce trees to trap wind-blown snow. Reduced windspeed within the forest also lessened erosion of snow from the site. As a result of a thicker snow cover, winter ground temperatures of the forest were much warmer than those of the tundra.

In contrast, closed forest canopies intercept snow, leading to reduced snow depths and cooler ground temperatures. At a closed-canopy, sub-arctic coniferous stand, over 30% of annual snowfall was intercepted by the canopy and consequently sublimated (Pomeroy and Goodison, 1997). In the east central Mackenzie Delta, snow cover at a closed-canopy site in the spruce forest was lower than that of an adjacent site vegetated by willow and alder with an open canopy, due to canopy interception. Mean annual ground temperatures at 15-m depth were approximately 1°C cooler in the spruce-forest (Smith, 1973). Generally, within sub-arctic forests, areas with less vegetation accumulate the greatest snow depths (Pomeroy and Goodison, 1997). Both open and closed canopy forests are found in the central and southern Mackenzie Delta.

The reflectivity of the vegetative canopy can also affect ground temperatures. Rouse (1984a) noted a significant difference between the albedo at an open canopy, sub-arctic coniferous forest site (0.32) and an open tundra site (0.78) during winter. The forest canopy had a relatively low albedo because much of its snow load was sublimated or had dropped to the ground, especially by late-winter (Pomeroy and Goodison, 1997; Thompson et al., 2004). During late-winter, the forest canopy serves as a heat sink for incoming short-wave radiation, and reflected short-wave radiation from the snow below (Rouse, 1984a). Since trees do not transpire in winter, the radiation trapped by the canopy must be dissipated by long-wave radiative or sensible heat flux. The forest canopy becomes a source of long-wave radiation to the snow below, increasing Q^* and the rate of snowmelt. Loss of the low thermal conductivity snow layer earlier in the spring leads to greater ground heating and increased ground surface temperatures.

2.4.3 Water bodies

In permafrost regions, lakes have a marked warming influence on the surrounding sediments, and affect ground temperatures. Water bodies effectively retain heat due to the high heat capacity of water, and cool more slowly in winter due to the release of latent heat during freezing. Heat loss from lakes is impeded by the presence of snow on the ice cover in winter (Smith, 1976). Though lakes are generally shallow in the Mackenzie Delta, with mean depths ranging from 0.5 to 4.5 m (Lesack et al., 1998), maximum ice thicknesses range from 0.6 to 1.2 m (Marsh and Lesack, 1996). In most lakes of the Mackenzie Delta, the depth of the lake exceeds the winter ice thickness, and an unfrozen talik forms in the sediments underneath (Mackay, 1962). Temperatures of the ground surrounding the lake are affected because heat flows from the warmer sediments under the lake to the colder sediments surrounding the lake (Williams and Smith, 1989). Lakes that freeze to the bottom in winter also increase mean annual ground temperatures beneath them due to delayed winter freeze-back (Crawford and Johnston, 1971).

The problem of the thermal disturbance of water bodies on ground temperatures has been well studied (Lachenbruch, 1957; Mackay, 1962; Johnston and Brown, 1964, 1966), and calculations can be used to estimate the disturbed and undisturbed ground temperature at a particular depth. In the absence of water bodies, the undisturbed ground temperature profile is:

$$T_z = T_g + z/I \qquad [7]$$

(from Burn, 2002b, eq. [4]) where T_z is the temperature (°C) at depth z (m), T_g is the mean annual ground temperature (°C), and I is the geothermal gradient (m°C^{-1}).

Land that is bounded by two water bodies can be thought of as a strip of a specified width that is bounded by a wide channel on one side, and a large lake on the other (Fig. 2.1). Under steady-state conditions, the disturbed ground temperature profile at a point on this strip of land is:

$$T_z = T_w + z/I + [(T_g\text{-}T_w)/\pi]\ [\tan^{-1}(H_{p1}/z) + \tan^{-1}(H_{p2}/z)] \qquad [8]$$

(modified from Burn, 2002b, eq. [4]) where T_w is the mean annual temperature (°C) of the surrounding water, H_{p1} is the width (m) of the strip of land from the channel to the particular point, and H_{p2} is the width (m) of the strip of land from the point to the lake.

Equation 8 indicates that, given a point of land at a specified depth, and a specified distance from a channel, ground temperatures decrease exponentially as the distance between the point of land and the nearest lake increases (Fig. 2.2). As the distance between the point of land and the nearest lake becomes larger, the rate at which ground temperatures decrease is reduced, as the undisturbed ground temperature is

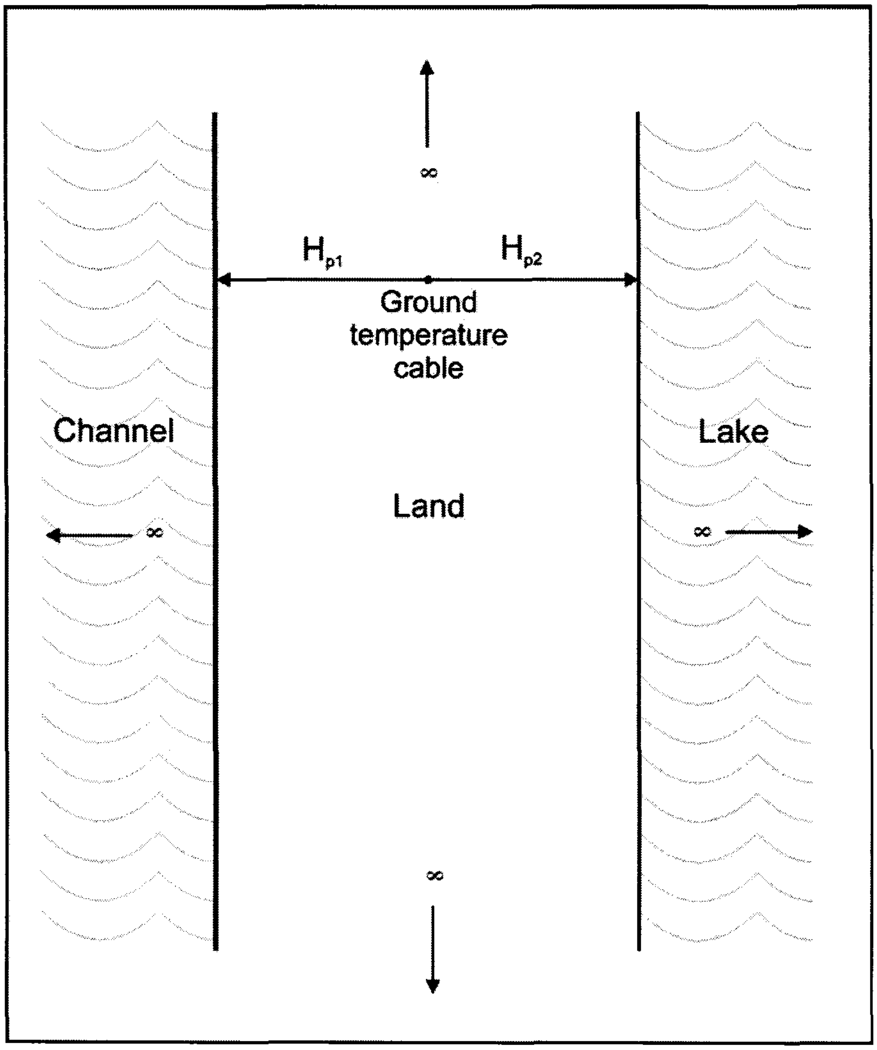

Figure 2.1 Theoretical configuration of ground and water for calculation of thermal disturbance of water in the delta environment.

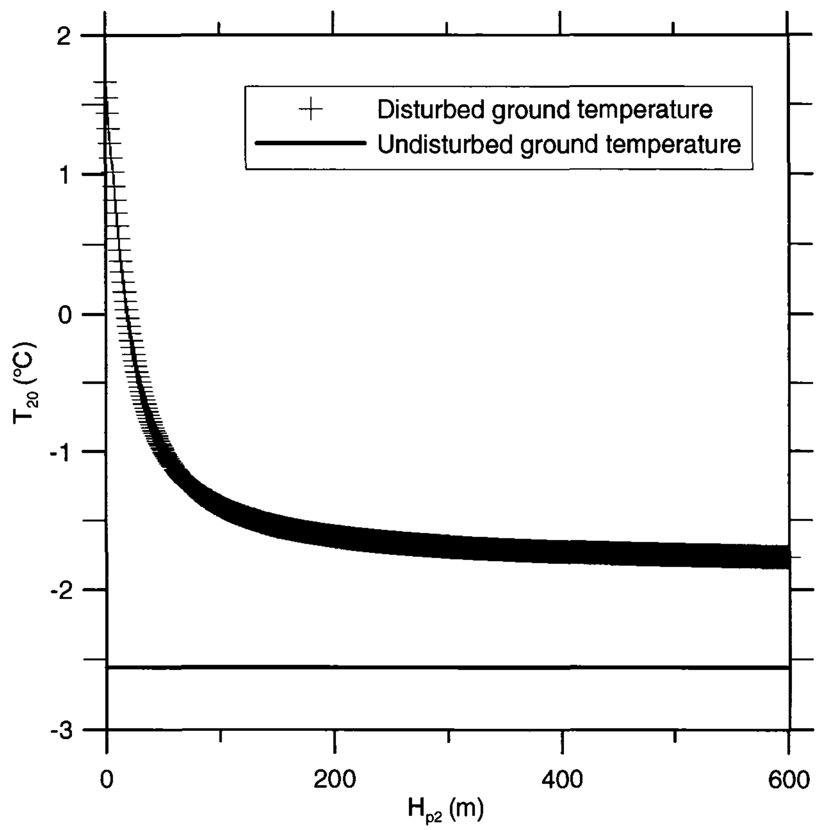

Figure 2.2 Relation between temperature at 20-m depth, and distance between ground temperature borehole and the nearest lake (H_{p2}) ranging from 0 to 600 m, as calculated by equation 8, assuming T_g = -3°C, T_w = 4°C, I = 45 m°C^{-1}, and H_{p1} = 60 m. The chosen values are considered to be representative of conditions in the Mackenzie Delta.

approached. This demonstrates that the thermal influence of water bodies is important when ground temperatures are measured in close proximity to a lake or channel. Water bodies have a lesser influence on ground temperatures at more distant sites.

Equation 8 also indicates that given a constant total distance between water bodies, the difference between disturbed and undisturbed ground temperatures decreases as the depth of the ground temperature measurement becomes more shallow (Table 2.1). This indicates that at a particular location, shallow points in the ground are less affected by the thermal influence of water bodies than deeper points, because they are affected by a smaller radius at the surface.

2.4.4 Organic layer

In summer, the presence of a low thermal conductivity surface organic layer reduces Q_G and lowers ground temperatures (Smith, 1975). The evaporative regime of non-vascular plants also promotes surface cooling (Nelson et al., 1985; Williams and Smith, 1989). During the cool fall and winter periods, wet and frozen organic layers have much higher thermal conductivities than when dry in the summer. This promotes ground heat loss. Thus, organic surface cover, including mosses and lichens, have the net effect of maintaining cold ground temperatures (Farouki, 1981; Oke, 1987).

In the east central Mackenzie Delta, spruce forests with a low thermal conductivity surface moss layer had higher July and August daytime surface temperatures than spruce-forest sites without an organic cover, but subsurface (10-cm) ground temperatures were much colder (Smith, 1975). In the same region, an experiment was conducted at a spruce-forest site with a moss ground cover in which 10-cm ground temperatures were measured at two locations, approximately 1 m apart (Smith, 1975).

Depth (m)	**Disturbed ground temperature (°C)**	**Undisturbed ground temperature (°C)**	**Difference (°C)**
20	-1.54	-2.56	1.02
15	-1.90	-2.67	0.77
10	-2.26	-2.78	0.52
5	-2.63	-2.89	0.26
1	-2.93	-2.98	0.05

Table 2.1 Differences between disturbed and undisturbed ground temperatures, calculated with equations 7 and 8, at varying depths, assuming $T_w = 4°C$, $T_g = -3°C$, $I = 45\ m°C^{-1}$, $H_{p1} = 60$ m, and $H_{p2} = 150$ m. The above values are representative of conditions in the Mackenzie Delta.

After one year of measurements, 10-cm temperatures at the two sites were found to be very similar. The top 10 cm of the surface organic layer were subsequently removed at one of the sites in early-June, and the thermistor was repositioned to the new 10-cm depth. Temperatures recorded for the following six weeks showed that the average daily 10-cm temperatures at the disturbed site were approximately 3°C warmer than that of the undisturbed site. This result indicates that the presence of the surface organic layer at the undisturbed site was responsible for lower summer ground temperatures.

2.4.5 Ground materials

Subsurface conditions can have an important influence on ground temperatures. Sediments in the Mackenzie Delta have generally uniform thermal properties (Smith, 1976), and a narrow range of grain sizes, from fine sands to silts (Gill, 1972; Kokelj and Burn, 2005a). Soils with slightly smaller grain sizes are found in spruce forests, compared to soils adjacent to channels (Gill, 1972; Kokelj and Burn, 2005a). Kokelj and Burn (2005a) found that the unfrozen water content characteristics of sandy silts and clayey silts of the delta were similar, and attributed near-surface ice enrichment to other environmental factors. Due to the uniformity of sediment sizes and their similar unfrozen water content characteristics, it is likely that the effects of variation in sediment texture on ground temperatures in the delta is also minimal in comparison with other environmental factors (Gill, 1971).

2.5 Ground thermal regime

2.5.1 Zero annual amplitude

Near-surface ground temperatures are controlled by the conduction of heat to and from the surface, which is influenced by ground thermal properties. Surface temperatures fluctuate annually with air temperatures, generally following a sinusoidal pattern that may be damped in winter due to snow cover (Carslaw and Jaeger, 1959; Williams and Smith, 1989). The amplitude of this temperature wave decreases exponentially with depth (Burn, 2004) because heat is absorbed by the soil as it is conducted downwards. Phase lag increases with depth at a rate dependent on the soil thermal conductivity and heat capacity (Burn, 2004). The depth at which the surface temperature wave is damped out and the temperature remains effectively constant is called the depth of zero annual amplitude (Fig. 1.2) (van Everdingen, 2005). The temperature at this depth responds to longer-term changes in climate or surface conditions (Williams and Smith, 1989).

2.5.2 Surface offset

Natural materials at the ground surface have varying thermal properties that affect the surface energy balance. For example, snow provides a low thermal conductivity layer between the atmosphere and the ground surface, reducing Q_H and the loss of ground heat. This modification of the surface energy balance leads to a difference between the annual mean air temperature and the annual mean ground surface temperature, called the surface offset (Karunaratne and Burn, 2004). Natural ground surface materials with thermal properties that particularly affect the surface offset include snow, vegetation and soil moisture.

2.5.3 Thermal offset

When ground is in thermal equilibrium, the heat gained in summer is equivalent to the heat lost in winter. Thermal equilibrium is maintained in northern latitudes because a relatively large amount of heat is supplied to the ground over a short summer, but in the longer winter, heat leaves the ground at a lower rate. Thermal equilibrium is achieved because the thermal conductivity of thawed soil in the summer is low relative to frozen soil in the winter since the conductivity of the ice in the frozen soil is almost four times that of water. Due to its low conductivity, the summer soil temperature gradient is steep, with warm ground temperatures near the surface, rapidly declining with depth. In winter, higher conductivity soils readily conduct heat away from the ground, leading to a soil temperature gradient that is less steep. Over a year, this seasonal thermal conductivity difference leads to a curvilinear mean annual ground temperature profile that declines with depth to the base of the active layer, where thermal properties change little over a year (Fig. 1.2). The difference between the mean annual ground surface temperature and the mean annual temperature at the top of permafrost is called the thermal offset (Burn, 2004). This offset can lead to the existence of permafrost in areas where the mean annual ground surface temperature is greater than 0°C (Burn and Smith, 1988). The thermal offset is particularly large in organic-rich soils due to the thermal properties of organic materials.

2.6 Concluding remarks

At the scale of the Mackenzie Delta, surface characteristics play an important role in buffering the ground from air temperatures, and modifying the ground thermal regime. The presence of numerous water bodies in the delta is a primary influence on ground temperatures. In sub-arctic spruce forests, snow has been identified as an important ground temperature control, and its distribution is related to the snow-accumulating ability of the canopy. The presence of a surface organic layer beneath the canopy also influences the ground thermal regime significantly.

CHAPTER THREE

STUDY AREA DESCRIPTION AND METHODS

3.1 Introduction

This study investigates variations of mean annual ground temperatures in relation to different site physical characteristics. Ground temperature cables were installed and site physical characteristics were measured from June 15 to July 21, 2006 at 28 spruce-forest sites in the central and southern Mackenzie Delta. Site physical characteristics were also measured during this period at an additional four existing ground temperature cables in the eastern central delta. To ensure that ground temperatures had re-equilibrated from the thermal disturbance of drilling with water, ground temperatures were measured in August 2006 and again in April 2007, at which time snow conditions were also measured. Ground temperatures and snow conditions were also measured at ten sites near Inuvik in late December 2006. In this chapter, the location and environmental conditions of the study area are described to provide a physical basis for the comparison of the four spruce-forest communities. Field methods are described, and the rationale for their use is explained.

3.2 Mackenzie Delta

3.2.1 Location and geomorphic setting

The Mackenzie Delta is approximately 210 km long, 65 km wide, and trends north-northwest (Fig. 1.1). The delta plain slopes gently from an elevation of 10 m a.s.l., at its apex near Point Separation (67°36'N, 134°04'W), to sea level at the coast (Rampton, 1988). In the central delta near Inuvik, surficial sediments are of a uniform silty texture ranging from 10 to 30 m in thickness, overlying a 20-m layer of fine sand,

and a 20-m layer of dense clay, reaching bedrock at 70-m depth (Johnston and Brown, 1964; Aylsworth et al., 2000). The delta is bounded to the west by the Richardson Mountains and to the east by the Caribou Hills (Mackay, 1963). The delta contains a northern extension of treeline due to an early snow-free season, relatively warm summer soil temperatures, and nutrient enrichment associated with annual flooding (Burn, 2002a; Kokelj and Burn, 2005b). Treeline divides the northern delta, characterized by shrub-tundra vegetation, from the central and southern delta, characterized by the presence of white spruce trees. The Mackenzie Delta contains numerous small, shifting channels and lakes. Three large channels of the Mackenzie River run through the delta, including East Channel, flowing to Kugmallit Bay, and Middle and West channels, flowing to Mackenzie Bay.

3.2.2 Climate

The climate of the Mackenzie Delta is characterized by long, cold winters and short, cool summers. Mean annual air temperatures south of treeline are 1 to 2°C higher than those at the Beaufort Sea coast (Table 3.1). Lower coastal air temperatures are attributed to cool on-shore winds in spring and early summer, when sea ice persists close to shore (Burn, 1997). Precipitation throughout the delta is generally low due to the rainshadow east of the Cordillera (Dyke, 2000). Coastal areas receive significantly less precipitation than areas further south (Table 3.1). The average annual precipitation at Tuktoyaktuk is 152 mm as compared with 243 mm at Inuvik. Lower precipitation at the coast is attributed to the dominance of dry arctic air, and a greater distance from moisture-carrying storms further south (Dyke, 2000).

a.)	Location	Temperature	Oct-Apr	May-Sep	Year
Tuktoyaktuk	69°27'N, 133°02'W	Mean (°C)	-20.7	4.9	-10.1
Inuvik	68°22'N, 133°44'W	Mean (°C)	-19.5	8.3	-7.9
Aklavik	68°13'N, 135°00'W	Mean (°C)	-19.4	8.0	-8.0
Fort McPherson	67°26'N, 134°53'W	Mean (°C)	-19.2	9.2	-7.3

b.)		Precipitation	Oct-Apr	May-Sep	Year
Tuktoyaktuk	69°27'N, 133°02'W	Total (mm)	70.4	81.3	151.8
Inuvik	68°22'N, 133°44'W	Total (mm)	103.8	139.3	243.1
Aklavik	68°13'N, 135°00'W	Total (mm)	128.0	149.1	277.2
Fort McPherson	67°26'N, 134°53'W	Total (mm)	137.7	165.1	302.8

Table 3.1 a) Mean air temperatures; and b) total precipitation at Tuktoyaktuk (1986-1993, 2000-2005), Inuvik (1986-1994, 1997-2005), Aklavik (1992-2005), and Fort McPherson (1986-2005).

Air temperature and precipitation are recorded at three communities in the central and southern delta study regions. Inuvik is located adjacent to the eastern central delta, well above the level of annual flooding, in the Campbell-Dolomite upland; Aklavik is located in the west central delta; and Fort McPherson is located on the Peel River, 10 km south of the delta. Air temperature records are intermittent for these communities, and this is reflected in the periods of record for comparison.

Annual and seasonal air temperature differences between the three meteorological stations in the study area are small (Table 3.1). Mean annual air temperatures are within 0.7°C, and mean winter (October to April) air temperatures are within 0.3°C. Mean summer (May to September) air temperatures are similar at Inuvik and Aklavik, but about 1°C warmer to the south at Fort McPherson. Since mean annual air temperatures are similar amongst the three stations, air temperatures are considered to be uniform throughout the central and southern delta. Substantial differences in mean annual ground temperature are thus related to surface conditions.

Total annual precipitation is similar between the communities, ranging from 243 to 303 mm. Of more importance to mean annual ground temperatures is total precipitation in winter, which represents snowfall (Goodrich, 1982). Total winter precipitation is also similar between the communities, ranging from 104 to 138 mm, with slightly less snow falling in Inuvik, and slightly more falling in Fort McPherson.

Since the climate record at Aklavik is the most complete in recent years, it is used to characterize the contemporary climate of the central and southern delta. Mean monthly air temperatures from 1992 to 2006 indicate that the coldest month is January

(-26.9°C), and the warmest month is July (13.7°C) (Fig. 3.1). Mean monthly precipitation data from 1992 to 2006 indicate that most precipitation falls as rain in the summer months, and that the majority of snow is received in early fall (Fig. 3.1).

The Mackenzie Delta is an area of particularly rapid climate warming (Serreze et al., 2000). Comparison of climate normals from Inuvik and Tuktoyaktuk from 1951 to 2000 indicates an increase in mean annual air temperature of approximately 1°C; however, there has been no corresponding trend in total annual precipitation (Burn et al., 2004).

3.2.3 Hydrology

The Mackenzie Delta is a Holocene feature that has been built up by the deposition of sediments from the Mackenzie and Peel rivers (Mackay, 1963; Cordes et al., 1985; Pearce, 1986). The Mackenzie River is the principal stream, with a mean discharge of 9140 m^3/s, while the Peel River has a mean discharge of 694 m^3/s (Brooks, 2000). Peak discharge occurs from late May to early June, in response to snowmelt (Brooks, 2000). Flooding of land surfaces at this time removes snow much earlier than in the adjacent uplands, initiating ground thaw, and contributing to warmer ground temperatures (Burn, 2002a).

Floodwaters typically inundate much of the land surface in the low-lying northern delta; however, land surface elevations increase southward in two steps, and rates of flooding correspondingly decrease (Mackay, 1963; Hirst et al., 1987). The first increase in elevation occurs between the northern and central delta, near treeline, where the height of the delta plain increases by several meters within a few kilometres (Mackay, 1963). The second increase in elevation occurs between the central and southern delta, just north

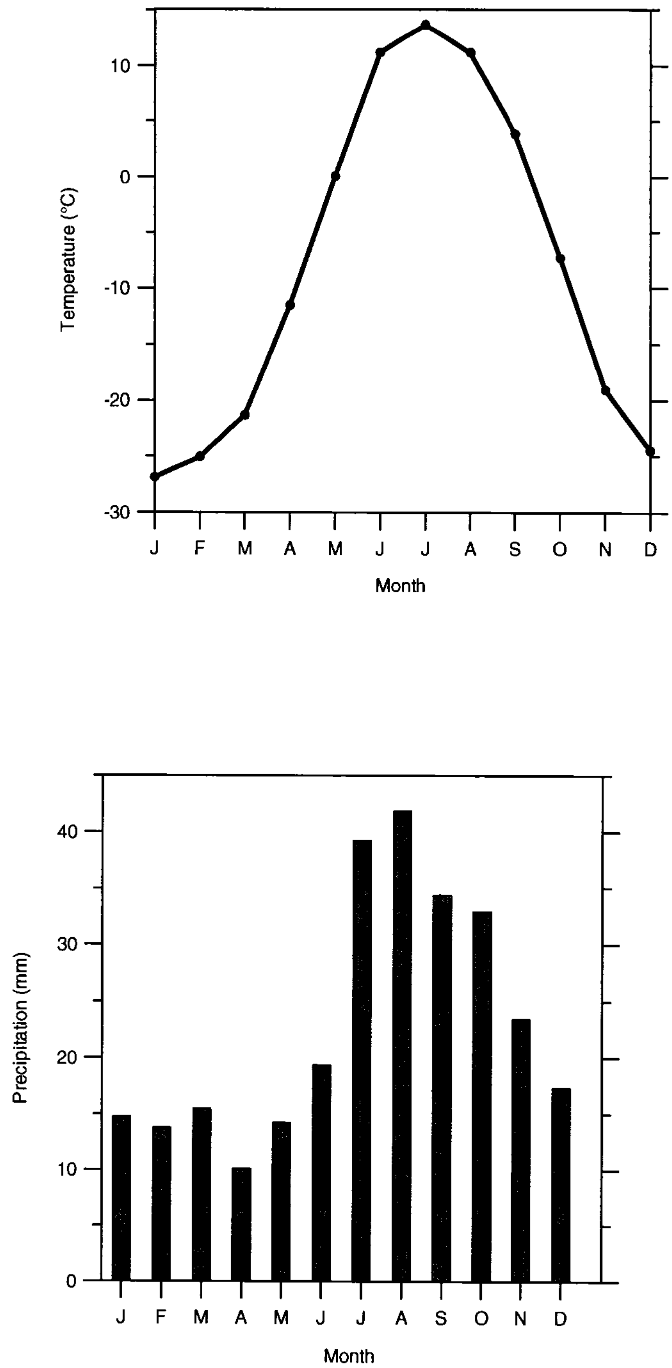

Figure 3.1 Mean monthly air temperature and precipitation at Aklavik, NT, 1992-2005 (Meteorological Service of Canada, 2007).

of Aklavik and Inuvik. The height of the delta plain increases by about 5 m within 15 km (Mackay, 1963). Land surfaces in the southern delta are less likely to flood than those in the central delta due to higher elevation (Cordes et al., 1985; Pearce et al., 1988; Pearce, 1994). Based on previous studies of vegetation patterns (Pearce, 1986; Pearce et al., 1988) and streamflow, flooding of elevated areas in the western delta appears to be much less frequent than in the eastern delta. The flooding regime has been linked to sedimentation and ecological succession (Gill, 1972; Smith, 1975). It may also be related to mean annual ground temperature differences.

The relative productivity of the Mackenzie Delta in relation to the adjacent tundra is attributed to the spring flood of sediment and nutrient-rich water (MacKay and Mackay, 1973; Carson et al., 1999; Kokelj and Burn, 2002b). Sediments from the Mackenzie and Peel rivers originate from glaciolacustrine, morainal and till deposits (Aylsworth et al., 2000). Sediment texture is relatively uniform throughout the delta, but larger grain sizes tend to be deposited close to channel edges, while silt-sized sediments are deposited away from the channels (Kokelj and Burn, 2005a). The average annual sedimentation rate is about 5 mm per year (Johnston and Brown, 1964), but a greater amount of sediment is deposited adjacent to channels. Sparsely vegetated areas beside channels accumulate 4 to 6 cm of sediment annually, while spruce-forest areas, located well away from channels, accumulate <1 mm of sediment in the years that flooding occurs (Pearce, 1998).

3.2.4 Vegetation

Vegetation succession in the delta is strongly influenced by the frequency and duration of flooding and sedimentation (Gill, 1972; Smith, 1975; Pearce et al., 1988).

Vegetative species are adapted to different amounts of flooding and sedimentation, and their dominance in an area changes over time as sediment is deposited or eroded (Viereck, 1970). Throughout the delta, a successional sequence is associated with point bar development. The horsetail (*Equisetum*) community establishes closest to the channel (Fig. 3.2) (Gill, 1973). Thin permafrost may be present beneath this community, as the ground has recently emerged from the river, and in the absence of tall vegetation snow cover is winnowed by wind, exposing the ground to winter air temperatures. Willow-horsetail (*Salix-equisetum*) communities colonize areas further from the channel bank. Permafrost may be absent below this community due to the insulating effect of large snow banks that develop as snow is blown off the channel and trapped by the tall shrubs (Gill, 1973; Smith, 1975). Alder (*Alnus*) communities colonize areas further from the channel (Gill, 1973). These three communities are well adapted to annual flooding, and in the low-lying northern delta, alder (*Alnus*) and willow (*Salix*) communities occupy the highest surfaces.

In the central and southern delta, white spruce (*Picea glauca*) and some poplar (*Populus balsamifera*) forests have colonized the delta plain, which is above the level of annual flooding (Pearce et al., 1988). Unlike the adjacent boreal forest, fire is rare in the central and southern Mackenzie Delta (Pearce et al., 1988), and in the absence of fire, and with reduced flood recurrence and duration, a surface organic layer develops in spruce forests. In conjunction with a thin snow cover associated with the increased interception of snowfall by the forest canopy, these factors lead to lower ground temperatures and thicker permafrost in spruce forests (Smith, 1975).

Spruce-forest succession in the central and southern Mackenzie Delta occurs in

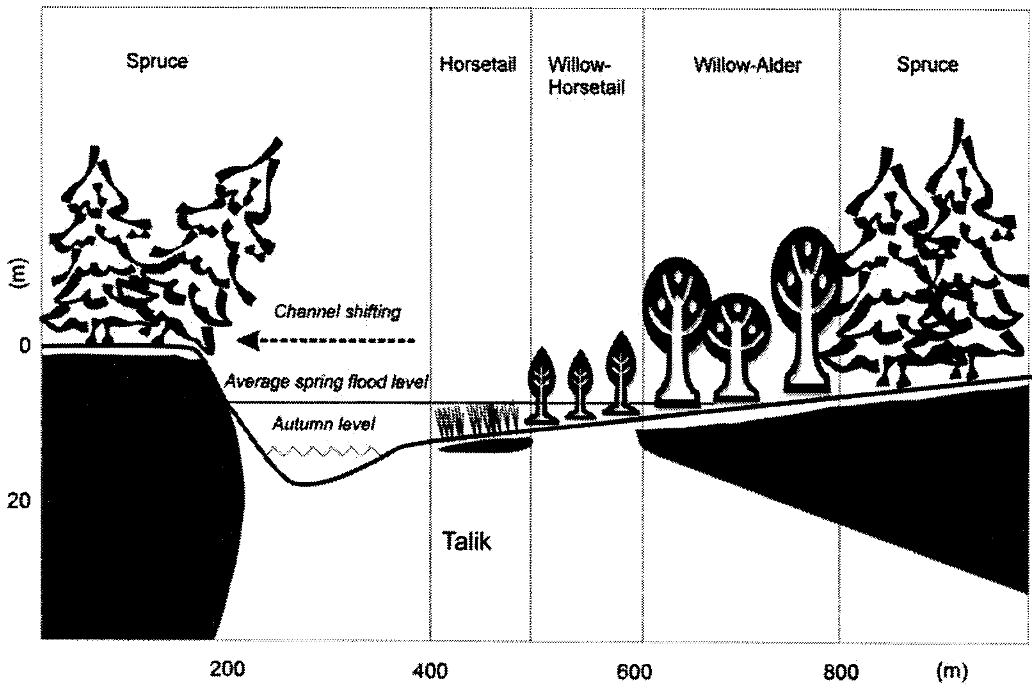

Figure 3.2 Relations between vegetation, flooding, sedimentation, and permafrost on point bars and cut-banks in the central and southern Mackenzie Delta (adapted from Smith, 1975, Fig. 4).

three stages, and four major spruce-forest communities have been described (Gill, 1972; Pearce et al., 1988). These communities have different surface conditions that may affect mean annual ground temperatures. Spruce seedlings initially colonize relatively low elevation sites that are subject to flooding every 5 to 10 years. Spruce/alder-bearberry (*Picea/Alnus-arctostaphylos*) communities subsequently develop that are characterized by dense shrub and herb layers, and the absence of an organic layer (Fig. 3.3a) (Pearce et al., 1988). Canopy cover is relatively open, and trees are well spaced, with an average age of about 200 years (Pearce et al., 1988). As sedimentation raises the land surface over time, flooding becomes less frequent. Spruce/feathermoss (*Picea/Hylocomium*) communities are found at slightly higher elevations that are subject to flooding every 10 to 50 years. Trees are older, with an average age of 300 years, and the canopy is closed. Due to the reduced frequency of alluvial deposition, organic litter accumulates and a moss layer dominates, while herb layers are poorly developed (Pearce et al., 1988).

In this study, it was necessary to divide spruce/feathermoss communities into two sub-groups to capture differences in canopy cover and flooding regime. Closed-spruce/feathermoss communities (Fig. 3.3b) have large white spruce trees, and a closed canopy, while open-spruce/feathermoss communities (Fig. 3.3c) have moderately-sized white spruce trees, and a more open canopy. Closed-spruce/feathermoss sites have thick organic layers, a low moss cover related to more frequent flooding. Open-spruce/feathermoss sites have well developed organic layers, and a high moss cover indicating less frequent flooding.

Sedimentation, organic accumulation and ground-ice development continue to elevate surfaces to heights that rarely flood (Pearce et al., 1988; Kokelj and Burn, 2005a).

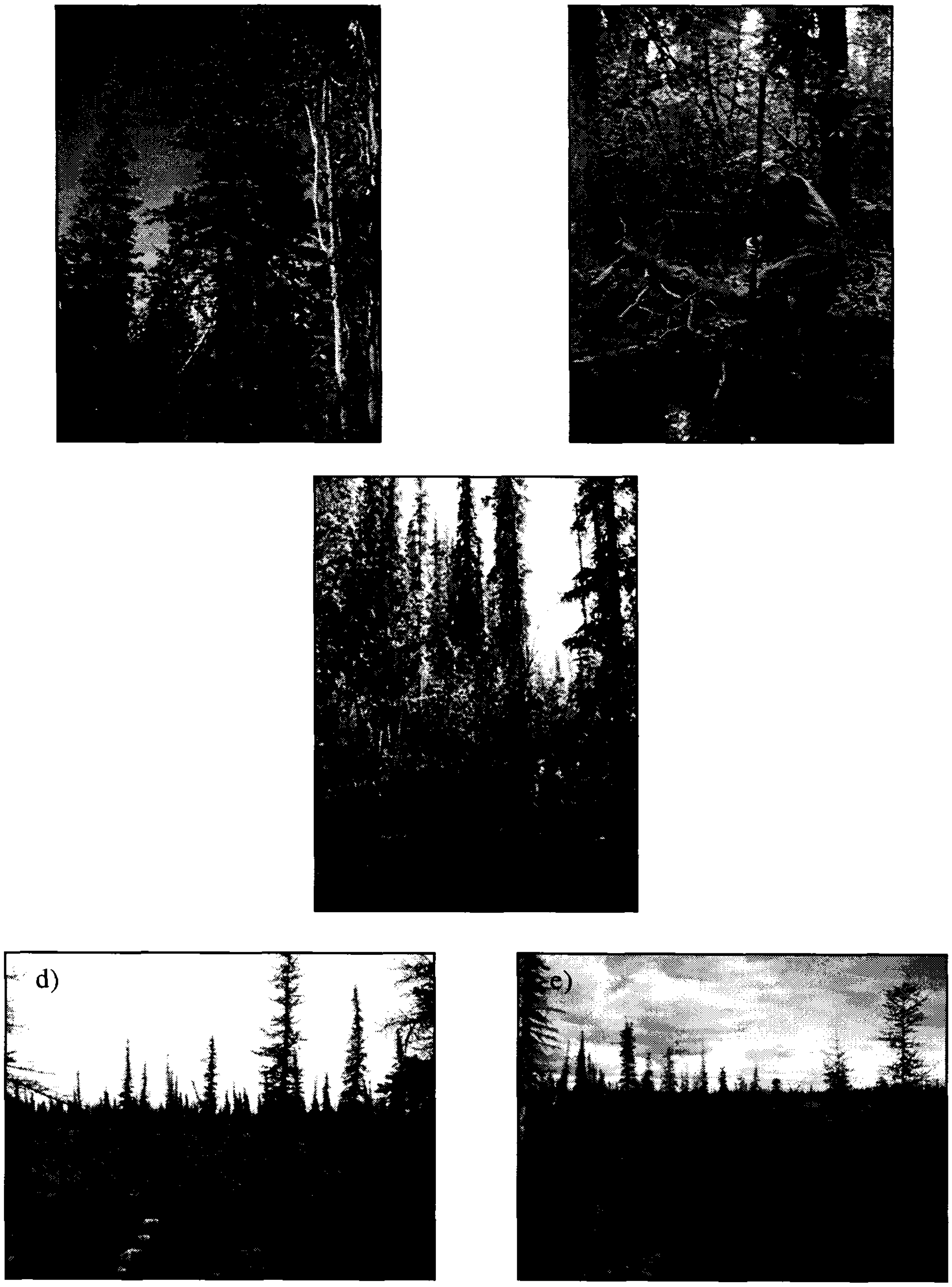

Figure 3.3 Spruce-forest communities: a) spruce/alder-bearberry, b) closed-spruce/feathermoss, c) open-spruce/feathermoss, d) spruce/crowberry-lichen, and e) spruce/tamarack-sphagnum.

Spruce/crowberry-lichen (*Picea/Empetrum-Cladonia*) communities are found at these highest and driest delta sites (Fig. 3.3d). The remaining trees are old, with an average age of 350 to 400 years, and are stunted due to nutrient poor conditions (Kokelj and Burn, 2005b). Canopy cover and tree density are sparse, with many standing dead trees. The herb and shrub layer is also sparse, but there is an abundant ground cover of moss and lichen.

Spruce/tamarack-sphagnum (*Picea/Larix-Sphagnum*) communities have also been identified at high-elevation, poorly drained sites in the western delta (Fig. 3.3e). Drainage is restricted by the high ridges of adjacent relict point bars, and vegetation is adapted to the bog-type conditions. Canopy cover, tree density and tree age characteristics are comparable to those of spruce-crowberry/lichen communities (Pearce et al., 1988).

3.2.5 Permafrost Conditions

3.2.5.1 Permafrost

Permafrost underlying the Mackenzie Delta is generally less than 100 m thick and is spatially discontinuous due to the thermal effect of water bodies (Smith, 1975). Channel shifting, flooding, ecological succession and snow accumulation all influence local variation in the thickness and temperature of permafrost (Gill, 1973; Smith, 1975, 1976). Calculations indicate that permafrost is absent under water bodies wider than 80 to 100 m (Smith, 1976). The talik beneath a river bed shifts with channel migration. Channel shifting can cut into mature, spruce-covered surfaces, leading to permafrost degradation, while permafrost aggrades under new deposits on point bars due to low mean annual surface temperatures (Fig. 3.2). On the bare ground of aggrading point bars, near-surface temperatures are higher (August 10 cm temperature, 13.0°C), while on the cut-bank side of the channel, beneath spruce forests, near-surface temperatures are lower (August 10 cm temperature, 4.8°C) (Smith, 1975). Permafrost is thinner beneath bare point bars (2.5 to 9 m), in comparison to below spruce-forests (50 to 65 m).

3.2.5.2 Ground temperatures

Ground temperature measurements over the past 35 years have been focussed in the northeastern delta, related to hydrocarbon exploration (Smith and Burgess, 2000), while relatively few ground temperature studies have been conducted in the central and southern delta (Mackay, 1967; Johnston and Brown, 1966; Smith, 1975; Tarnocai, 1984). Mackay (1974) produced a generalized map of mean annual ground temperature zones of the Mackenzie Delta region based on 125 measurements from seismic shot holes (Fig. 3.4). Ground temperatures were measured at sites where the thermal disturbance of waterbodies was believed to be negligible, including spruce forests in the Mackenzie Delta.

Mackay's (1974) map shows that mean annual ground temperatures within the central and southern delta are 2 to 3°C higher than those of the adjacent uplands. At a regional scale, higher mean annual ground temperatures in the delta are due to the abundance of water bodies, and their warming effect on underlying sediments. As discussed, annual spring flooding also affects mean annual ground temperatures by removing snow from the delta much earlier than in the uplands, allowing for a longer period of ground heating (Burn, 2002a). Snow is also a more effective insulator in the delta because it is deeper and less dense than on the tundra, since there is less drifting and packing due to wind (Burn, 2002a).

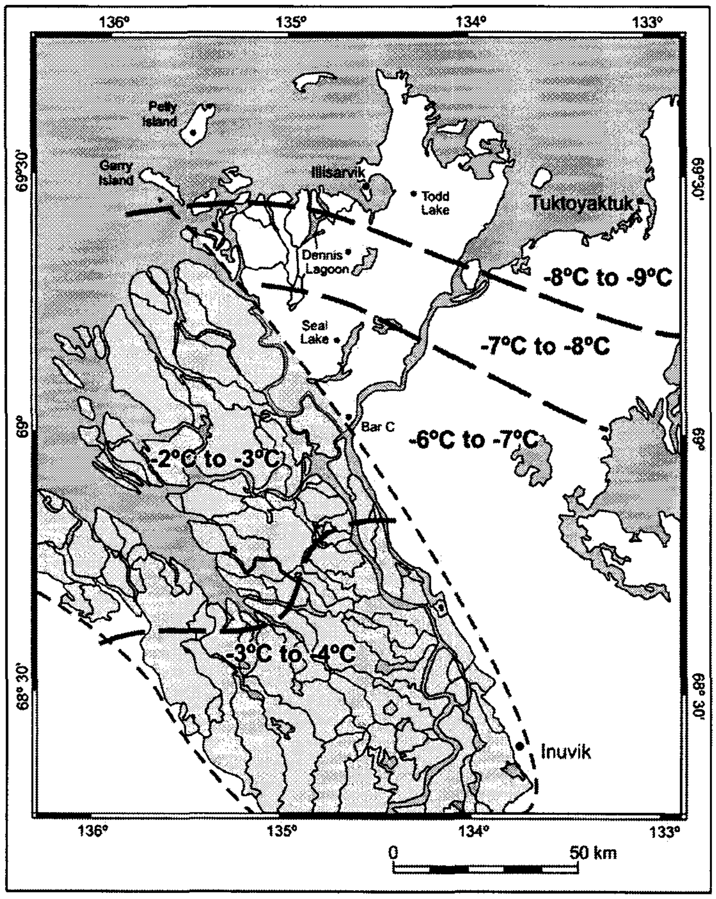

Figure 3.4 Mean annual ground temperatures of the Mackenzie Delta region (from Burn, 2004, unpublished; adapted from Mackay, 1974, Fig. 2).

Mackay's map also shows that ground temperatures within the delta, south of treeline are slightly lower (-3 to -4°), than those north of treeline (-2 to -3°C). Warmer ground in the northern delta is partly due to recent emergence, and more frequent flooding, including storm surges (Pearce, 1986). Ground-temperature differences between the northern and southern delta may also be attributed to vegetation. Low willows of the northern delta capture snow, retarding heat loss in the winter, while snow is retained within spruce-forest canopies of the southern delta, where the thinner layer of snow on the ground leads to a loss of heat.

Mackay's map provides a basis for understanding ground temperature variation in the Mackenzie Delta region; however, it was based on few observations in the central and southern delta, and was measured over thirty years ago. Ground temperatures may have responded to recent climate warming. Recent ground ice studies in the delta have demonstrated that surface conditions associated with different alluvial environments affect vegetation growth and lead to varying ground ice conditions (Kokelj and Burn, 2005a). Variable surface conditions may also lead to mean annual ground temperature differences between the spruce-forest communities. Regional differences in flooding and sedimentation regime may also affect ground temperature variation. There is a need for further study of the variability of mean annual ground temperatures within the central and southern Mackenzie Delta.

3.2.5.3 Near-surface ground ice

Sediment cores collected from the central and southern delta indicate a lack of significant ice accumulation in the profile, with the exception of a concentration of segregated ice near the top of permafrost (Johnston and Brown, 1964; Williams, 1968;

Kokelj and Burn, 2005a). Flooding and sedimentation regimes associated with vegetation succession have been related to near–surface ground-ice development so that vegetation communities have characteristic near-surface ground-ice conditions (Kokelj and Burn, 2005a). In the central and southern delta, elevated, rarely flooded spruce/feathermoss and spruce/crowberry-lichen communities have been associated with particularly high near-surface ground-ice content. A 1 to 2-m layer of near-surface ice accumulation, underlain by alluvium bonded by pore ice is typical at these sites. Ice wedges are also common in the Mackenzie Delta (Mackay, 1963; Kokelj and Burn, 2004). The presence of near-surface ground ice and ice wedges in most spruce-forest communities in the delta implies the terrain may be sensitive to changes in ground surface temperature related to climate warming.

3.3 Field methods

3.3.1 Site selection

Four clusters of six ground temperature measurement sites were established in the west central, east central, southwestern and southeastern regions of the Mackenzie Delta to determine the range of ground temperatures associated with spruce-forest communities in the different regions (Figs. 3.5 – 3.9). Within each cluster, sites were located within spruce/alder-bearberry, closed-spruce/feathermoss, open-spruce/feathermoss, spruce/crowberry-lichen and spruce/tamarack-sphagnum communities. Three additional sites in spruce forests of the east central delta clustered near Inuvik (Fig. 3.9) were previously established by S.V. Kokelj (INAC) in 2004 using the same methods described below. Potential sites were identified on aerial photographs, and final selections were made in the field at the time of drilling.

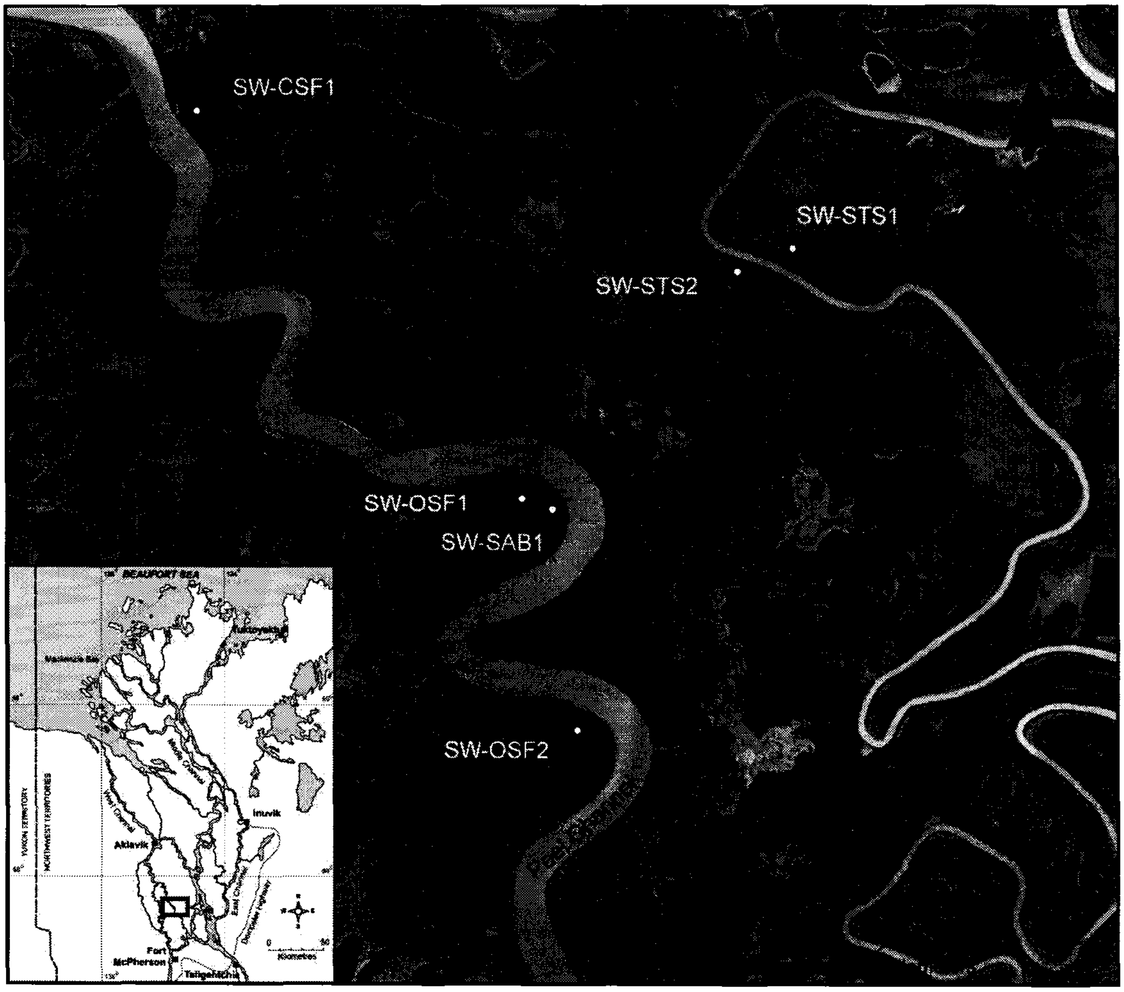

Figure 3.5 Six spruce-forest study sites in the southwestern delta (SW). Sites are identified by two letters representing the delta region, followed by a three letter abbreviation of the spruce-forest community, and a site number.

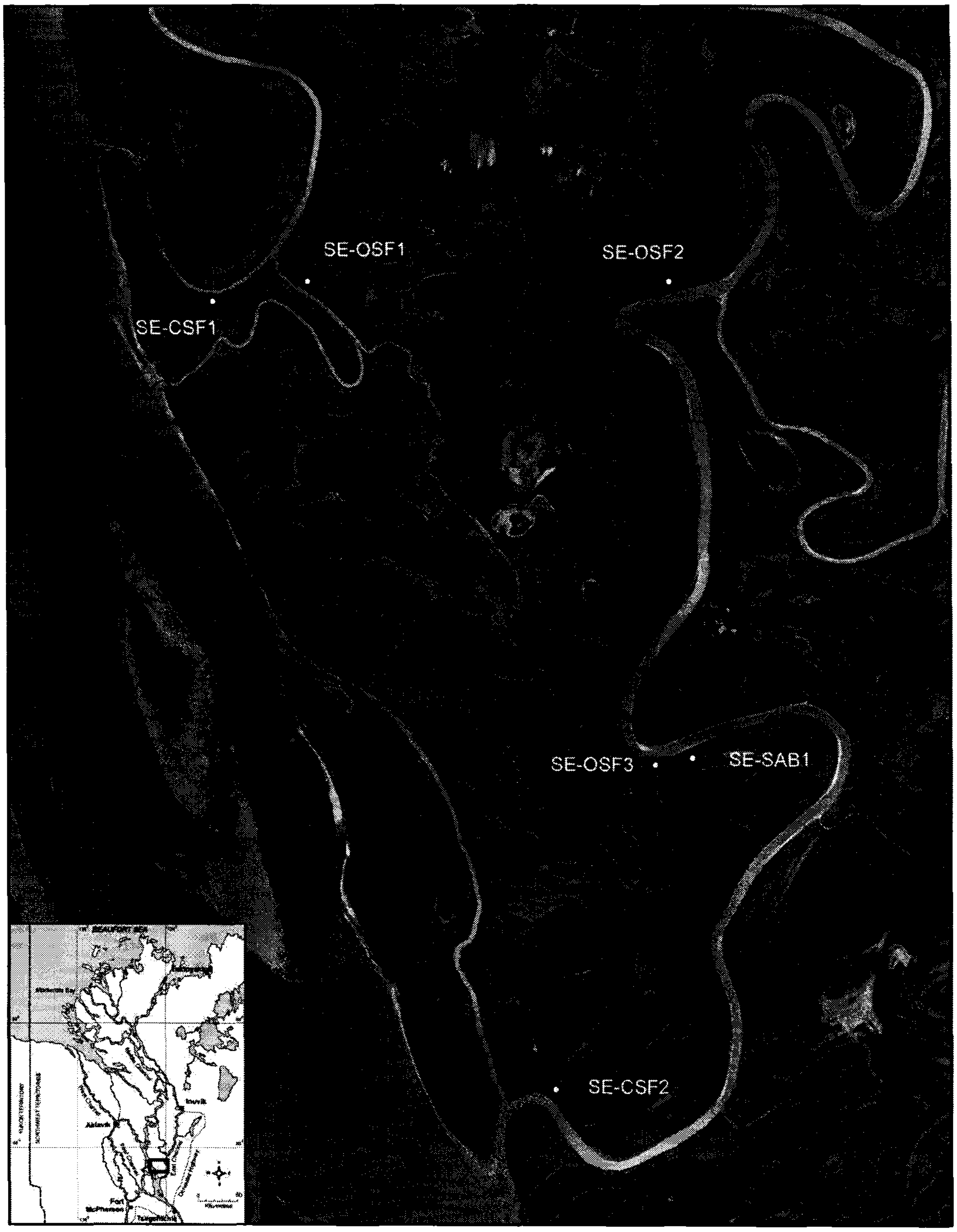

Figure 3.6 Six spruce-forest study sites in the southeastern delta (SE). Sites are identified by two letters representing the delta region, followed by a three letter abbreviation of the spruce-forest community, and a site number.

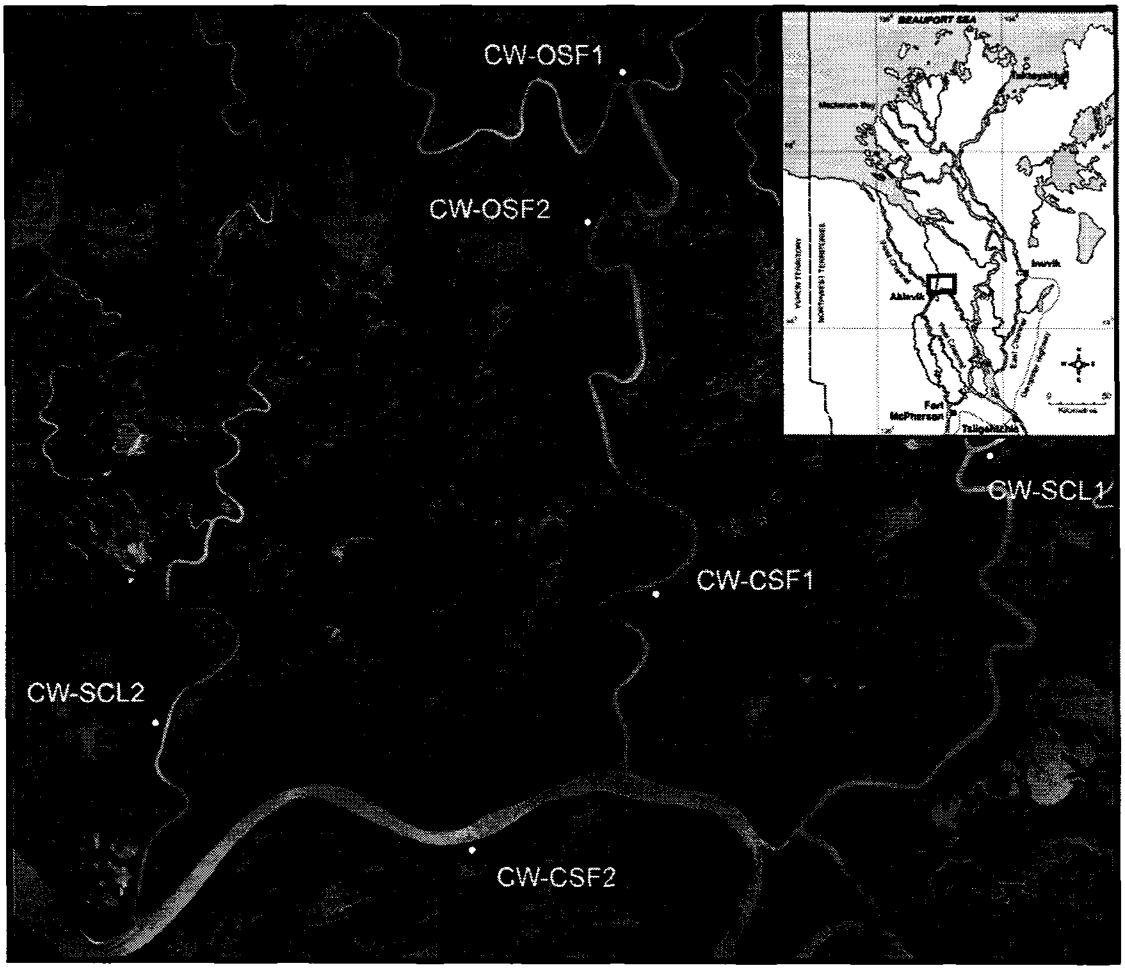

Figure 3.7 Six spruce-forest study sites in the west central delta (CW). Sites are identified by two letters representing the delta region, followed by a three letter abbreviation of the spruce-forest community, and a site number.

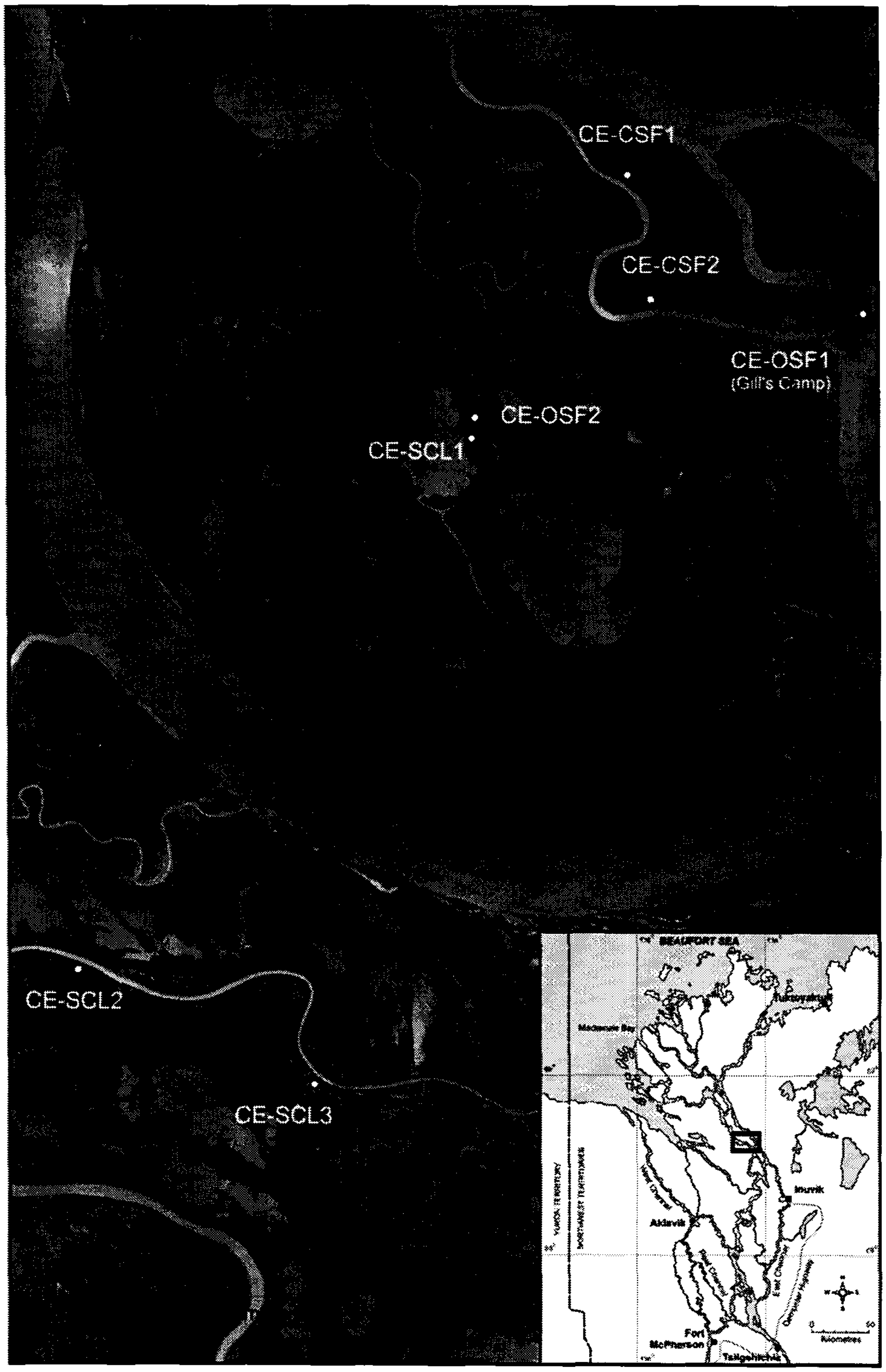

Figure 3.8 Seven spruce-forest study sites in the east central delta (CE), north of Inuvik. Sites are identified by two letters representing the delta region, followed by a three letter abbreviation of the spruce-forest community, and a site number.

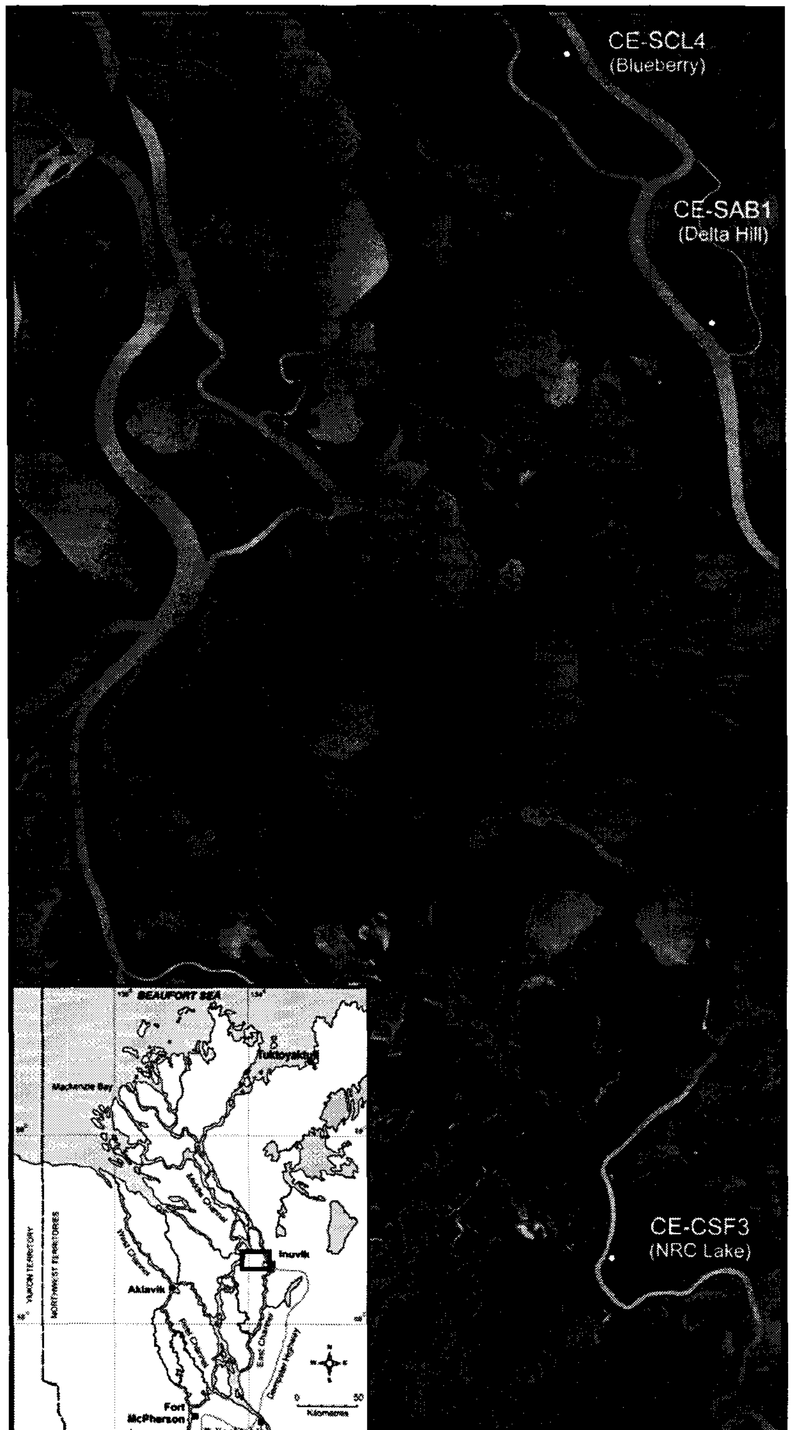

Figure 3.9 Three spruce-forest study sites in the east central delta (CE), near Inuvik. Sites are identified by two letters representing the delta region, followed by a three letter abbreviation of the spruce-forest community, and a site number.

To measure the natural variability of ground temperatures, ground temperature cables were located away from lakes and channels to minimize the thermal disturbance of water bodies. Due to drilling equipment limitations, cables were located approximately 60 m from a channel, and at least 150 m from a lake. To measure the mean annual ground temperature at the depth of zero annual amplitude, boreholes were drilled to 20-m depth. Equation 8 was used to calculate the influence of water bodies on the temperature at 20-m depth. It was assumed that T_w for lakes and rivers in the east central Mackenzie Delta is approximately 4°C (Smith, 1976). An estimate of T_g in the region is -3°C (Mackay, 1974), and an estimate of I in the region is 45 m°C^{-1} (Burn, 2002b). T_{20} was calculated using a value of 60 m for H_{p1}, and 150 m for H_{p2}. The calculated ground temperature for such a site is -1.54°C. This is 1.02°C warmer than the calculated undisturbed ground temperature. Since all sites were established at approximately the same distance from water bodies, their relative temperatures are comparable.

3.3.2 Ground temperatures

A 20-m borehole was drilled at each site using a water-jet pump. The borehole was cased with 1" PVC pipe, and a 3-m length of more durable black iron pipe was used for the final section that extends approximately 1.5 m above ground. At most sites, a 20 m-long, low-voltage, 14-gauge electrical cable instrumented with two BetaTHERM 2.2K3A1A thermistor beads was inserted to the bottom of the casing. Depending on the drilling depth achieved at a particular site, the beads were located between 17 and 21 m depth. The thermistor beads have a range of -80 to 150°C, an accuracy of ±0.1°C from -40 to 100°C, and a resolution of 0.01°C from -40 to 100°C. The thermistor beads were calibrated using an ice bath prior to installation. This improved the accuracy to close to

±0.01°C at 0°C. At seven sites, 20-m length cables instrumented with BetaTHERM 2.2K3A1A thermistor beads at 0.5, 1.0, 1.5, 2.0, 4.0, 7.0, 12.0 and 20.0 m depth were installed to obtain full ground temperature profiles. Thermistor beads at these sites were factory calibrated. Casings were filled with silicone oil to ensure the cables did not freeze in place if moisture was present and to impede convection within the pipe.

3.3.3 Vegetation

Vegetative species composition, frequency, density, and cover were measured at each site to identify the particular spruce-forest community. Species composition was recorded by compiling lists of plant species encountered during sampling. Frequency records the presence of a particular species, and is defined as the number of times a species occurs in a given number of sample points (Mueller-Dombois and Ellenberg, 1974). Density is a quantitative measure that expresses the number of each species per unit area (Mueller-Dombois and Ellenberg, 1975). Cover is the percent of ground occupied by the aerial projection of individuals of a particular species (Greig-Smith, 1983). Several aspects of vegetative structure, including breast-height diameter, height and leaf area index, were measured to assess the relation between vegetation and ground temperatures of the sites. Sampling was stratified into tree, shrub, herb, and ground-cover layers as defined by Pearce et al. (1988). At each site, two perpendicular 20-m transects, centered at the ground temperature cable were established, and vegetative measurements for all layers were conducted along them.

3.3.3.1 Trees

To determine the frequency and density of tree species, all trees greater than 30 cm tall with a stem within 1 m of either side of the two transect centerlines were counted using a strip-width transect method (Mueller-Dombois and Ellenberg, 1974). The species name was recorded and the breast-height diameter (diameter at 1.5 m above the ground) of each tree was measured using a breast-height diameter tape. Breast-height diameter (DBH) is proportional to the area of ground covered by the tree stem, known as the basal area (BA) (Mueller-Dombois and Ellenberg, 1974).

$$BA = \pi(1/2\ DBH)^2 \qquad [9]$$

Basal area and canopy cover have been found to be well correlated in stands of ponderosa pine (*Pinus ponderosa Douglas*) in Colorado and Wyoming, with a canopy cover of less than 60% (Mitchell and Popovich, 1997). The relation breaks down in forests with greater than 60% canopy cover, as trees mature. In boreal forests of Russia, for trees of the same species, the percentage volume of branches increases with increasing DBH (Anuchin, 1970). An increase in the volume of branches implies a more complete canopy cover. Though there are no studies correlating the DBH, BA and canopy cover of white spruce in the Mackenzie Delta, it is inferred from studies in other regions that there is a general positive correlation between DBH and canopy cover. Canopy cover may be related to the mean annual ground temperature by providing ground shading and intercepting snow.

The frequency and density of tree species less than 30 cm tall were counted separately as saplings since they can be diagnostic of a particular spruce-forest community (Pearce et al., 1988). Measurements were conducted along the two 20-m transects using the strip-width transect method described for trees.

3.3.3.2 Shrubs

To determine the frequency and cover of shrubs, those greater than 30 cm tall overlying the two transects were counted at 42 points at meter intervals using a point transect method (Mueller-Dombois and Ellenberg, 1974). The species or genus name was recorded, and the height of these shrubs was determined by an ocular estimate of the highest branch of each intercepted shrub. For consistency, the ocular estimate was performed by the same person at each site. Relative shrub height can be diagnostic of a particular spruce-forest community (Pearce et al., 1988). For all shrub species there is a general positive relation between shrub height and shrub biomass, the total weight of plant material (Buech and Rugg, 1995). In relation to its effect on mean annual ground temperatures, shrub biomass gives an indication of shrub size, and the ability of this layer to shade the ground.

The frequency and cover of shrubs less than 30 cm tall were counted separately as saplings following Pearce et al. (1988). Measurements were conducted along the two 20-m transects using the point transect method described for shrubs.

3.3.3.3 Herbaceous plants and ground cover

The frequency and cover of herbaceous and ground cover species were also determined using the point transect method as described for shrubs (Mueller-Dombois and Ellenberg, 1974). The ground cover layer included bryophytes, lichens, and recently deposited alluvium. Ground cover was recorded at the family level with the exception of feathermoss (*Hylocomium splendens*), sphagnum moss (*Sphagnum*), and reindeer lichen (*Cladina*) since these geni and species are diagnostic of particular spruce-forest communities.

3.3.4 Leaf area index

The leaf area index (LAI), a ratio of the total leaf area of the plant canopy to the ground surface (Mueller-Dombois and Ellenberg, 1974), was measured at each site with a Licor LAI-2000 optical plant canopy analyzer. LAI is related to canopy cover and vegetation structure (Shippert et al., 1995; Riedel et al., 2005). Sites with dense canopy cover or more complex vegetation structure have higher LAI values. LAI may be related to mean annual ground temperatures since canopy cover describes vegetative shading and vegetation structure is associated with snow-holding capacity. Optical analyzers have been effectively used to calculate LAI in boreal forests, though underestimation may occur where vegetation is closely spaced (Chen et al., 1997). Since the relative differences between LAI measurements will be analyzed in terms of their effects on ground temperatures, this underestimation is likely not important.

LAI measurements were made in isotropic conditions, or in cases where direct sun could not be avoided, the lens was shielded. A 45° field of view shield was used to prevent interference from the operator. A reference open-sky measurement was taken out of the forest canopy, at the channel bank, followed by six measurements under the spruce-forest canopy at locations representative of the range of canopy conditions within a 20 m radius of the ground temperature borehole. Measurements were taken at approximately 5 cm above the ground surface. The plant canopy analyzer averaged the sample measurements, and calculated the error. The maximum acceptable error was defined as ±10%, and measurements were redone if this level of error was exceeded. As coniferous white spruce dominate the canopy in these spruce-forest communities, and alder and willow budding begins in May, it was assumed that summer canopy cover remains fairly constant after late June, so that one LAI measurement provides a reliable estimate of a consistent summer canopy cover.

3.3.5 Organic layer

To investigate the effect of the surface organic layer on mean annual ground temperatures, the depth of the surface organic layer was determined by excavating a soil pit near the ground temperature cable at each site.

3.3.6 Thaw depth

Thaw depths were measured at all sites in the last week of August, at the time of maximum thaw, to determine the active-layer depth. Eight thaw depths were measured at locations representative of the range of conditions within a 20 m radius of the ground temperature borehole using a metal probe.

3.3.7 Snow

To determine the effect of snow on mean annual ground temperatures, snow depth and snow density were measured at all sites in April 2007. Snow depths were measured with a graduated snow probe at 5-m intervals along two perpendicular 20-m transects centered near the ground temperature cable. The borehole casing was avoided as standing objects can cause irregularities in snow measurement due to wind scouring and increased melt (Woo, 1997). Five snow density measurements were made at evenly spaced intervals along the two transects using an Eastern Snow Conference snow sampler.

3.4 Identification of spruce-forest communities

Study sites were grouped into spruce/alder-bearberry (SAB), closed-spruce/feathermoss (CSF), open-spruce/feathermoss (OSF), spruce/crowberry-lichen

(SCL), and spruce/tamarack-sphagnum (STS) communities based on previous ecological classifications of spruce forests in the Mackenzie Delta (Gill, 1972; Pearce et al., 1988). Vegetative characteristics of the spruce-forest communities, including frequency, percent cover, and mean density of plant species are presented in Tables 3.2 and 3.3.

3.4.1 Cluster analysis

A hierarchical cluster analysis was used to confirm the grouping of the study sites into spruce-forest communities using SPSS v.14.0. Clusters were grouped by agglomeration so that sites with the shortest amalgamation distance were clustered first, using the squared Euclidean distance, and minimum variance clustering (Ward, 1963; Shaw, 2003). These techniques were used because they are the most widely-used clustering techniques (Shaw, 2003). Attribute data for each site included the number of times each plant species or newly deposited alluvium was encountered on the survey transect, and the mean white spruce DBH at each site. Given the importance of tree size in defining the spruce-forest communities (Pearce et al., 1988), the DBH values were double weighted in the cluster analysis (Heeler and Day, 1975). A variety of clustering algorithms were tested, and similar clusters were formed using several methods, indicating the validity of the clusters. The raw data were randomly re-ordered several times, and using the minimum variance algorithm, the same clusters were generated, indicating that the classification is a meaningful ordering of the data, and not an artefact of the data entry order.

Interpretation of the cluster analysis resulted in five groups: SAB, CSF, OSF, SCL, and STS (Fig. 3.10). The cluster analysis is based on a dissimilarity matrix that indicates the degree of dissimilarity between pairs of sites (Table 3.4). Lower values

	Total sites (n=28)	SAB (n=3)		CSF (n=8)		OSF (n=9)		SCL (n=6)		STS (n=2)	
Common name	*Family/Genus/Species*	**Freq.** (%)	**Mean Density** (m^{-2})	**Freq.** (%)	**Mean Density** (m^{-2})	**Freq.** (%)	**Mean Density** (m^{-2})	**Freq.** (%)	**Mean Density** (m^{-2})	**Freq.** (%)	**Mean Density** (m^{-2})
Tree layer											
White spruce	*Picea glauca*	100	0.15	100	0.08	100	0.14	100	0.1	100	0.3
Seedlings	*Picea glauca*	67	0.24	63	0.04	56	0.08	83	0.06	-	-
Tamarack	*Larix larcina*	-	-	-	-	-	-	-	-	50	0.09
Poplar	*Populus balsamifera*	67	0.05	-	-	-	-	-	-	-	-

Table 3.2 Species composition, frequency, and mean density for the tree layer of the spruce-forest communities. Frequency refers to the percent of sites in a community at which a particular species was present. Data based on 2 x 20 m transects.

	Total sites (n=28)	SAB (n=3)		CSF (n=8)		OSF (n=9)		SCL (n=6)		STS (n=2)	
Common name	*Family/Genus/Species*	**Freq. (%)**	**Mean % cover**	**Freq. (%)**	**Mean % cover**	**Freq. (%)**	**Mean % cover**	**Freq. (%)**	**Mean % cover**	**Freq. (%)**	**Mean % cover**
Shrub layer											
Green alder	*Alnus crispa*	67	51	100	52	100	48	100	40	100	30
Seedlings	*Alnus crispa*	67	19	88	20	78	12	67	9	-	-
Willow	*Salix spp.*	100	57	100	14	100	12	100	37	100	11
Seedlings	*Salix spp.*	33	2	63	7	44	9	100	21	50	4
Herb layer											
Prickly rose	*Rosa acicularis*	67	2	100	28	89	14	83	5	-	-
Alpine sweet-vetch	*Hedysarum alpinum*	100	15	88	34	56	7	33	1	-	-
Arctic wintergreen	*Pyrola grandiflora*	100	38	100	31	100	53	83	17	100	2
Red bearberry	*Arctostaphylos rubra*	100	34	100	31	100	26	100	66	50	2
Common horsetail	*Equisetum arvense*	33	2	75	17	67	11	17	3	-	-
Dwarf scouring rush	*E. scirpoides*	67	2	25	3	67	10	100	62	100	17
Bog blueberry	*Vaccinium ulignosum*	-	-	13	1	-	-	83	26	100	92
Lingonberry	*V. vitis-idaea*	33	3	25	4	33	9	83	27	100	65
Labrador tea	*Ledum*	-	-	13	0.3	11	1	67	21	100	64
Crowberry	*Empetrum nigrum*	-	-	13	3	33	11	100	43	100	54
Sedge	*Carex*	-	-	-	-	-	-	17	1	100	2
Cloudberry	*Rubus chameaemorus*	-	-	-	-	-	-	-	-	100	12
Moss layer											
Feathermoss	*Hylocomium splendens*	33	1	88	6	100	56	100	41	100	51
Sphagnum moss	*Sphagnum*	-	-	50	5	22	2	50	7	100	23
Other moss	*Moss*	100	13	75	4	44	6	83	13	50	5
Reindeer lichen	*Cladina*	-	-	-	-	11	1	33	6	-	-
Other lichen	*Lichen*	-	-	-	-	33	4	50	6	50	11
New alluvium		100	95	88	60	-	-	-	-	-	-

Table 3.3 Species composition, frequency and mean percent cover for the shrub, herb and moss layers. Frequency refers to percent of sites in a community at which a particular species was present. Data based on 2 x 20 m transects.

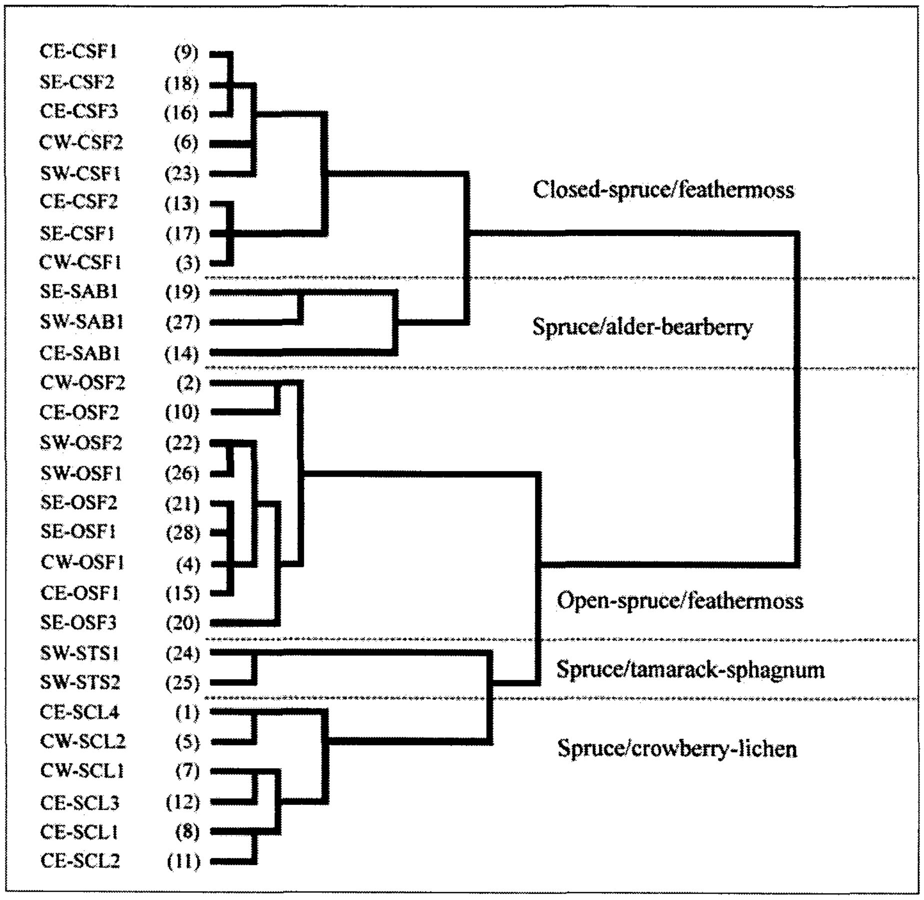

Figure 3.10 Cluster dendrogram of spruce-forest vegetation data. Dotted lines separate sites by spruce-forest community. Site names are given, and corresponding numbers used to identify sites in Table 3.4 are shown in parentheses.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
1	0.00																											
2	3.61	0.00																										
3	7.35	5.83	0.00																									
4	4.50	2.44	2.15	0.00																								
5	2.15	2.27	5.93	3.01	0.00																							
6	6.14	5.50	***1.95***	***1.94***	4.51	0.00																						
7	3.24	4.53	4.91	3.08	3.47	3.29	0.00																					
8	4.40	3.16	4.60	***1.86***	2.53	3.48	3.46	0.00																				
9	5.63	4.47	***1.44***	3.00	4.63	***1.81***	4.38	4.33	0.00																			
10	4.54	2.70	4.85	2.33	3.60	4.38	2.39	3.06	3.96	0.00																		
11	4.13	5.88	5.94	4.34	2.56	4.08	3.27	2.44	5.48	5.10	0.00																	
12	4.35	5.84	4.56	2.93	3.51	3.04	***1.68***	2.01	4.69	3.56	***1.72***	0.00																
13	5.73	4.39	***1.23***	***1.64***	4.19	2.14	3.71	3.03	***1.76***	3.57	4.15	3.35	0.00															
14	8.28	6.43	8.29	7.15	6.32	5.81	7.92	8.08	4.96	8.55	7.88	9.04	7.09	0.00														
15	3.62	***1.97***	2.73	***1.26***	2.60	2.81	3.23	***1.90***	2.08	2.31	3.66	3.67	***1.18***	5.64	0.00													
16	6.72	5.73	2.05	3.75	5.22	2.00	5.71	5.12	**0.66**	5.67	5.82	5.73	2.65	3.65	2.94	0.00												
17	6.02	4.09	**0.87**	***1.09***	4.61	***1.77***	3.84	2.45	***1.98***	3.79	4.48	3.51	**0.80**	6.50	***1.34***	2.50	0.00											
18	5.63	4.64	2.07	3.28	5.10	2.18	5.22	5.02	**0.48**	4.27	6.38	5.76	2.74	5.78	2.24	***1.07***	2.69	0.00										
19	9.61	5.44	6.46	5.66	5.93	4.84	8.52	8.08	4.99	6.73	10.01	9.83	6.55	8.28	6.32	5.41	6.66	5.49	0.00									
20	4.44	4.09	4.10	***1.89***	5.30	3.56	3.35	3.84	4.51	3.67	6.86	3.64	3.36	10.59	3.15	6.23	3.31	4.65	8.48	0.00								
21	3.69	2.18	2.71	**0.54**	3.07	3.08	3.44	***1.95***	2.78	2.01	4.83	3.33	***1.79***	7.71	***1.10***	3.91	***1.74***	3.16	6.38	***1.65***	0.00							
22	3.28	2.31	3.76	***1.54***	3.27	4.06	3.55	2.67	3.05	2.39	5.63	3.62	2.77	6.95	***1.41***	4.33	2.62	3.29	7.05	2.00	**0.83**	0.00						
23	7.52	7.81	***1.62***	3.89	7.45	2.01	5.91	5.54	***1.39***	6.10	6.47	5.11	2.69	7.81	3.40	2.05	2.28	***1.34***	8.21	4.95	4.20	4.09	0.00					
24	3.06	5.37	10.76	7.40	5.27	9.23	4.59	7.69	8.26	5.35	8.42	8.52	8.74	10.90	5.84	9.78	9.54	7.96	11.90	7.40	6.50	6.25	11.26	0.00				
25	2.04	5.71	9.07	6.30	5.04	7.62	2.70	6.99	7.22	4.35	7.52	6.21	7.52	11.38	5.42	9.01	8.03	7.16	11.30	5.33	5.48	5.05	9.42	***1.84***	0.00			
26	3.88	2.06	3.20	***1.19***	3.32	3.66	3.97	3.15	3.17	2.27	6.24	4.48	2.66	7.86	***1.53***	4.45	2.35	3.24	4.98	2.01	**0.94**	**0.53**	4.19	6.91	5.38	0.00		
27	5.49	3.19	5.54	4.34	4.90	4.13	6.20	6.19	2.37	4.01	8.31	8.31	4.85	5.85	3.15	3.50	5.30	***1.91***	4.26	5.35	3.70	4.26	5.11	6.13	6.45	3.86	0.00	
28	4.74	2.24	2.30	**0.57**	3.61	2.89	3.92	2.17	2.71	2.26	5.19	4.13	***1.55***	7.24	**0.83**	3.30	***1.35***	2.77	6.16	2.42	**0.53**	***1.61***	4.11	6.56	6.28	***1.41***	3.70	0.00

Table 3.4 Dissimilarity matrix for cluster analysis of spruce-forest vegetation data. Site numbers correspond with those on the cluster dendrogram. Pairs with lower values have a similar vegetative composition. Values less than 2.00 are underlined in bold italics, and those less than or equal to 1.00 are underlined in bold.

indicate a high degree of similarity between a pair. Dissimilarity values can be used to quantify the differences within spruce-forest communities. Values are low (≤ 1.8) between sites within the CSF and STS communities, indicating that within these groups, sites are relatively homogeneous. Values are higher (≤ 2.8) between sites within the OSF and SCL communities, demonstrating that there is more variation between these sites. Dissimilarity values are highest (~ 6.2) between sites in the SAB community. The SAB sites are more variable in terms of vegetative characteristics; however, their grouping is confirmed by shared physical characteristics that were not considered in the cluster analysis, including thicker snow covers and active layers and thin organic layers.

Dissimilarity values can also be used to quantify differences between spruce-forest communities. Values are lowest (~ 4.1) between sites in the SAB and CSF communities. These values indicate that these two communities are most closely related in terms of vegetative composition. In addition, the flooding regime is similar, evidenced by the observations of newly deposited alluvium in these communities, and its absence from the others (Table 3.3). Dissimilarity values between the OSF and SCL communities are also relatively low (~ 4.2), indicating a high degree of vegetative similarity. Vegetation assemblages at OSF communities are less related (~5.3) to those of CSF communities. The STS community is the most unique assemblage, and is most closely related (~ 6.3) to the SCL community.

CHAPTER FOUR

SURFACE CONDITIONS IN THE SPRUCE-FOREST COMMUNITIES

4.1 Introduction

The previous chapter described the range of environmental conditions in the central and southern Mackenzie Delta. Characteristics of the five spruce-forest communities were discussed. In this chapter, surface conditions of the 28 spruce-forest study sites are described. The relations between spruce-forest communities and site physical characteristics are presented to provide context within which to examine variation in ground temperatures.

4.2 Surface conditions

Variation in surface conditions among spruce-forest communities were compared graphically using box and whisker plots. Based on previous ecological classifications of spruce-forests in the Mackenzie Delta outlined in chapter 3 (Gill, 1972; Pearce et al. 1988), it was expected that the distributions of white spruce DBH, shrub height, snow depth and organic-layer depth would differ between the communities. Following graphical comparison of these variables, pair-wise testing of differences between the distributions of these variables was conducted using a two-tailed, non-parametric Mann-Whitney U test (Table 4.1). Pair-wise testing was conducted instead of a multiple group comparison because the Mann-Whitney U test can be used with small sample sizes ($n \geq 3$). The very small sample size ($n=2$) of the STS community precluded its inclusion in the statistical comparisons. The Bonferroni correction was used to adjust p-values when multiple comparisons were made using the same data, to account for cumulative Type 1 error (Scheiner, 2001).

		Critical value	Mann-Whitney U	P-value	Significance level
Mean white spruce DBH					
SAB	CSF	2	0	0.028	0.05
CSF	OSF	15	1.5	0.002	0.05
Mean shrub height					
CSF	SCL	8	5	0.014	0.05
Mean April snow depth					
SAB	CSF	2	2	0.082	0.05
CSF	SCL	8	5.5	0.034	0.05

Table 4.1 Mann-Whitney U two-tailed tests of independence of surface condition data distributions for SAB, CSF, OSF and SCL communities. If U is less than the critical value, then the null hypothesis is rejected, and the communities are significantly different. The p-value is the chance that random sampling would result in the observed value of U if there is no significant difference between the two communities. In cases where multiple comparisons were made, the p-value was adjusted using the Bonferroni correction by multiplying by the number of tests.

Data from all of the study sites were used to determine correlations between the surface conditions using Spearman's rank correlation coefficient (R_s), a non-parametric test of the direction and strength of the relation between two variables (Triola, 1994) at the 0.01 and 0.05 levels of significance (α) (Table 4.2).

4.2.1 White-spruce canopy cover

The smallest diameter white spruce trees are located in the SAB and STS communities (Fig. 4.1). As described in chapter 3, there is a positive correlation between breast height diameter and canopy cover in southern forests. Thus it is inferred that small diameter white spruce trees in the Mackenzie Delta have relatively open canopies with a low degree of snow interception. In contrast, the largest white spruce trees are located at CSF sites, indicating closed canopies, with a high degree of snow interception. White spruce trees of the CSF community are significantly larger than those of the SAB and OSF communities (Table 4.1). White spruce trees are similarly sized in the OSF and SCL communities, and canopy cover is more open in these two communities than in the CSF community.

Tree density is the sum of white spruce, poplar and tamarack densities, and is a measure of tree spacing. Tree densities are similar between the spruce-forest communities (Fig. 4.2). The higher median value in the STS community is caused by one site with an extremely high density. Trees are very small at this site, so the greater number of trees does little to affect canopy cover. The lack of variation of tree density between sites suggests that coniferous canopy cover is best described by the white spruce DBH, which is more variable between sites.

	Mean white spruce DBH	Tree density	Mean snow depth (Dec.) [n=10]	Mean snow depth (Apr.)	Mean snow density	Mean shrub height	Leaf area index	Shrub cover	Organic layer depth	Distance between channel and lake
Mean spruce DBH	1									
Tree density	**-0.612** p=0.001	1								
Mean snow depth	***-0.712*** p=0.021	0.35	1							
Mean snow depth (Apr.)	**-0.501** p=0.008	0.231	**0.969** p=0.001	1						
Mean snow density	-0.006	0.119	0.171	0.131	1					
Mean shrub height	***0.459*** p=0.014	-0.195	**-0.884** p=0.001	**-0.731** p=0.001	-0.258	1				
Leaf area index	***0.45*** p=0.021	0.004	**-0.828** p=0.006	**-0.595** p=0.001	0.197	**0.615** p=0.001	1			
Shrub cover	0.087	-0.333	0.104	0.06	-0.172	0.195	0.254	1		
Organic layer depth	0.177	-0.021	0.453	0.241	0.018	-0.189	-0.145	-0.358	1	
Distance between	-0.248	0.13	0.512	0.297	***0.402*** p=0.034	-0.358	-0.108	0.019	-0.023	1

Table 4.2 Spearman's rank correlation coefficients for spruce-forest vegetation and surface condition data. Significant correlations at the 0.05 level of significance are presented in bold italics, and at the 0.01 level of significance in bold. The p-value is the percent chance that random sampling would result in an R_s value as far from zero as observed, if there is no relation between the two variables.

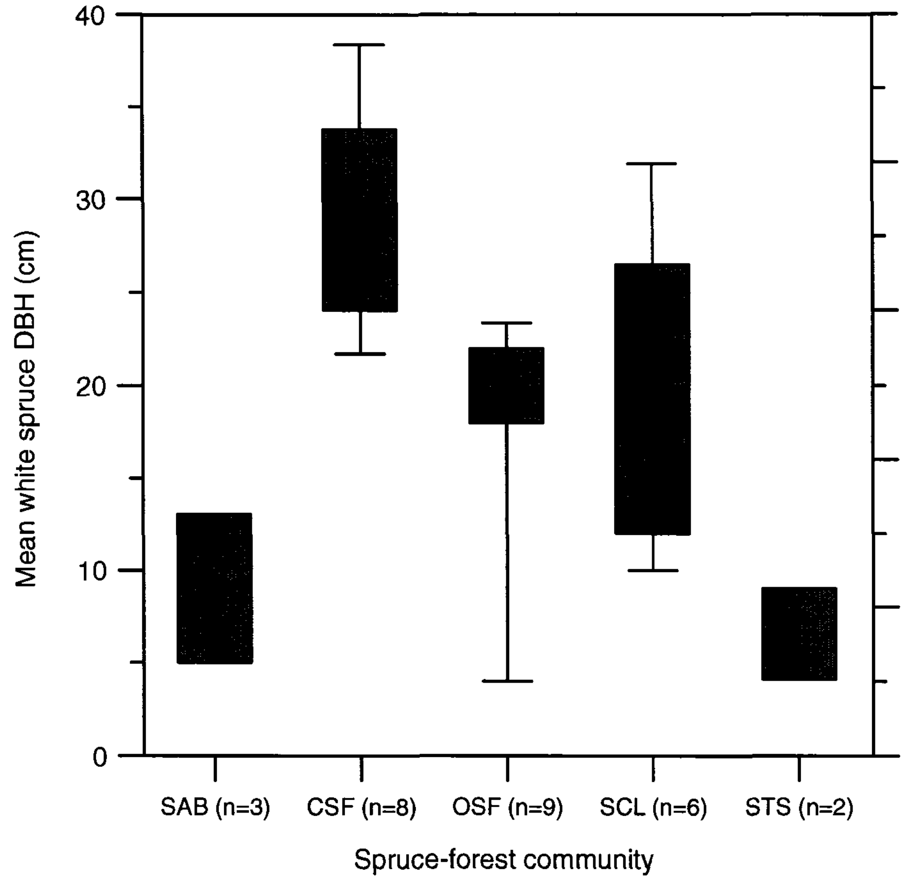

Figure 4.1 White spruce diameter by spruce-forest community. Maximum and minimum indicated by whiskers, interquartile range indicated by box, and median indicated by line in box. Spruce-forest communities include spruce/alder-bearberry (SAB), closed-spruce/feathermoss (CSF), open-spruce/feathermoss (OSF), spruce-crowberry/lichen (SCL), and spruce/tamarack-sphagnum (STS).

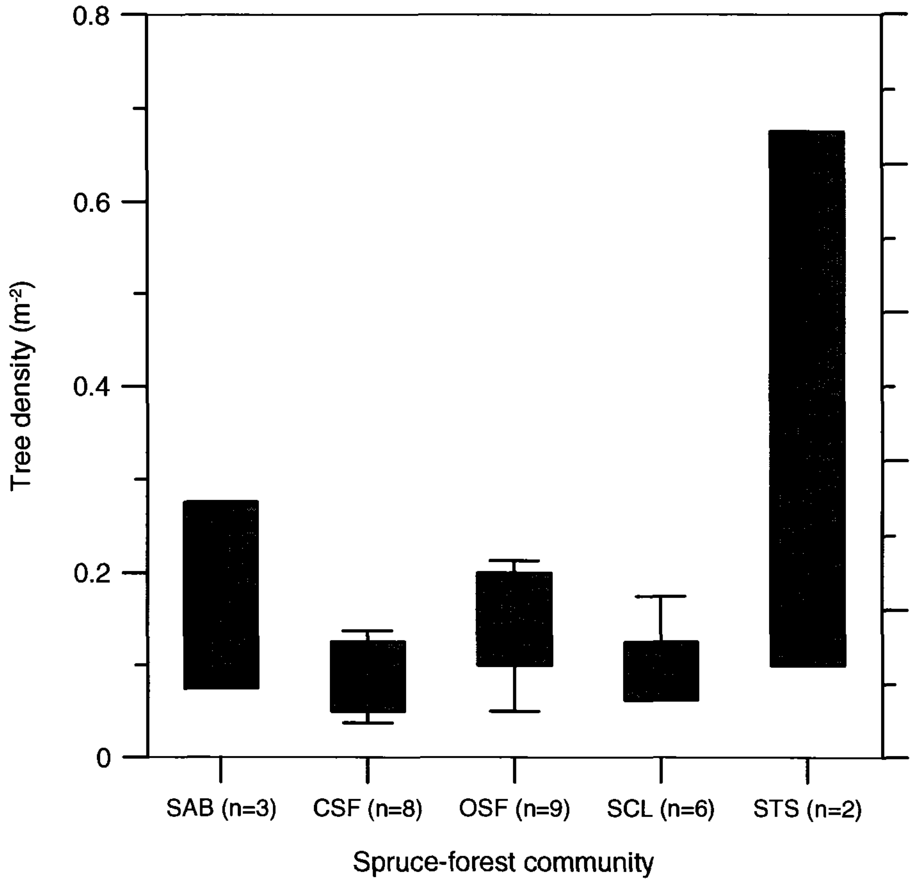

Figure 4.2 Tree density by spruce-forest community. Maximum and minimum indicated by whiskers, interquartile range indicated by box, and median indicated by line in box. Spruce-forest communities include spruce/alder-bearberry (SAB), closed-spruce/feathermoss (CSF), open-spruce/feathermoss (OSF), spruce-crowberry/lichen (SCL), and spruce/tamarack-sphagnum (STS). Note that the difference between the STS community and the others is exaggerated due to its small sample size.

4.2.2 Shrub canopy cover

Mean alder and willow height were averaged for each site to give the mean shrub height (Fig. 4.3). Percent cover of alder and willow were summed to give the percent shrub cover (Fig. 4.4), which can result in total values over 100%, due to overlapping canopies. Both mean shrub height and percent shrub cover are estimates of the shrub canopy cover, which is present in the summer. Mean white spruce DBH is positively correlated with mean shrub height ($R_s = 0.459$, $\alpha = 0.05$), indicating that sites with large white-spruce trees, and a closed coniferous canopy will generally have taller shrubs that contribute to greater interception of incoming radiation in the summer. This relation is confirmed by the positive correlation between mean white spruce DBH, and the July leaf area index, a measure of ground shading (Fig. 4.5).

Excepting STS, all of the spruce-forest communities have a relatively high shrub canopy cover, with some minor differences. The SAB sites have a high percent cover of tall shrubs, leading to a high degree of ground shading. The CSF community has a moderate cover of tall shrubs. Combined with a closed white spruce canopy, this leads to high ground shading in summer. Shrubs of the CSF community are significantly taller than those of the SCL community (Table 4.1). Both the OSF and SCL communities have a lower cover of shorter shrubs than the CSF community. Summer ground shading is lowest at the two STS sites with the smallest shrubs, and the lowest percent shrub cover.

4.2.3 Snow cover

Snow depths were measured at all sites in April 2007 to capture the total winter snow accumulation. Mean site snow depths ranged from 39 to 72 cm, with an average value of 56 cm. There is a strong negative correlation between mean April snow depth

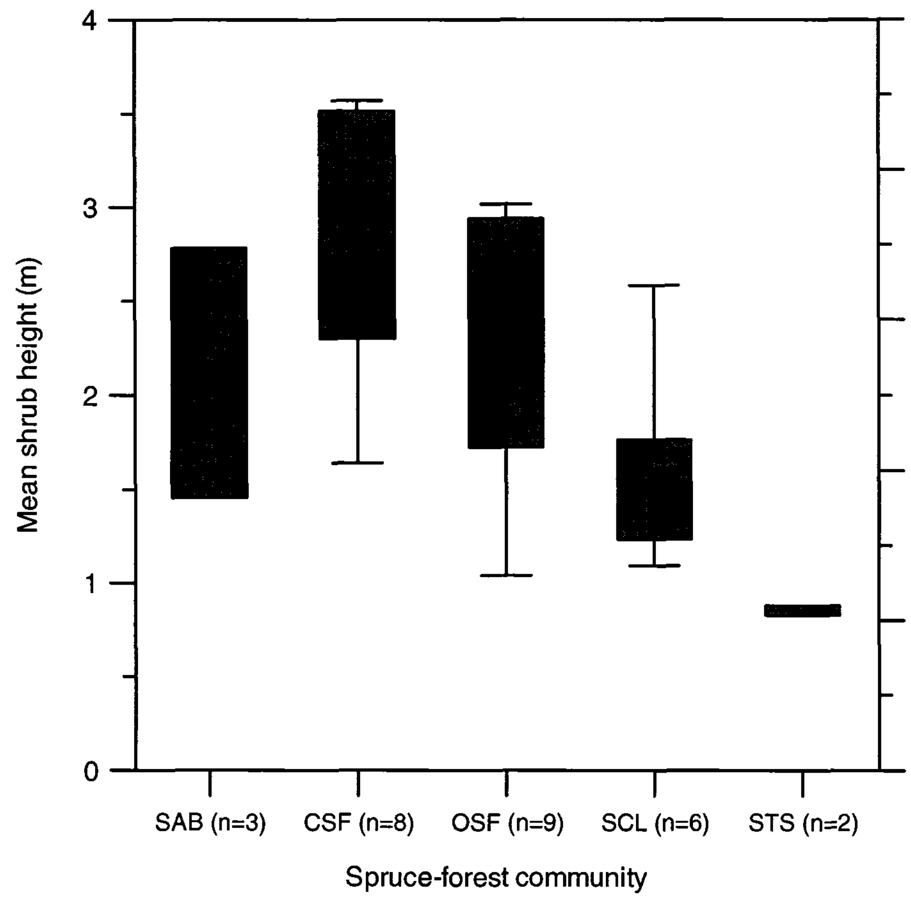

Figure 4.3 Mean shrub height by spruce-forest community. Maximum and minimum indicated by whiskers, interquartile range indicated by box, and median indicated by line in box. Spruce-forest communities include spruce/alder-bearberry (SAB), closed-spruce/feathermoss (CSF), open-spruce/feathermoss (OSF), spruce-crowberry/lichen (SCL), and spruce/tamarack-sphagnum (STS).

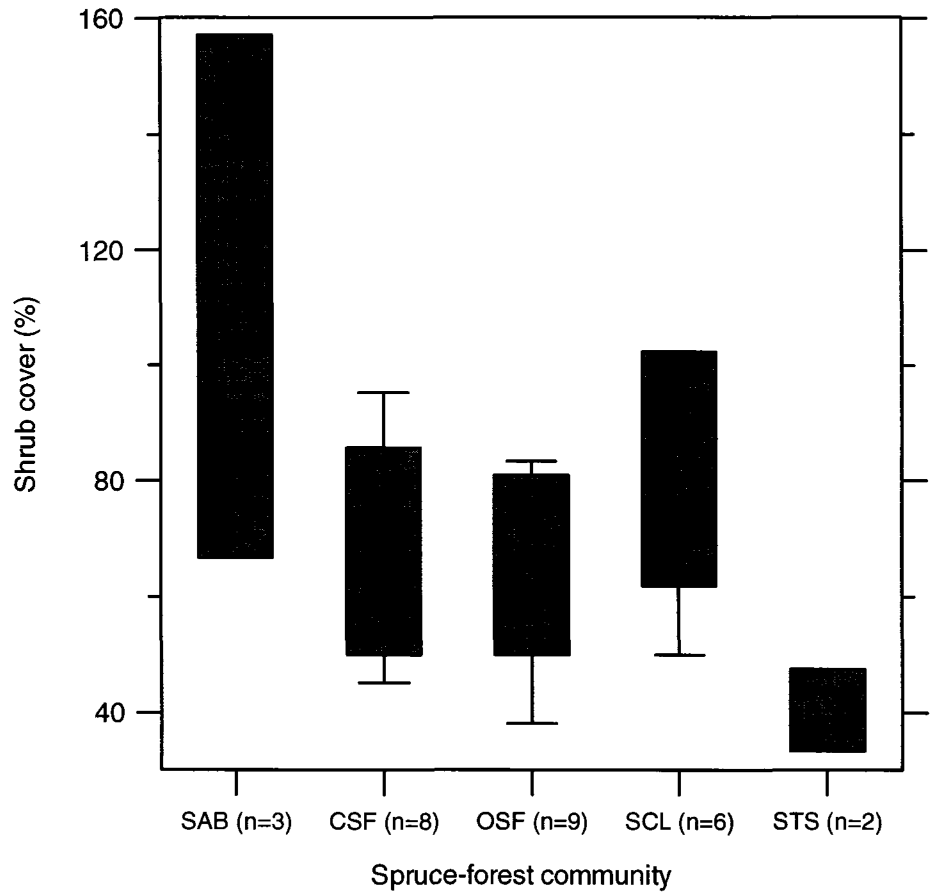

Figure 4.4 Percent shrub cover by spruce-forest community. Maximum and minimum indicated by whiskers, interquartile range indicated by box, and median indicated by line in box. Spruce-forest communities include spruce/alder-bearberry (SAB), closed-spruce/feathermoss (CSF), open-spruce/feathermoss (OSF), spruce-crowberry/lichen (SCL), and spruce/tamarack-sphagnum (STS). Total shrub covers of over 100% are due to overlapping alder and willow canopies.

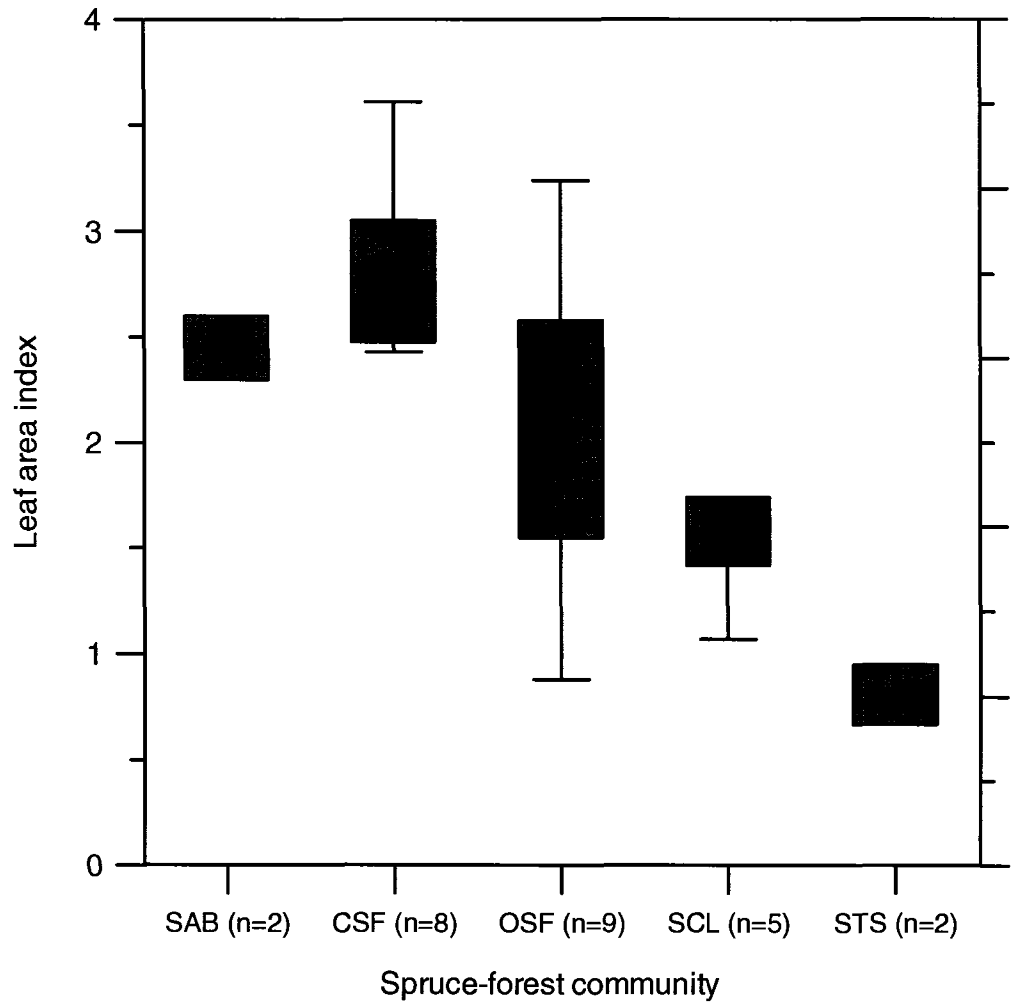

Figure 4.5 Leaf area index by spruce-forest community. Maximum and minimum indicated by whiskers, interquartile range indicated by box, and median indicated by line in box. Spruce-forest communities include spruce/alder-bearberry (SAB), closed-spruce/feathermoss (CSF), open-spruce/feathermoss (OSF), spruce-crowberry/lichen (SCL), and spruce/tamarack-sphagnum (STS).

and mean white spruce DBH (R_s= -0.501, α = 0.01). This indicates that less snow accumulates in forests with large trees and closed canopies.

Large treed, CSF sites have the thinnest median April snow depths (Fig. 4.6), and the low range of snow depths in this community is significantly different than that of the SCL community, with a more open canopy and deeper snow (Table 4.1). Snow depths of the CSF community may also be statistically lower than those of the SAB community, but it is unlikely since the p-value is higher than the corrected significance level (Table 4.1). Mean April snow depths are generally higher beneath the more open canopy, SAB, OSF and SCL communities as compared to the CSF community. The STS community has the highest median snow depth, associated with the smallest white spruce trees and most open canopy.

Snow depths were also measured at ten sites in the central delta in mid-December 2006 to capture early snow cover conditions. Measurements were made in the CSF, OSF and SCL communities. Snow depths in December were thinner, ranging from 20 to 47 cm, but highly correlated with measurements taken in April (R_s = 0.969, α = 0.01). Similar to late-winter, December snow depths at CSF sites were thinner than those at OSF and SCL sites (Fig. 4.7).

The ranges of snow densities between the spruce-forest communities are very similar (Fig. 4.8). It is likely that there is little variation in snow density because most spruce forests in the Mackenzie Delta are relatively sheltered from wind, and both temperature and radiation conditions are similar throughout the southern and central delta in winter.

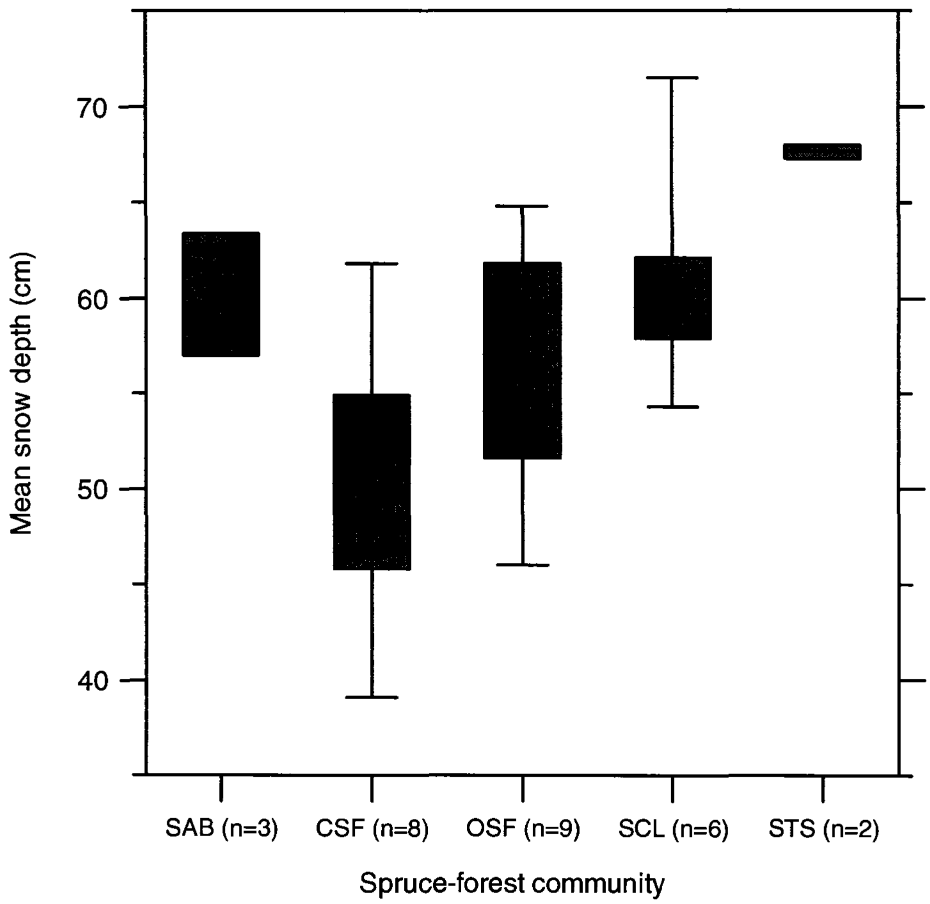

Figure 4.6 Mean snow depth by spruce-forest community. Data collected in April 2007. Maximum and minimum indicated by whiskers, interquartile range indicated by box, and median indicated by line in box. Spruce-forest communities include spruce/alder-bearberry (SAB), closed-spruce/feathermoss (CSF), open-spruce/feathermoss (OSF), spruce-crowberry/lichen (SCL), and spruce/tamarack-sphagnum (STS).

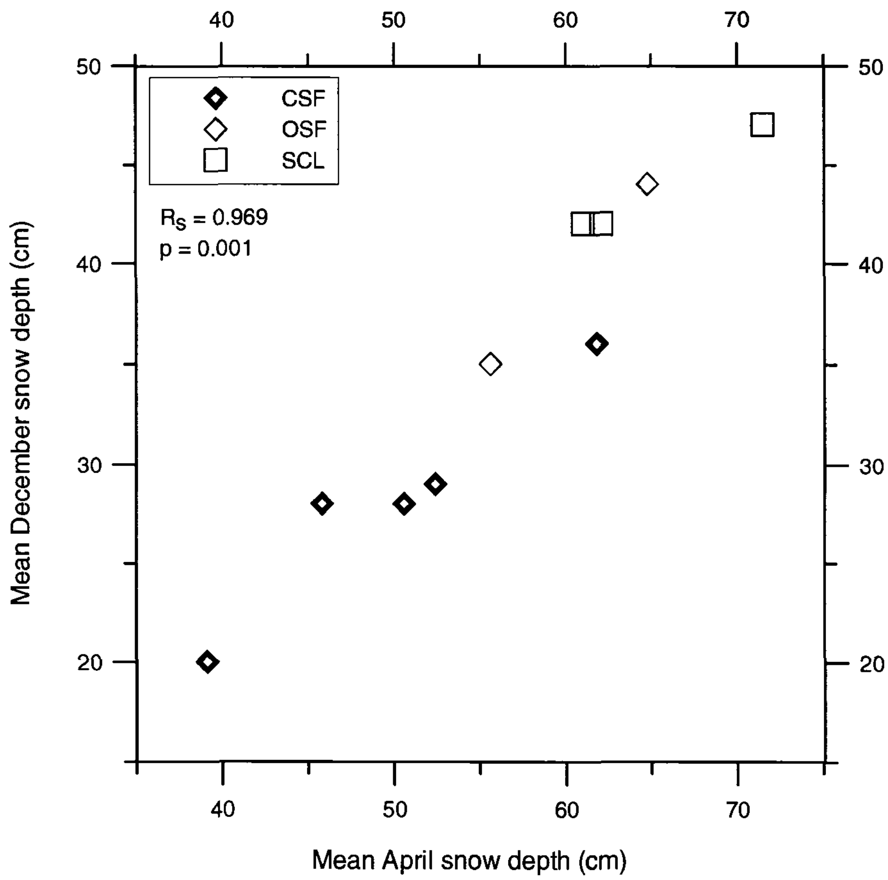

Figure 4.7 Mean snow depth measured at ten sites in December 2006 and April 2007. Sites are identified by spruce-forest community, including closed-spruce/feathermoss (CSF), open-spruce/feathermoss (OSF), and spruce-crowberry/lichen (SCL).

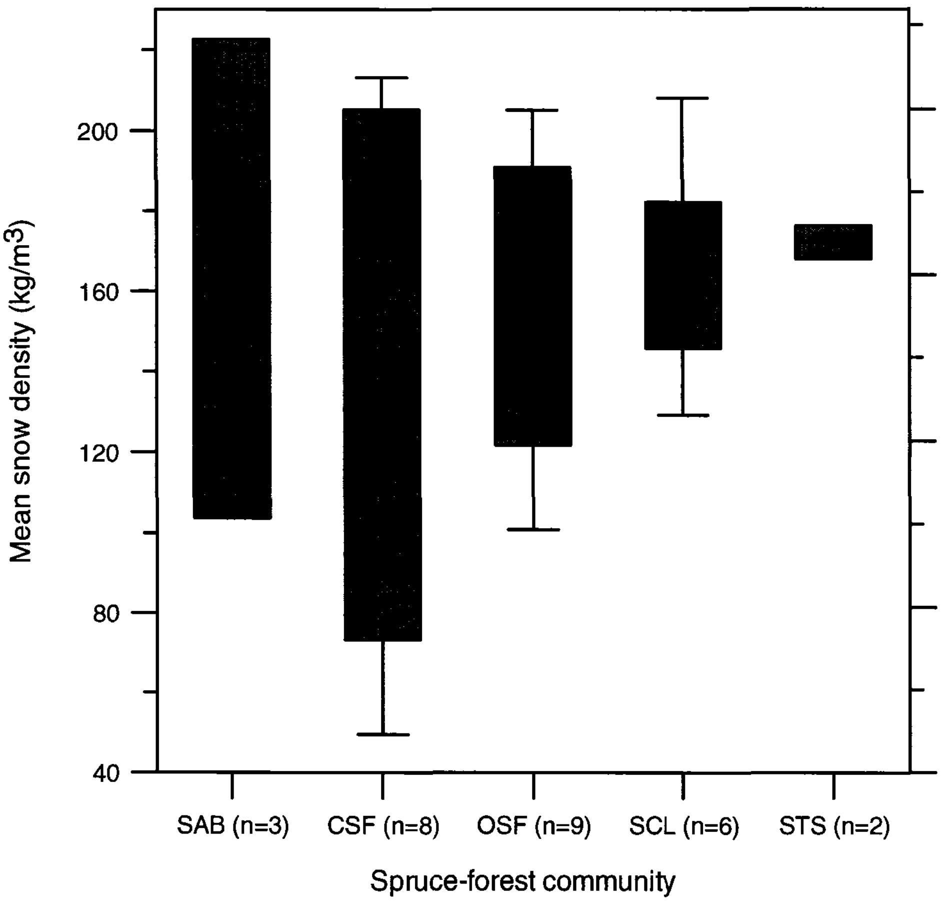

Figure 4.8 Mean snow density by spruce-forest community. Data collected in April 2007. Maximum and minimum indicated by whiskers, interquartile range indicated by box, and median indicated by line in box. Spruce-forest communities include spruce/alder-bearberry (SAB), closed-spruce/feathermoss (CSF), open-spruce/feathermoss (OSF), spruce-crowberry/lichen (SCL), and spruce/tamarack-sphagnum (STS).

4.2.4 Organic layer

The herb and moss layers of the study sites suggest that flood frequency decreases along the spruce-forest successional sequence. Most herbs in the SAB community are adapted to flooding, some herbs in the CSF and OSF communities are intolerant of flooding, and most herbs in the SCL and STS communities have tundra affinities, and are unrelated to a flooding environment (Table 3.3). The percent total moss cover increases along the successional sequence, and the percent of newly deposited alluvium decreases (Table 3.3). Reduced frequency and duration of flooding at more mature spruce-forest sites allows for the establishment of a moss cover, and the development of an organic layer.

Median organic-layer depths of the communities are similar (Fig. 4.9), but a plot of organic-layer depths shows that they are somewhat lower at the SAB sites than at the other communities. Sites in the SAB community flood regularly and organic-layer development is limited. The CSF community includes more sites with thick organic layers than the OSF community. Organic-layer development at CSF sites may be more rapid because mosses continue to grow through regularly deposited, thin layers of alluvium, while alluvium is deposited less frequently at OSF sites. The regular addition of nutrients may also help to explain the larger trees at CSF sites. The SCL community also includes more sites with thick organic layers than the STS community. Thick organic layers are expected at SCL sites because they rarely flood. At the time of sampling in mid-June, organic layers at STS sites continued into frozen ground. Organic layers at STS sites may appear to be thin since they are located in wet depressions, and significant energy is required to thaw the ice-rich surface layer.

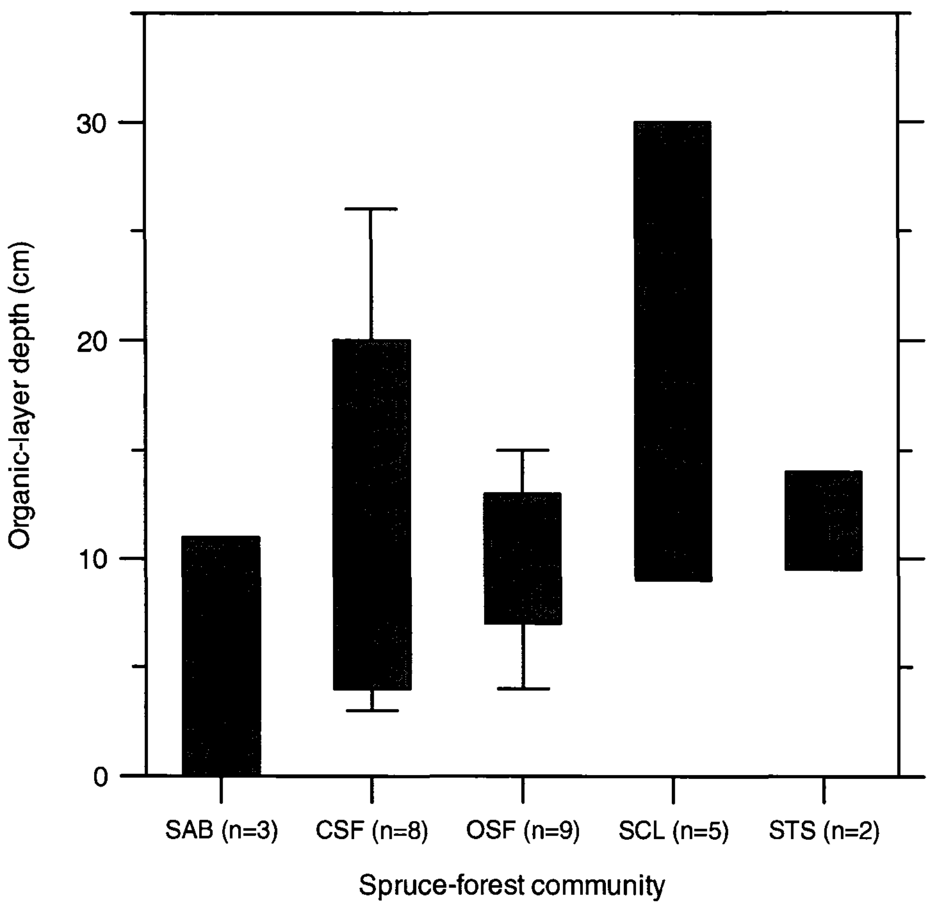

Figure 4.9 Organic-layer depth by spruce-forest community. Maximum and minimum indicated by whiskers, interquartile range indicated by box, and median indicated by line in box. Spruce-forest communities include spruce/alder-bearberry (SAB), closed-spruce/feathermoss (CSF), open-spruce/feathermoss (OSF), spruce-crowberry/lichen (SCL), and spruce/tamarack-sphagnum (STS).

4.2.5 Water bodies

The warming effect of a river channel or a lake on a location in the ground between them is dependent on the depth of that point, and its distance from the water bodies (Fig. 2.8). In this study, ground temperature cables were installed at a constant 20-m depth, and the distance between the cable and the water bodies varied. Distances from the channel to the cable are less variable, since there was a maximum drill hose length. There is a wider range of distances from the cable to the nearest lake. Calculations using equation 8 (p. 19) demonstrated that given a constant depth, ground temperatures are affected by the total distance between the channel and the nearest lake.

Distances between the study sites and the water bodies were determined using 1:30,000 scale, georeferenced, orthorectified aerial photographs in ArcMap (Northwest Territories Centre for Geomatics, 2004). The photographs were taken in August at a period of low streamflow, and channel edges were defined as the location of the channel edge at that time. Unvegetated alluvium adjacent to channels was considered to be a part of the land as for most of the year it remains above water.

The minimum total distance between a channel and a lake at any study site is 100 m (Fig. 4.10). The total distance between water bodies at the majority of sites (64%) is between 100 and 200 m; 29% of the sites have a distance between 200 and 300 m between water bodies; and there is a distance of greater than 350 m at the remaining 7% of sites. Two sites are located well away from the nearest lake. Based on calculations using equation 8, it is expected that these variations in the distance from lakes will have a minimal effect on mean annual ground temperatures at these sites. The calculated 20-m

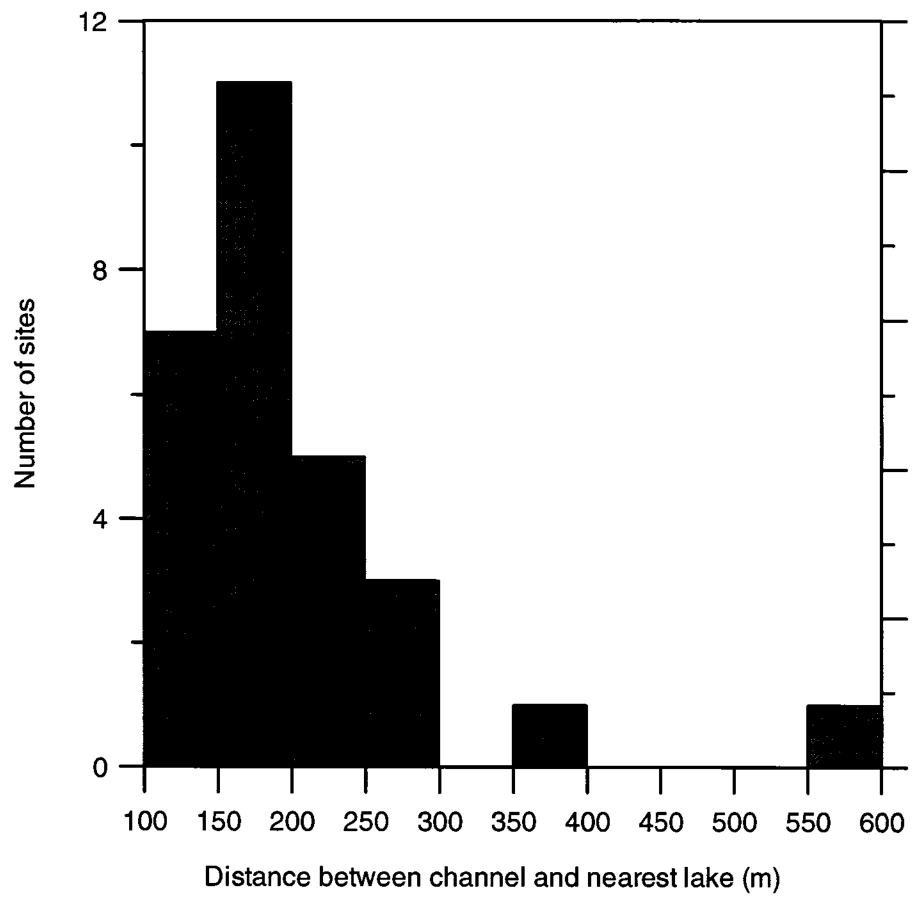

Figure 4.10 Distance between channel bank and nearest lake at 28 study sites.

ground temperature for a site with a total distance of 350 m is 0.15°C lower than that at an average site with a total distance of 210 m.

4.3 Summary

This chapter has established the relations between physical characteristics of the study sites, and demonstrated that there are differences in surface conditions between the spruce-forest communities (Table 4.3). There are statistically significant differences between the spruce-forest communities with respect to mean white spruce DBH, mean shrub height, and mean snow depth. There are variations between the spruce-forest communities that are not statistically significant with respect to the percent shrub cover and organic layer depth. There is little variation between the study sites with respect to mean snow density and tree density. Most study sites are located at a similar distance from water bodies, so that the warming influence of water is relatively uniform. It is recognized that the spruce-forest communities are a successional sequence, and that there is some overlap of surface conditions between them; however, the grouping of sites is useful so that generalizations can be made regarding the relation of surface conditions to ground temperatures.

	SAB	CSF	OSF	SCL	STS
Tree layer characteristics					
Median white spruce DBH (cm)	9	29	19	22	7
Median tree density (m^{-2})	0.25	0.08	0.13	0.09	0.39
Physical significance	More open canopy in winter, more snow.	Closed canopy in winter, less snow.	More open canopy in winter, more snow.	More open canopy in winter, more snow.	Very open canopy, more snow.
Median April snow depth (cm)	60	51	56	61	68
Shrub layer characteristics					
Median shrub height (m)	2.6	2.8	2.3	1.7	0.9
Median shrub cover (%)	100	75	60	71	40
Physical significance	Closed canopy in summer, high ground shading.	Closed canopy in summer, high ground shading	Closed canopy with gaps, moderate ground shading.	Open canopy in summer, low ground shading.	Very open canopy, low ground shading.
Median July LAI	2.5	2.8	1.7	1.4	0.8
Herb and moss layer characteristics					
Dominant herbs	Flood adapted	Mostly flood adapted	Mostly flood adapted	Mostly flood intolerant	Flood intolerant
Mean total moss cover (%)	5	15	67	60	79
Median new alluvium cover (%)	95	79	0	0	0
Physical significance	Frequent flooding, thin organic layer.	Moderately frequent flooding, rapid organic layer development.	Infrequent flooding, moderate organic layer.	Rarely flooded, thick organic layer.	Rarely flooded, thick organic layer.
Interquartile range of organic layer depths (cm)	0-11	4-20	7-13	9-30	10-14

Table 4.3 Summary of major vegetative characteristics of the tree, shrub, herb and moss layers by spruce-forest community, and their physical significance.

CHAPTER FIVE

RELATIONS BETWEEN MEAN ANNUAL GROUND TEMPERATURES AND SURFACE CONDITIONS IN SPRUCE-FOREST COMMUNITIES

5.1 Introduction

The central and southern Mackenzie Delta is an area of relatively uniform climate and lithology so that spatial variation in permafrost temperature may be attributed to differences in surface conditions and proximity to water bodies. In Chapter 4, surface conditions were shown to vary, in some cases significantly, between the spruce-forest communities. In this chapter, ground temperatures and active-layer depths are presented, and relations with surface conditions and spruce-forest communities are explored using univariate and multivariate approaches. Previous studies have suggested that regions of the central and southern delta have distinct flooding regimes (Cordes et al., 1985; Pearce et al., 1988). Patterns of variation in mean annual ground temperatures are examined at similar sites across the delta regions. A comparison of contemporary mean annual ground temperatures with those measured over thirty years ago is presented for two sites in the east-central delta.

5.2 Mean annual ground temperatures

Mean annual ground temperatures were measured at 27 of the spruce-forest study sites, as data from one STS site could not be retrieved. Mean annual ground temperatures range from -0.6 to -2.9°C. Ground temperatures at almost all of the sites are between -1.5 to -2.9°C, and are higher at three SAB sites (-0.6 to -1.5°C). SAB sites have higher ground temperatures (Fig. 5.1), and their distribution is significantly different from those of the other communities, as determined by a Mann-Whitney U test (Table 5.1), though

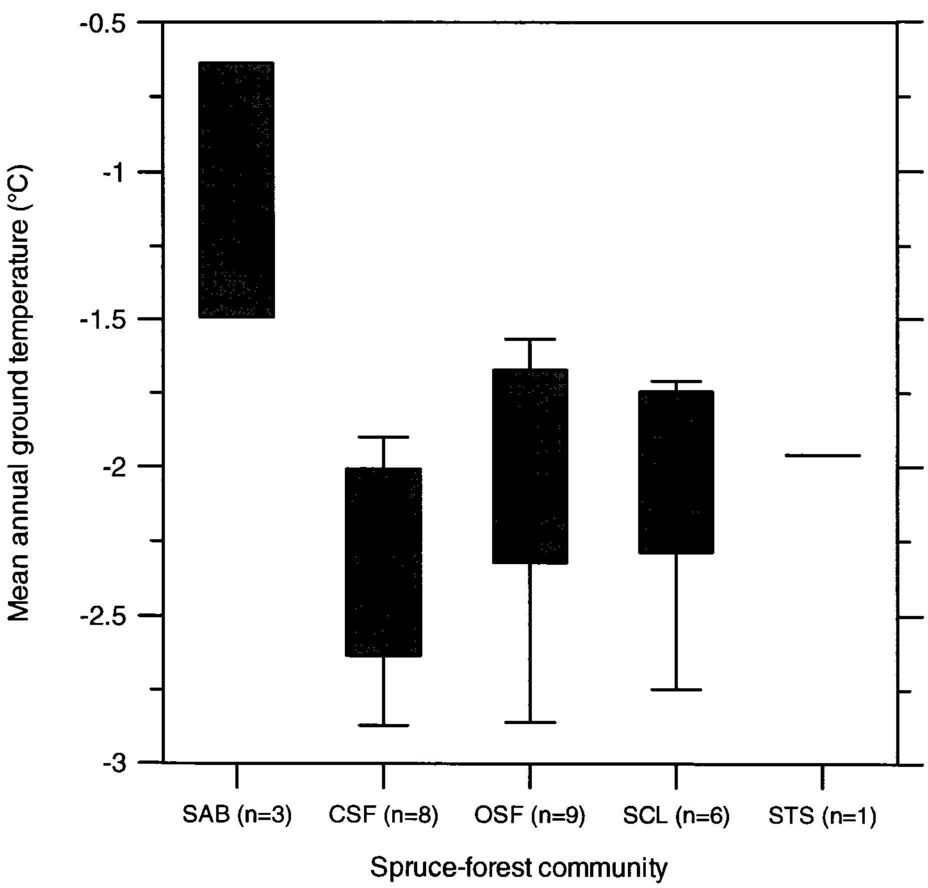

Figure 5.1 Mean annual ground temperatures by spruce-forest community. Maximum and minimum indicated by whiskers, interquartile range indicated by box, and median indicated by line in box. Spruce-forest communities include spruce/alder-bearberry (SAB), closed-spruce/feathermoss (CSF), open-spruce/feathermoss (OSF), spruce-crowberry/lichen (SCL), and spruce/tamarack-sphagnum (STS). Note STS community is represented by a single site.

		Critical value	Mann-Whitney U	P-value	Significance Level (α)
Mean annual ground temperature					
SAB	CSF	2	0	0.042	0.05
SAB	OSF	2	0	0.036	0.05
SAB	SCL	1	0	0.060	0.05
Mean active-layer depth					
SAB	OSF	2	0	0.056	0.05
SAB	SCL	1	0	0.080	0.05
CSF	OSF	13	12	0.144	0.05
CSF	SCL	8	5	0.056	0.05

Table 5.1 Mann-Whitney U two-tailed tests of independence of ground temperature and active-layer depths for SAB, CSF, OSF and SCL communities. If U is less than the critical value, then the null hypothesis is rejected, and the communities are statistically significantly different. The p-value is the chance that random sampling would result in the observed U value, if there is no significant difference between the two communities. Since multiple comparisons were made, p-values were adjusted using the Bonferroni correction by multiplying by the number of tests.

the p-value is greater than the significance level when comparing SAB and SCL communities. There are no significant differences between mean annual ground temperature distributions of the other communities. The CSF community is characterized by the lowest median ground temperature, and the remaining communities have similar median ground temperatures that are higher than the CSF community and lower than the SAB community. Ground temperature profiles are presented for four sites representative of the SAB, CSF, OSF and SCL communities (Figs. 5.2 & 5.3). Measurements were made in late-August, mid-December, and early-April, and the profiles show differences in the range of near-surface temperatures between the sites. The profiles also confirm that thermal equilibrium was re-established at 20-m depth after the disturbance of drilling since there is little fluctuation of ground temperatures at this depth at any of the sites.

The Spearman correlation coefficient indicates that mean annual ground temperatures at the study sites are negatively correlated with mean white spruce DBH ($R_s = -0.442$, $\alpha = 0.05$) (Table 5.2). Warm SAB sites with smaller trees contrast to cold CSF sites with larger trees. This relation suggests that a thicker canopy cover associated with larger trees may be related to lower mean annual ground temperatures through the interception of incoming radiation in summer and snow in winter. A plot of mean annual ground temperatures and white spruce DBH shows that there is considerable scatter in the relation, indicating that maximum snow depths in 2007 may not have been indicative of average snow conditions in the delta, or that other environmental factors are also important drivers of ground temperatures (Fig. 5.4).

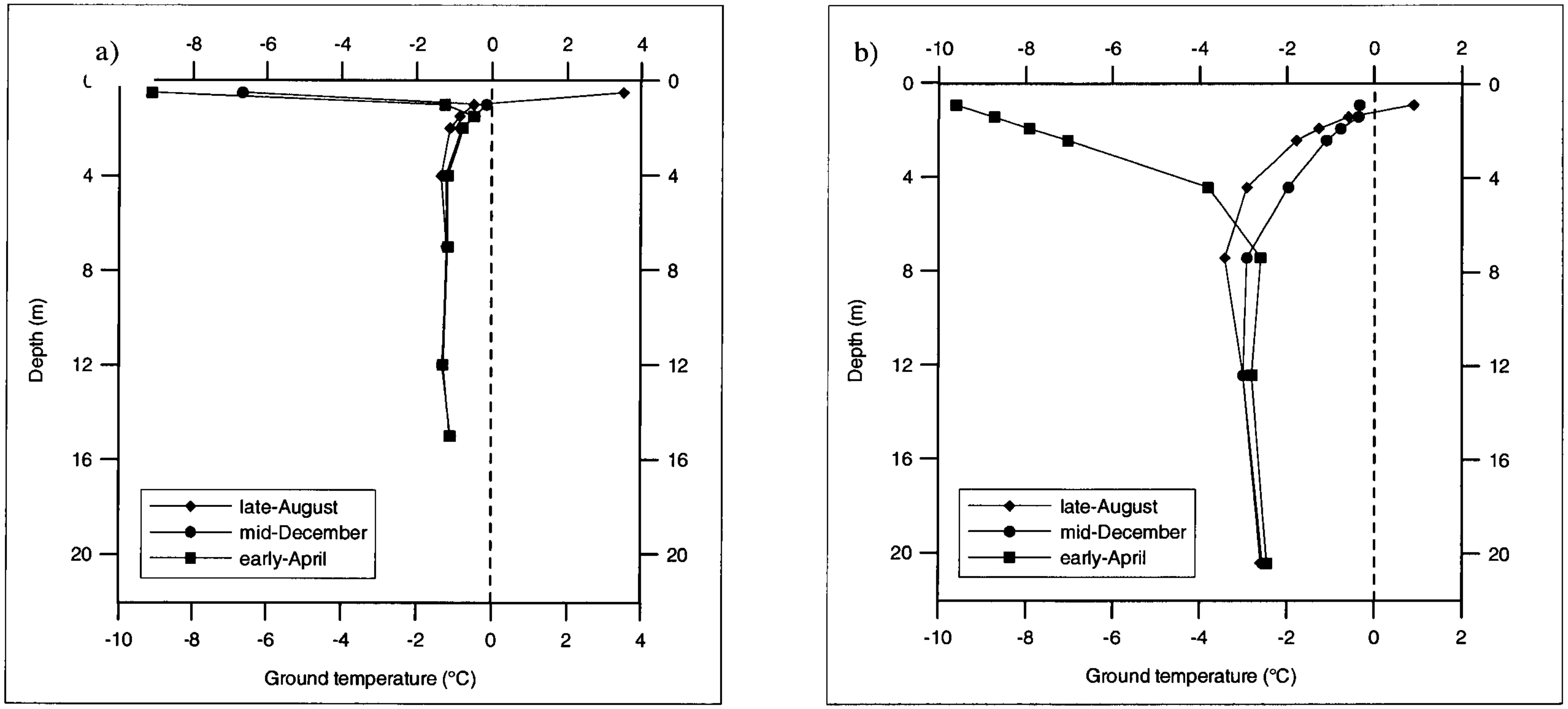

Figure 5.2 Ground temperature profiles at a) SAB site CE-SAB1 (Delta Hill), and b) CSF site CW-CSF1.

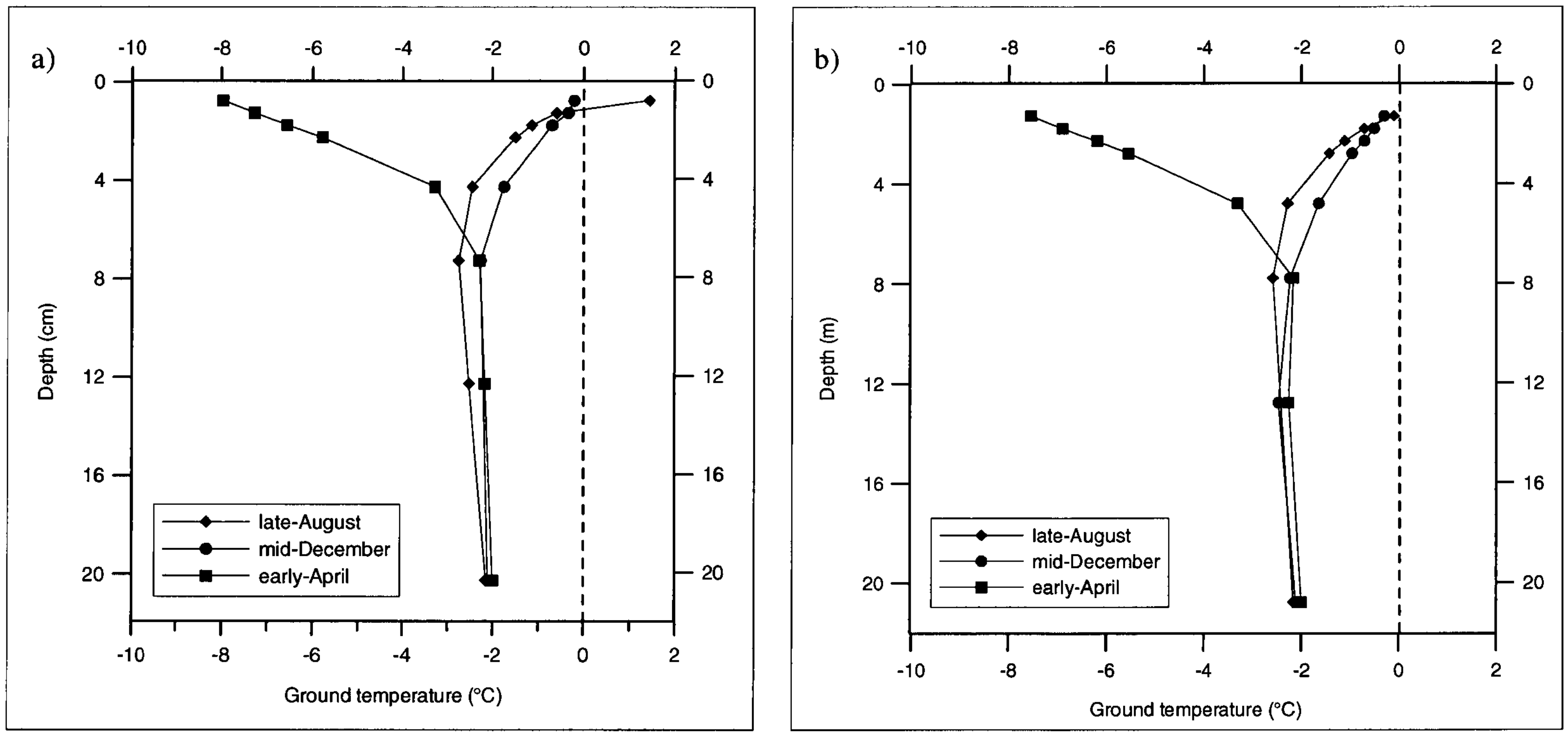

Figure 5.3 Ground temperature profiles at a) OSF site CW-OSF2, and b) SCL site CW-SCL1.

	Mean annual ground temperature	Mean active - layer depth	Mean white spruce DBH	Mean late-winter snow depth	Mean shrub height	Leaf area index	Shrub cover	Organic -layer depth	Distance between channel and lake
Mean annual ground temperature	1.000	0.031	***-0.442*** p=0.021	0.108	0.035	-0.169	0.232	-0.217	-0.301
Mean active- layer depth	0.031	1.000	0.146	**-0.640** p=0.001	***0.446*** p=0.020	**0.697** p=0.001	0.319	***-0.444*** p=0.023	0.069

Table 5.2 Spearman's rank correlation coefficients for mean annual ground temperatures, mean active-layer depths, and surface conditions. Significant correlations at the 0.05 level of significance are in bold italics, and at the 0.01 level of significance in bold. The p-value is the percent chance that random sampling would result in an R_s value as far from zero as observed, if there is no relation between the two variables.

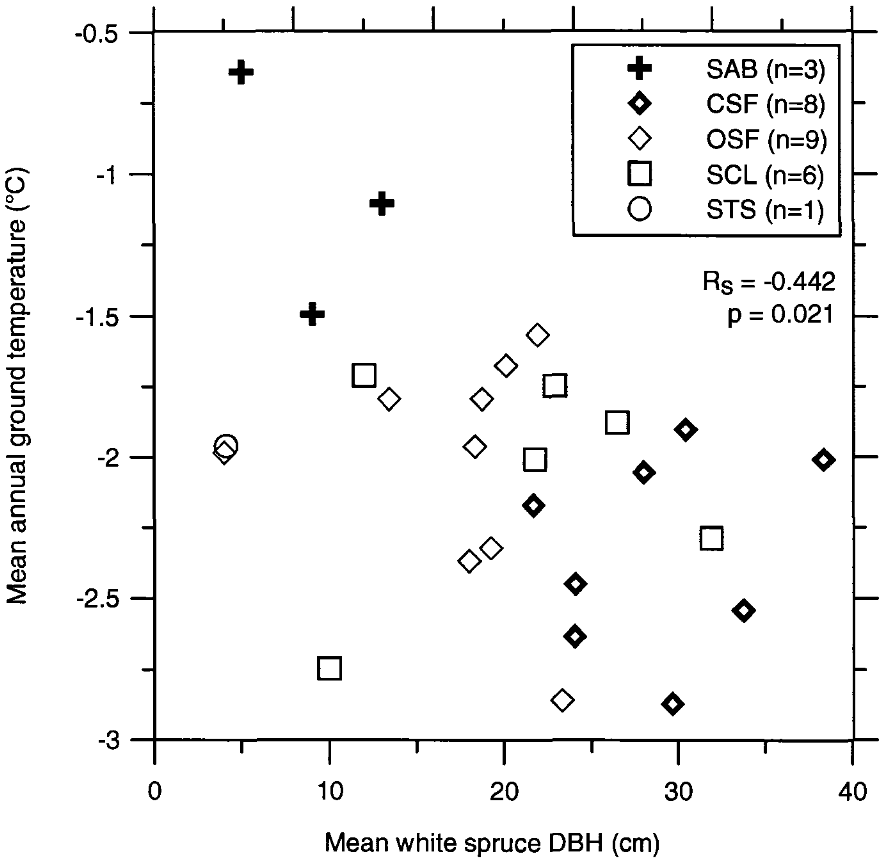

Figure 5.4 Correlation between mean annual ground temperature and mean white spruce DBH Sites are labelled by spruce-forest community, including spruce/alder-bearberry (SAB), closed-spruce/feathermoss (CSF), open-spruce/feathermoss (OSF), spruce-crowberry/lichen (SCL), and spruce/tamarack-sphagnum (STS).

Mean annual ground temperatures are influenced by conditions over the long-term. Since winter conditions are present in the Mackenzie Delta for the majority of the year, it was hypothesized that the coniferous canopy cover and the associated snow layer at a site would be related to mean annual ground temperatures. However, the correlation between mean annual ground temperatures and the mean snow depth measured in late-winter was not found to be statistically significant (Table 5.2). This result could be explained by the relatively high snow depths measured at most sites in April (average depth, 57 cm). Previously, Smith (1975) showed that differences in snow depths above 50 cm had minimal influence on near-surface ground temperatures (Smith, 1975). The presence of a significant relation between mean annual ground temperatures and mean white spruce DBH, coupled with the lack of a significant relation between mean annual ground temperatures and late-winter snow depths likely indicates that besides snow cover, mean annual ground temperatures are also influenced by other environmental factors, possibly including snow cover earlier in the winter.

Early-winter snow depths measured at ten sites in mid-December were thinner than those measured at the time of maximum snow accumulation in April, with an average snow depth of 34 cm. However, there was also no statistically significant correlation between early-winter snow depth and mean annual ground temperatures (R_s = 0.146). Early-winter snow conditions may only have a small impact on mean annual ground temperatures because snow depths of greater than 50 cm accumulate quickly, and are present for most of the winter in spruce forests. The average winter condition in spruce forests, which mean annual ground temperatures respond to, is a thick snow layer.

It is possible that the smaller sample size of early-winter snow depths may have also affected the results.

5.3 Active layer

Active-layer depths were measured at 27 sites, as measurements were not obtained from one OSF site. A wide range of active-layer depths were observed (33 – 107 cm), but active layers at most sites measured less than 65 cm. Median active-layer depths of the SAB and CSF communities are similar, but the range of the SAB community is larger (Fig. 5.5). Visual inspection of the data indicates that there is a trend of decreasing active-layer depth with increasing forest community age, with thick active layers at spruce-alder/bearberry sites grading to thin active layers at spruce-tamarack/sphagnum sites. According to the results of the Mann-Whitney U test, active-layer depths of the SAB and CSF communities are significantly thicker than the OSF and SCL communities, though the p-values exceed the significance levels for these comparisons.

Mean active-layer depths of the study sites are positively correlated with shrub height ($R_s = 0.446$, $\alpha = 0.05$), and leaf area index ($R_s = 0.697$, $\alpha = 0.01$), and negatively correlated with mean April snow depths ($R_s = -0.640$, $\alpha = 0.01$). A plot of the relation between mean active- layer depths and mean April snow depths indicates that sites in the CSF community, with thinner snow depths and taller shrubs are associated with thicker active layers (Fig. 5.6), while sites in the SCL and STS communities, with thicker snow depths and shorter shrubs are associated with thinner active layers. Differences in active-layer thickness between these communities could be related to flood frequency. CSF sites appear to flood occasionally, while SCL and STS sites rarely flood. The early

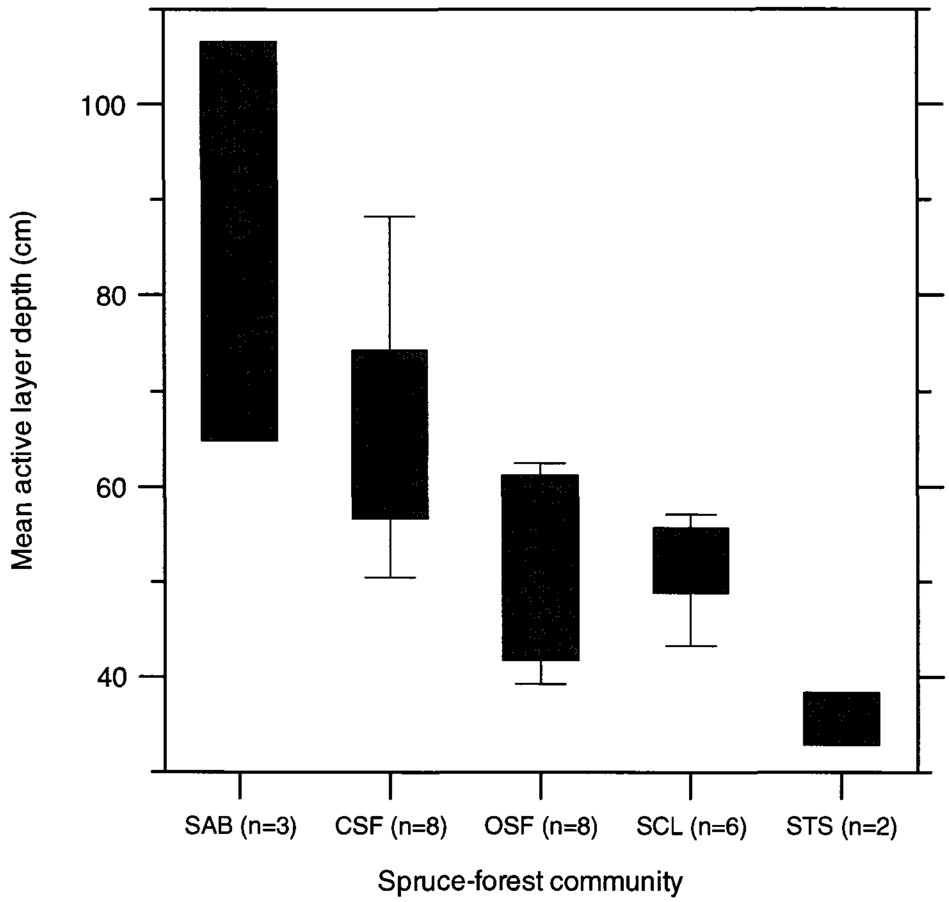

Figure 5.5 Mean active-layer depths by spruce-forest community. Maximum and minimum indicated by whiskers, interquartile range indicated by box, and median indicated by line in box. Spruce-forest communities include spruce/alder-bearberry (SAB), closed-spruce/feathermoss (CSF), open-spruce/feathermoss (OSF), spruce-crowberry/lichen (SCL), and spruce/tamarack-sphagnum (STS).

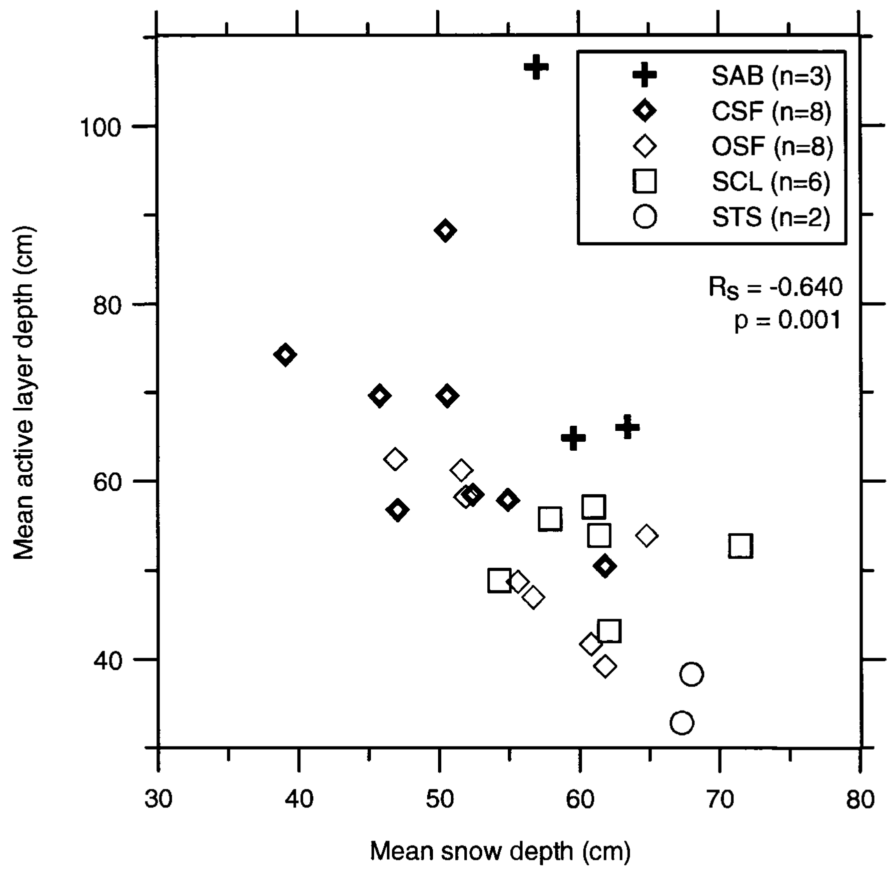

Figure 5.6 Correlation between mean active-layer depth and mean late-winter snow depth. Sites are labelled by spruce-forest community, including spruce/alder-bearberry (SAB), closed-spruce/feathermoss (CSF), open-spruce/feathermoss (OSF), spruce-crowberry/lichen (SCL), and spruce/tamarack-sphagnum (STS).

removal of snow at CSF sites may enhance active layer development somewhat by allowing ground heating to occur earlier than at SCL and STS sites. Lower near-surface ground ice content at SAB and younger spruce feathermoss communities, such as CSF sites (Kokelj and Burn, 2005a) may also explain the deeper active layers at these sites since incoming radiation contributes directly to ground warming rather than to melting ice, as is required at sites with high near-surface ground ice content.

There is a negative correlation between mean active-layer depths and organic-layer depths ($R_s = -0.444$, $\alpha = 0.05$). A plot of this relation shows that sites with thinner organic layers, such as SAB sites, have thicker active layers, while those with thicker organic layers have thinner active layers (Fig. 5.7). A wet or frozen surface organic layer conducts heat away from the ground in the fall and winter, and is a poor conductor of heat into the ground in the summer. The inverse relation between organic-layer depth and active-layer thickness likely occurs because a thick organic layer fulfills these roles more effectively than a thinner one. These results are consistent with active-layer thickness monitoring in the adjacent Mackenzie Valley region. Nixon (2000) found that active-layer thickness decreased with increasing latitude, however, this relation was confounded by site-specific factors, particularly organic cover, snow depth and density. It is noted that this relation is dominated by a single SAB site with the thickest active layer, and an absent organic layer contrasting with two sites with the thickest organic layers and relatively thin active layers.

5.4 Principal components analysis

The use of univariate statistics has resulted in several correlations between mean annual ground temperatures, active-layer depths and surface conditions, but these

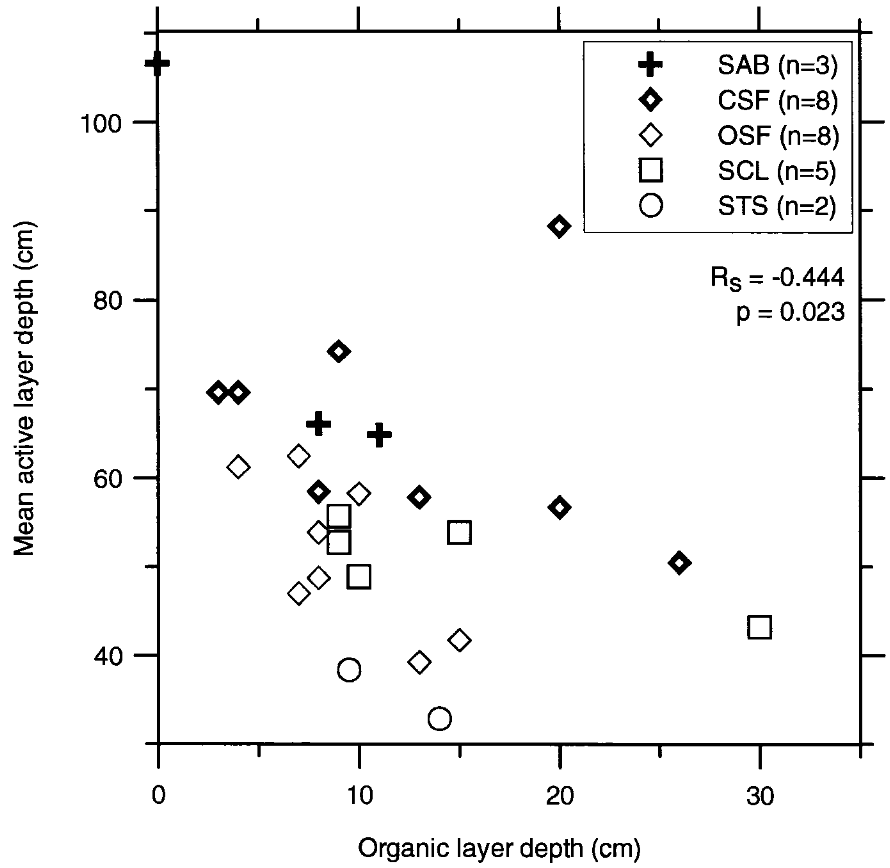

Figure 5.7 Correlation between mean active-layer depth and organic-layer depth. Sites are labelled by spruce-forest community, including spruce/alder-bearberry (SAB), closed-spruce/feathermoss (CSF), open-spruce/feathermoss (OSF), spruce-crowberry/lichen (SCL), and spruce/tamarack-sphagnum (STS).

single correlations do not explain how multiple surface conditions interact to influence ground temperatures and active layers. A multivariate analysis provides further explanation. Principal components analysis (PCA) is an ordination technique that reduces a multivariate dataset into several synthetic components, which are composed of different weightings of the input variables (Hotelling, 1936; Shaw, 2003). The analysis maximizes the weighting of a variable in one component and minimizes it in the others, so that each component describes a unique set of surface conditions. A multivariate approach is also important in order to control the Type 1 error rate, the probability of rejecting the null hypothesis when it is true, since in the case of multiple univariate correlations, the Type 1 error rate expands geometrically.

A PCA was conducted with SPSS v.14.0 to determine the relations between measured surface conditions in spruce forests of the Mackenzie Delta. Seven surface condition variables that have been demonstrated in Chapter 4 to vary between the study sites were input, including: mean white spruce DBH, mean shrub height, percent shrub cover, leaf area index, mean late-winter snow depth, surface organic-layer depth and the total distance from water bodies. The analysis identified three components with eigenvalues of greater than one that explained 79% of the variability of the dataset (Table 5.3). Three sets of synthetic variables were calculated for each site based on the variable weightings of each component (Table 5.4). These scores have been tested for correlations with mean annual ground temperatures and active-layer depths using Spearman's rank correlation coefficient (Table 5.5).

Component	Percent of variance	Cumulative percent
1	39.5	
2	20.7	60.2
3	18.7	78.9

Table 5.3 Percent of total variance of the surface condition variables explained by first three principal components.

	Component 1	Component 2	Component 3
White spruce DBH	**0.677**	**0.481**	0.050
Shrub height	**0.878**	0.018	0.093
Shrub cover	0.016	**-0.441**	**0.805**
Leaf area index	**0.775**	0.018	0.296
Snow depth	**-0.911**	0.073	0.160
Organic-layer depth	-0.128	**0.914**	0.003
Distance between channel and lake	-0.292	**0.432**	**0.726**

Table 5.4 Variable weightings for the first three principal components. Variables with strong weightings in bold.

	Component 1 scores	Component 2 scores	Component 3 scores
Mean annual ground temperature	-0.166	**-0.493** p=0.009	0.029
Active-layer depth	**0.588** p=0.001	***-0.405*** p=0.036	***0.460*** p=0.016

Table 5.5 Spearman's rank correlation coefficients for mean annual ground temperatures, mean active-layer depths, and principal components scores. Significant correlations at the 0.05 level of significance in bold italics, and at the 0.01 level of significance in bold. The p value is the percent chance that random sampling would result in an R_s value as far from zero as observed, if there is no relation between the two variables.

5.4.1 First component

The first component describes the greatest amount of variability of surface conditions. It contrasts mean late-winter snow depth with shrub height, LAI, and mean white spruce DBH (Table 5.4). There is a significant correlation between the first component scores and active-layer depth ($R_s = 0.588$, $\alpha = 0.01$).

Constituents of the first component are the same as those observed with univariate active layer correlations, with the addition of mean white spruce DBH. The role of canopy cover in controlling snow depth was implied in the univariate analysis, and is now explicitly included in the first component. A plot of mean active-layer depths, and the first component scores provides an ordering of sites into spruce-forest communities (Fig. 5.8). High first component scores indicate sites with larger white-spruce trees, taller shrubs, and thinner snow depths, and are associated with thicker active layers. Low first component scores indicate sites with smaller white-spruce trees, shorter shrubs, and thicker snow depths, and are associated with thinner active layers.

Most sites in the CSF community have high first component scores, and thick active-layer depths. SAB sites have thick active layers, and lower first component scores than the CSF sites. OSF and SCL sites have lower first component scores, and thinner active layer depths. STS sites have the lowest first component scores, and the thinnest active layers. As was discussed with the univariate correlations, these differences in active-layer thickness between the communities could be related to flood frequency, since CSF and SAB sites appear to be flooded more frequently than OSF, SCL and STS sites. Scatter in the relation suggests that other environmental variables play a role in determining active-layer thickness.

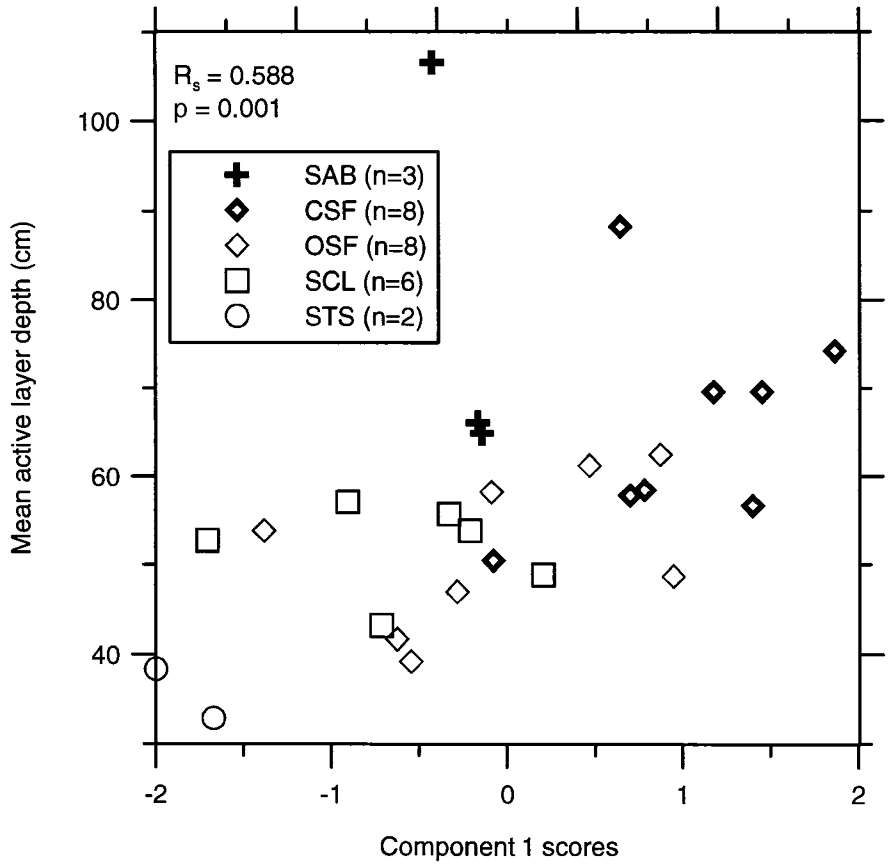

Figure 5.8 Mean active-layer depths and scores from first component of PCA. Sites are labelled by spruce-forest community, including spruce/alder-bearberry (SAB), closed-spruce/feathermoss (CSF), open-spruce/feathermoss (OSF), spruce-crowberry/lichen (SCL), and spruce/tamarack-sphagnum (STS).

5.4.2 Second component

The second component is mainly weighted on the surface organic-layer depth (Table 5.4). There is a significant negative correlation between the second component scores and mean annual ground temperatures ($R_s = -0.493$, $\alpha = 0.01$).

Second component scores separate the sites with the highest and lowest ground temperatures from the rest of the population (Fig. 5.9). Two SAB sites with very thin organic layers have the highest ground temperatures. High mean annual ground temperatures at these sites may be related to the lack of an organic layer. As well, more regular flooding of SAB sites removes snow cover early in spring. These two SAB sites contrast with several CSF and SCL sites with the low ground temperatures, thick organic layers. The significantly higher mean annual ground temperatures at SAB sites could be due to the thin organic layer, and a thicker snow layer associated with more open canopies.

The remaining sites are not organized into spruce-forest communities, reflecting the fact that there is no significant pattern of organic-layer development between the communities. In this study it is assumed that the measured ground temperatures at zero annual amplitude are in thermal equilibrium with the current atmospheric and surficial conditions; however, this may not be the case. Land surfaces in the delta are continually emerging from underneath meandering channels or drained lakes (Smith, 1975). Permafrost aggradation and thermal recovery occur over a long period of time, and may still be in progress though a mature spruce forest has established at a site. Sites in thermal disequilibrium may explain some of the variation of mean annual ground temperatures within spruce-forest communities. Equation 8 also indicates that the ground

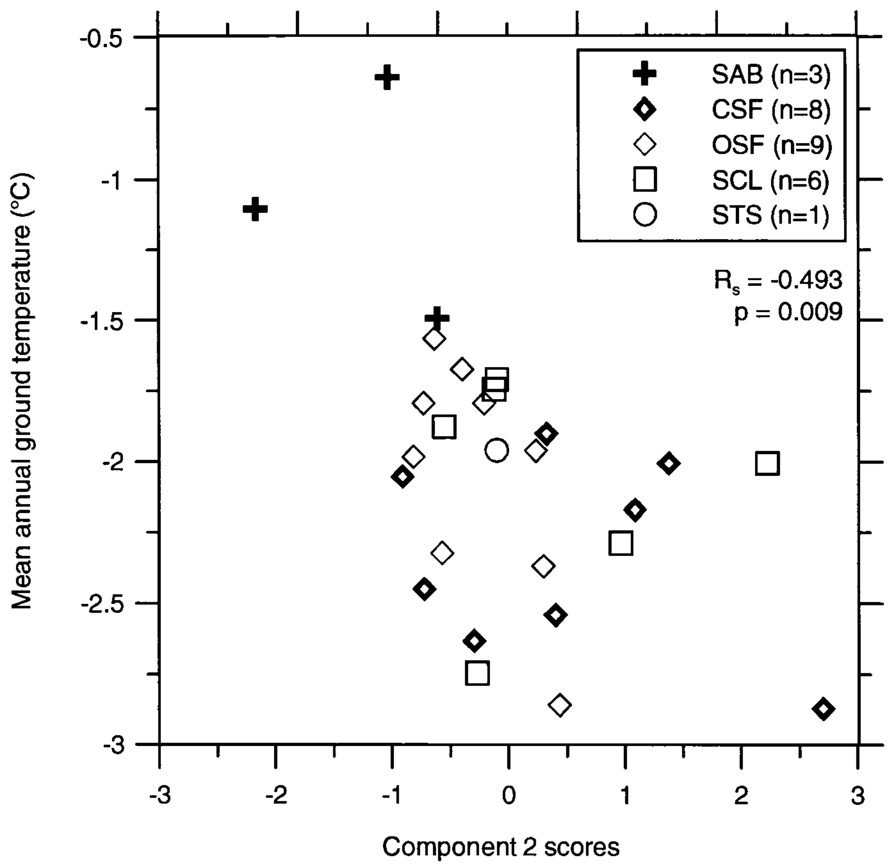

Figure 5.9 Mean annual ground temperatures and scores from second component of PCA. Sites are labelled by spruce-forest community, including spruce/alder-bearberry (SAB), closed-spruce/feathermoss (CSF), open-spruce/feathermoss (OSF), spruce-crowberry/lichen (SCL), and spruce/tamarack-sphagnum (STS).

temperature measurement sites in this study are influenced by lakes, even at distances beyond 60 m from a lake or channel edge. It is possible that this warming effect swamps the effects of surface conditions at 20-m depth, and this may explain why the relations between surface conditions and mean annual ground temperatures are unclear.

The second component is also significantly negatively correlated with mean active-layer depth (R_s = -0.405, α = 0.05). The relation between mean active-layer depths and organic-layer thickness was previously discussed in reference to univariate correlations. A plot of this relation shows that the previously discussed SAB site with an absent organic layer, and a very thick active layer contrasts with the remaining sites (Fig. 5.10). The relation between mean active-layer depths and component 2 scores is not significant if this SAB site is removed from the calculation.

5.4.3 Third component

The third component includes the combined influence of the percent shrub cover and the total distance from water bodies (Table 5.4). Mean active-layer depth is significantly correlated with the third component scores (R_s = 0.460, α = 0.05). Two sites with extremely high third component scores are located at large distances from water bodies (Fig. 5.11). The other sites are separated by differences in percent shrub cover, which organizes the sites into spruce-forest communities. The third component repeats the first component groupings. STS sites with low shrub cover have thin active layers, SCL and OSF sites with moderate shrub cover have moderate active-layer depths, and SAB and CSF sites with the highest shrub cover have thick active layers.

5.5 Delta regions

Four geographic regions have been defined in the central and southern

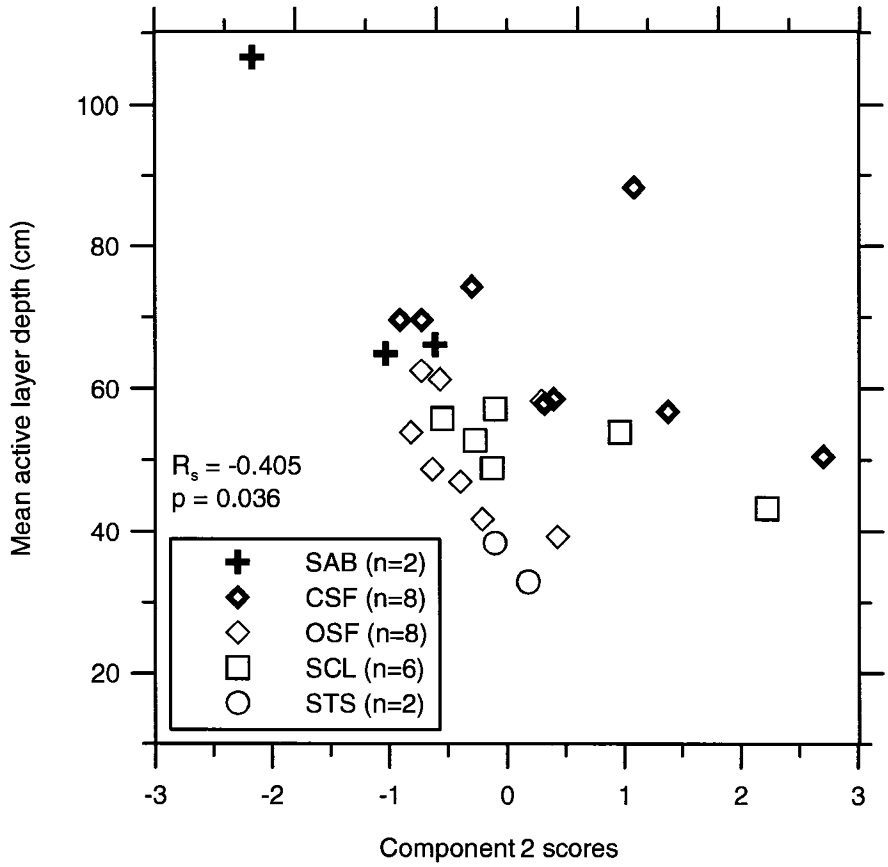

Figure 5.10 Mean active-layer depths and scores from second component of principal PCA. Sites are labelled by spruce-forest community, including spruce/alder-bearberry (SAB), closed-spruce/feathermoss (CSF), open-spruce/feathermoss (OSF), spruce-crowberry/lichen (SCL), and spruce/tamarack-sphagnum (STS).

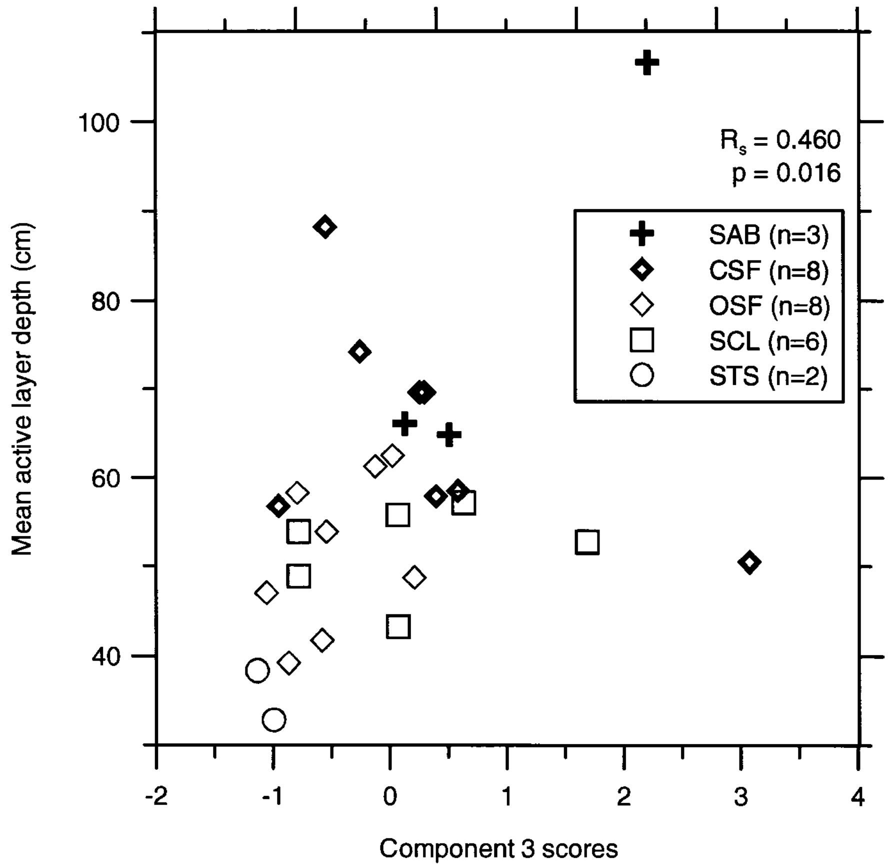

Figure 5.11 Mean active-layer depths and scores from third component of PCA. Sites are labelled by spruce-forest community, including spruce/alder-bearberry (SAB), closed-spruce/feathermoss (CSF), open-spruce/feathermoss (OSF), spruce-crowberry/lichen (SCL), and spruce/tamarack-sphagnum (STS).

Mackenzie Delta based on flooding regime (Cordes et al., 1985; Pearce, 1986). Flooding influences ground temperatures and active layers by adding heat to the ground, and removing the snow cover early in spring so that ground heating can begin (Burn, 2002a). Channel-bank levees in the central delta are at lower elevation than in the southern delta, indicating that flooding occurs more often in the central delta. Dominant vegetation associations in the western delta indicate that flooding is less frequent than in the eastern delta (Cordes et al., 1985; Pearce, 1986). Given spruce-forest sites with uniform surface conditions, it is hypothesized that ground temperatures at sites located in the central delta will be higher than at sites in the southern delta, and that ground temperatures will be higher in the eastern delta than in the western delta due to more frequent flooding.

The CSF community was used to compare mean annual ground temperatures between the delta regions because it is the most uniform community in terms of vegetative characteristics and related surface conditions (Table 3.4). At least two CSF sites are located in each delta region, with the exception of the southwestern delta, which has one. Comparisons were also made using the OSF community to verify the results. Though surface conditions of the OSF sites are less uniform, there are at least two sites in each region. It is recognized that this comparison is limited due to the small number of sites in each region.

Mean annual ground temperatures of CSF sites are higher in the southern region than in the central region (Fig. 5.12). This is the opposite of the expected pattern, and could be attributed to higher ground temperatures at two sites in the southern region that are located less than 60 m from a water body. Most mean annual ground temperatures at the OSF sites are lower in the southern delta than in the central delta (Fig. 5.13);

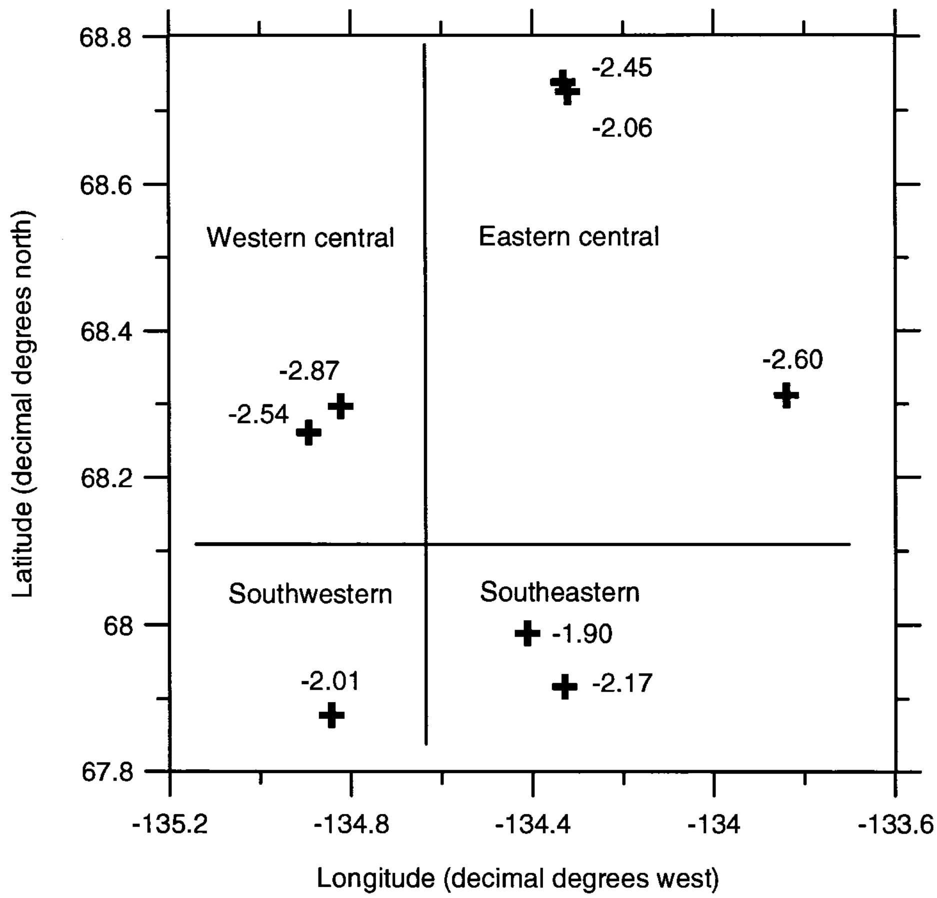

Figure 5.12 Locations of CSF sites in delta regions labelled with mean annual ground temperatures.

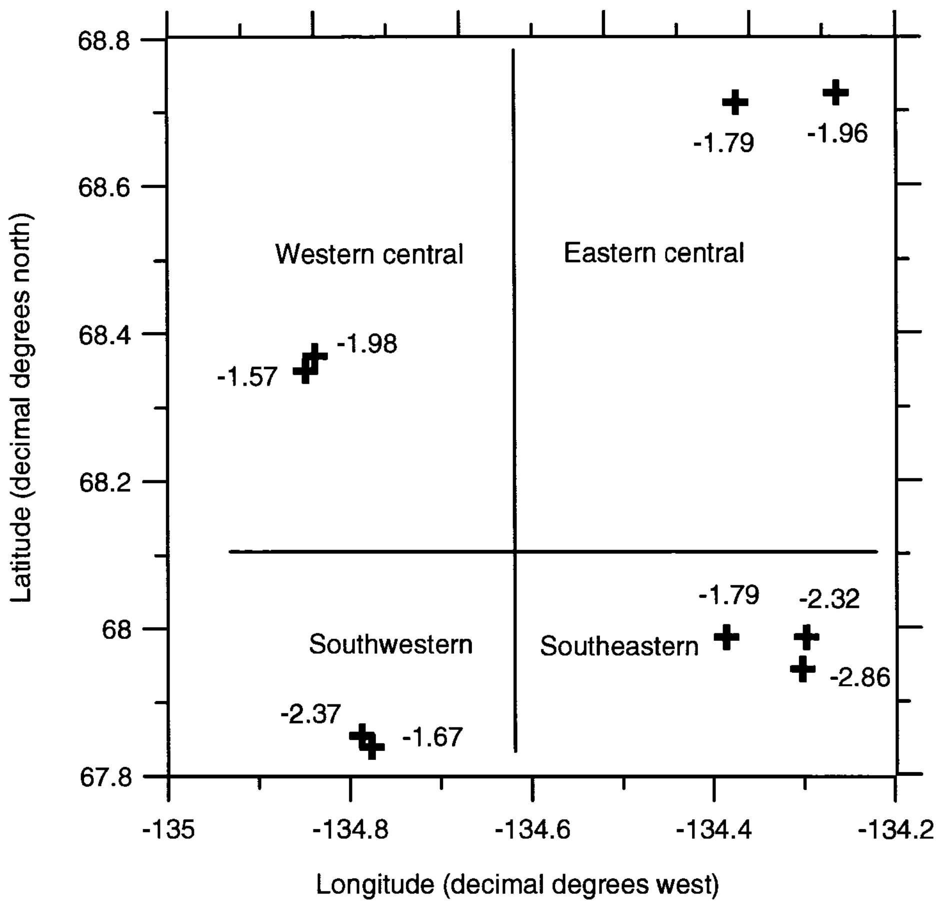

Figure 5.13 Locations of OSF sites in delta regions labelled with mean annual ground temperatures.

however, several sites in the southern delta have similar ground temperatures to those in the central delta. Mean annual ground temperatures are similar in the western and eastern regions for both CSF and OSF sites. From this limited data, there is no basis to conclude that there is a difference between mean annual ground temperatures of the delta regions south of treeline. It appears that mean annual ground temperatures within a particular spruce-forest community are consistent throughout the regions of delta, south of treeline.

5.6 Temporal comparison

Contemporary mean annual ground temperatures were measured at two spruce-forest sites in the Mackenzie Delta at which mean annual ground temperatures were previously measured over 35 years ago, to determine if temperatures have changed over time. Mean annual air temperatures in the Mackenzie Delta area have increased by 1 °C over the last 30 years (Burn et al., 2004), and may have led to higher mean annual ground temperatures. Ground temperature cables were installed as close as possible to the original measurement location so that the results would be comparable.

In May 1961, Johnston and Brown (1964) measured the ground temperature at 15.24-m, within the range of the depth of zero annual amplitude, with a thermocouple cable at a spruce-forest site in the eastern central delta (Fig. 5.14). The NRC Lake hole was drilled in April 1961 with a diamond bit drill, and water was used to circulate the drill cuttings. It is likely that the measured temperature was not the equilibrium temperature. It is assumed that the disturbance was minimal, but equilibrium ground temperatures may have been lower than those reported. In August 2005, a new hole was drilled by water jet near the old location, and a thermistor cable was installed to 14.8-m

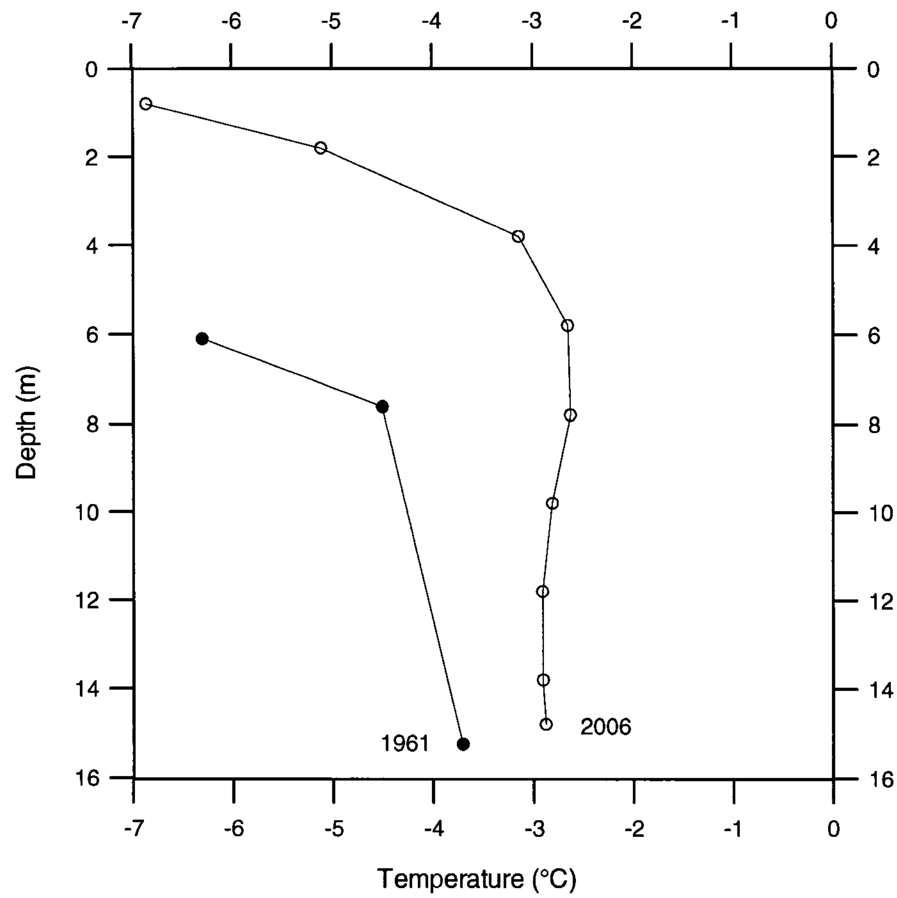

Figure 5.14 Ground temperature profiles at NRC Lake measured in May 1961 by Johnston and Brown (1964), and in the current study on April 9, 2006. It is unlikely that the May 1961 temperatures had returned to equilibrium following drilling, so reported temperatures may be warmer than equilibrium temperatures.

depth. Ground temperatures were recorded beginning in January 2006, and their minimal variation indicates that thermal equilibrium was re-established. The 15.24-m ground temperature reported in May 1961 was -3.7°C,and the 14.8-m ground temperature measured in April 2006 was -2.8°C, a difference of 0.9°C.

Between September 1969 and July 1971, ground temperatures were measured with a thermistor cable at 15.0-m depth at a spruce-forest site in the eastern central delta named Gill's Camp SF (Fig. 5.15) (Smith, 1973). A new hole was drilled by water jet in August 2005 near the old location, and a thermistor cable was installed to 15.0-m depth. Ground temperatures were recorded beginning in January 2006, and their minimal variation indicates that thermal equilibrium was re-established. The 15.0-m ground temperature measurement in September 1969 was -2.5°C, and the 15.0-m ground temperature measurement in September 2006 was -2.2°C, a difference of 0.3°C.

Mean annual ground temperatures have increased at both sites. Some of the difference may be attributed to changes in the accuracy and resolution of the historical and current instrumentation, and some variation may also be attributed to the measurements being taken in slightly different locations. However, it is likely that since ground temperatures have increased at both sites by a similar amount, that the differences are real. The result is also corroborated by the fact that mean annual ground temperatures measured at all 27 sites in the southern Mackenzie Delta in 2006 are higher (-0.6 to -2.9°C) than the range of mean annual ground temperatures for the same region reported by Mackay in 1974 (-3 to -4°C).

Mean annual ground temperatures at these two sites have increased by less than air temperatures have over the same time period. This could be due to site-specific

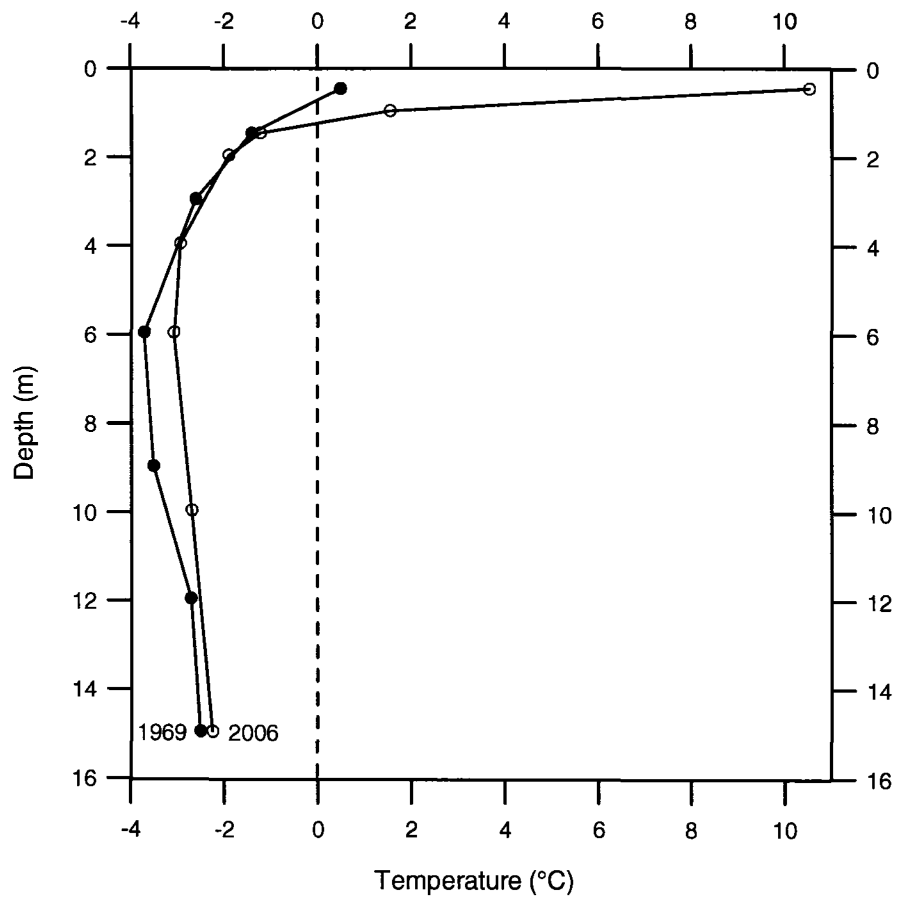

Figure 5.15 Ground temperature profiles at Gill's Camp SF measured in September 1969 by Smith (1973), and in the current study on September 16, 2006.

conditions. Both sites are spruce/feathermoss forests with moderate organic-layer depths, and large white spruce trees (Table 5.6), and according to previous site descriptions taken during the initial measurements, the surface conditions have not changed over the past 35 years. Mean annual ground temperatures may be buffered by the low thermal conductivity of the organic layer in summer.

The two delta sites display a rate of change of between 0.01 to 0.02°C/year, whereas the reported rate of change of three sites in the uplands adjacent to the delta between 1992 and 2002 ranged between 0.02 to 0.07°C/year (Smith et al., 2005). The delta sites may respond more slowly to climate change due to the presence of numerous water bodies. Climate warming may not affect water temperatures in the same way as ground surface temperatures if air temperatures continue to follow the current trend of more warming in the winter when lakes are ice covered and remain close to 0°C (Meteorological Service of Canada, 2007). The water bodies may moderate the response of mean annual ground temperatures in the region to climate warming by increasing at a slower rate than land surfaces.

5.7 Summary

Mean annual ground temperatures at SAB sites are significantly higher than in the other communities. White-spruce DBH was found to be significantly correlated with mean annual ground temperatures, suggesting that some of the variation of ground temperatures may be explained by snow depths and the interception of radiation associated with the forest canopy (Table 5.7). However, the lack of statistically significant relations between mean annual ground temperatures and early and late-winter

	Historical mean annual ground temperature (°C)	Current mean annual ground temperature (°C)	Spruce-forest community	Organic layer (cm)	White spruce DBH (cm)	Shrub cover (%)	Distance between channel and nearest lake (m)
NRC Lake	-3.7°C	-2.8°C	CSF	9	24	67	149
Gill's Camp SF	-2.5°C	-2.2°C	OSF	11	18	40	211

Table 5.6 Historical and current mean annual ground temperatures at two spruce-forest sites in the Mackenzie Delta, and the surface conditions at these sites associated with mean annual ground temperatures.

	SAB	CSF	OSF	SCL	STS
Median of site mean annual ground temperatures (°C)					
	-1.1	-2.3	-2.0	-1.9	-2.0
Median of average site active-layer depths (cm)					
	66	64	51	53	36
Related surface conditions					
Median white spruce DBH (cm)	9	29	19	22	7
Interquartile range of organic- layer depths (cm)	0-11	4-20	7-13	9-30	10-14
Flood frequency	Frequent	Moderately frequent	Infrequent	Rare	Rare
Relation					
	Small trees, open canopy, frequent flooding, thin organic layer, higher ground temperature, thick active layer.	Large trees, closed canopy, moderately frequent flooding, mostly thick organic layers, lower ground temperature, thick active layer.	Medium-sized trees, partially closed canopy, infrequent flooding, moderate organic-layer depth, moderate ground temperature and active-layer depth.	Medium-sized trees, partially open canopy, rarely flooded, some thicker organic layers, moderate ground temperature and active-layer depth.	Small trees, open canopy, rarely flooded, moderate organic layer, moderate ground temperature, thin active layer.

Table 5.7 Mean annual ground temperatures, active-layer depths and related surface conditions of each spruce-forest community.

snow depths indicates that other environmental conditions should be considered. Results from a principal components analysis separated sites with the highest and lowest ground temperatures from the rest of the population based on organic-layer depths. Some of the unexplained variation of ground temperatures may be due to sites that are still in thermal disequilibrium despite a mature spruce-forest cover, and to the warming effect of water bodies on sediments at 20-m depth.

SAB and CSF communities have similarly thick active-layer depths that are significantly different from the thinner active layers of OSF and SCL communities. STS communities had the thinnest active layers. Active-layer depths were positively correlated with shrub height and LAI, and negatively correlated with late-winter snow depths and organic-layer depths. These correlations suggest that some of the variation in active-layer thickness may be explained by both the removal of snow by spring flooding, near-surface ground ice content, and by the organic- layer thickness. These results are confirmed by the principal components analysis.

From the limited amount of data it was not possible to conclude that there is regional variation of mean annual ground temperatures. Significant change was detected in a temporal comparison of mean annual ground temperatures over 35 years at two spruce-forest sites. Mean annual ground temperatures may respond more slowly to climate change in the delta due to the presence of water bodies that warm more slowly.

CHAPTER SIX

SUMMARY OF RESULTS AND CONCLUSIONS

6.1 Summary of results

This study examines the variation of mean annual ground temperatures and active-layer depths in spruce-forests of the Mackenzie Delta. Analysis of site surface conditions at 28 spruce-forest sites demonstrated that surface conditions are relatively homogeneous within spruce-forest communities, and vary between the communities. Mean annual ground temperatures and active-layer depths are related to surface conditions, and there is some variation by spruce-forest community (Figs. 5.1 & 5.2). This chapter summarizes the relations between mean annual ground temperatures, active-layer depths, and surface conditions, in the context of spruce-forest communities, and presents the conclusions of the thesis.

6.1.1 Surface conditions

Spruce-forest study sites were grouped into five communities, based on previous ecological classifications (Gill, 1972; Pearce et al., 1988). The groupings were confirmed by analyzing the vegetation survey data using a hierarchical cluster analysis. The analysis showed that vegetative characteristics were more similar within spruce-forest communities than between them. Examination of field data from the 28 spruce-forest sites showed that surface conditions also vary between spruce-forest communities, though it is recognized that the communities are a successional sequence with a continuum of surface conditions.

The CSF community is characterized by white spruce trees that are significantly larger than those of the SAB and OSF communities, and shrubs that are significantly taller than the SCL community. The thick canopy cover intercepts high amounts of snow in the winter, leading to significantly thinner snow depths than in the SAB and OSF communities. The thick canopy cover also intercepts a high amount of incoming radiation in the summer. Many CSF sites have thick organic layers that develop in the absence of regular flooding.

The SAB community is characterized by significantly smaller white spruce trees than the CSF community. The relatively open canopy leads to significantly thicker snow depths in winter than the CSF community, but tall shrubs intercept incoming solar radiation in the summer. Organic layers are thin at SAB sites since annual flooding prevents the establishment of mosses.

The OSF and SCL communities are differentiated by the dominance of different vegetative species, but in terms of surface conditions they are both characterized by moderately sized white spruce trees and low shrubs. The relatively open canopy leads to greater snow depths, and thicker organic-layer depths are related to infrequent flooding.

STS communities have very small white spruce trees, and low shrubs associated with an open canopy, thick snow packs, and low interception of incoming radiation in the summer. Organic layers are moderately thick since flooding is rare.

6.1.2 Mean annual ground temperatures

Mean annual ground temperatures measured at 28 sites in spruce forests of the Mackenzie Delta ranged from -0.6 to -2.9°C. Permafrost in the delta is warmer than the adjacent tundra uplands because of the presence of numerous waterbodies, and flooding at some sites removes snow from the ground earlier in the year. Mean annual ground temperatures were significantly higher in the SAB community, ranging from -0.6 to

-1.5°C (Fig. 5.1). Ground temperatures in the remaining communities were lower, ranging between -1.5 and -2.9°C.

Using univariate correlations with data from all of the sites, mean annual ground temperatures were significantly correlated with white spruce DBH. This relation suggests that some of the variation of ground temperatures can be explained by the interception of radiation and snow by the forest canopy. However, there is considerable scatter in the relation, and relations between mean annual ground temperatures and early and late-winter snow depths were not statistically significant, which suggests that other surface conditions are also important.

A multivariate PCA was used to combine the influence of multiple surface condition variables into three synthetic components, and reduce the level of Type 1 error associated with multiple univariate correlations. The second component was significantly correlated with mean annual ground temperatures, and represented the organic-layer depth. The second component separated sites with the highest and lowest ground temperatures from the rest of the population. SAB communities had thin organic layers and more open canopies associated with high ground temperatures. The absence of an organic layer, thicker snow cover, and the removal of snow earlier in spring due to flooding may be associated with warmer ground. CSF and SCL sites with thick organic layers and closed canopies had the lowest ground temperatures. Canopy cover, associated snow and radiation interception, and organic-layer thickness affect mean annual ground temperatures, but the weak correlations between them may be explained by the damping effect of water bodies at 20-m depth.

Mean annual ground temperatures were measured at sites in four regions of the central and southern delta that have been identified as having different flooding regimes in previous studies (Fig. 1.3). The central delta is subject to more frequent flooding than the southern delta, and the eastern delta may flood more often than the western delta. It was hypothesized that different flooding regimes could affect ground temperatures; however, based on a comparison of a relatively small sample of mean annual ground temperatures at spruce-forest sites with uniform surface conditions in the four regions, no systematic ground temperature differences between the regions were found.

Two historical ground temperature measurement sites were re-occupied in the eastern central delta. Mean annual ground temperatures measured in 1961 and 1969 were compared with current mean annual ground temperatures from the same locations. The results indicate that mean annual ground temperatures at the two sites have increased by up to 0.9°C in association with recent permafrost warming in the region. These results are supported by the fact that all of the mean annual ground temperatures measured at spruce-forest sites in 2006 were higher (-0.6 to -2.9°C) than those reported by Mackay in 1974 in the same region (-3 to -4°C). The rate of climate warming in the delta is slower than that reported in the adjacent tundra uplands by Smith et al. (2005). At the delta sites, the ground may be buffered from increasing air temperatures by a moderately thick organic layer. In addition, the numerous lakes in the delta may respond more slowly to climate warming than ground surface temperatures because most climate warming is expected in the winter when they are ice-covered. This could slow the response of mean annual ground temperatures to climate warming in the delta.

6.1.3 Active-layer depths

Active-layer depths at 27 of the study sites ranged from 33 to 107 cm, being thicker in the youngest spruce-forest communities, and thinner in the oldest communities. Specifically, active- layer depths were significantly thicker in the SAB and CSF communities, than in the OSF and SCL communities. The STS community had the thinnest active-layer depths.

Using univariate correlations with data from all of the sites, active-layer depths were significantly positively correlated with shrub height and the leaf area index, and negatively correlated with late-winter snow depth and organic-layer thickness. These correlations imply that active layer differences may partly be explained by the organic-layer thickness, the removal of snow by spring flooding, and near-surface ground ice content. Significant correlations were found between active-layer thickness and all three components of the PCA. The first component contrasted the late-winter snow depth with white spruce DBH, associated with shrub height and leaf area index, the second component was dominated by the organic-layer depth, and the third component described shrub cover. Correlations between these components and active-layer depths support the implications of the univariate correlations.

6.2 Conclusions

The following conclusions can be drawn regarding ground temperature conditions in spruce-forests of the Mackenzie Delta from the examination of surface conditions, mean annual ground temperatures and active-layer depths in this thesis:

1. Surface conditions vary systematically between spruce-forest communities. White spruce tree diameters are significantly larger in CSF communities than in SAB and

OSF communities, implying a thicker canopy cover at CSF sites. Shrubs are also significantly taller in CSF communities than in SCL communities. Due to the thicker winter canopy cover, snow depths at CSF communities are significantly thinner than at SAB and SCL sites.

2. Mean annual ground temperatures of the SAB community are significantly higher than those of other communities, ranging between -0.6 to -1.5°C.
3. Mean annual ground temperatures are significantly correlated to mean white spruce DBH, implying that the interception of snow and the resulting snow depth may affect ground temperature variability. Results of a PCA suggest that organic-layer thickness may also affect mean annual ground temperatures, however, the damping effect of warm lakes may obscure these relations at depth.
4. Based on a limited number of samples, there is no evidence to conclude that mean annual ground temperatures vary systematically by delta region.
5. Mean annual ground temperatures have warmed by up to 0.9°C over the last 35 years at two spruce/feathermoss sites in the eastern-central Mackenzie Delta. The response of ground temperatures to climate warming may be slower in the delta than in the adjacent tundra uplands due to the presence of numerous lakes in the delta and their response to climate warming.
6. Active-layer depths vary systematically between spruce-forest communities, most significantly the more regularly flooded SAB and CSF communities have thicker active layers than the OSF and SCL communities.
7. Active-layer depths are significantly positively correlated with shrub height and LAI, and negatively correlated with late-winter snow depth, and organic-layer depth.

These correlations imply that active-layer variation may be associated with organic-layer depth, the removal of the snow cover in early spring at regularly flooded sites, or near-surface ground ice content.

6.3 Future considerations

The main objective of this thesis was to determine the natural variation of ground temperatures in central and southern Mackenzie Delta. Calculations and field measurements have shown that boreholes at 20-m depth, are influenced by water bodies up to 600 m distant. Future work could consider methods to reduce that impact. Measurements at 15 m depth are also near zero annual amplitude, yet are less affected by water bodies. Inspection of aerial photographs may reveal a few sites in the delta that are at least 600 m from any water body. According to equation 8, boreholes at 20-m depth at these sites would be relatively undisturbed.

REFERENCES

Anuchin, N.P. 1970. Forest mensuration. Israel Program for Scientific Translations, Jerusalem.

Aylsworth, J.M., Burgess, M.M., Desrochers, D.T., Duk-Rodkin, A., Robertson, T., and Traynor, J.A. 2000. Surficial geology, subsurface materials, and thaw sensitivity of sediments. *In* The physical environment of the Mackenzie Valley, Northwest Territories: a base line for the assessment of environmental change. *Edited by* L.D. Dyke and G.R. Brooks. Geological Survey of Canada, Bulletin 547. pp. 41-48.

Banin, A., and Anderson, D.M. 1974. Effect of salt concentration changes during freezing of the unfrozen water content of porous media. Water Resources Research, **10**: 124-128.

Beringer, J., Chapin III, F.S., Thompson, C.C., and McGuire, A.D. 2005. Surface energy exchanges along a tundra-forest transition and feedbacks to climate. Agricultural and Forest Meteorology, **131**: 143-161.

Brooks, G.R. 2000. Streamflow in the Mackenzie valley. *In* The physical environment of the Mackenzie Valley, Northwest Territories: a base line for the assessment of environmental change. *Edited by* L.D. Dyke and G.R. Brooks. Geological Survey of Canada, Bulletin 547. pp. 21-30.

Brown, R.J.E. 1966. Influence of vegetation on permafrost. *In* Proceedings of the International Conference on Permafrost, National Academy of Science and Natural Resources Council publication 1287, Washington, D.C., pp. 20-25.

Brown, R.J.E., and Péwé, T.L. 1973. Distribution of permafrost in North America and its relationship to the environment: a review, 1963-1973. *In* Proceedings, 2nd International Conference on Permafrost, 13-28 July 1973, Yakutsk, U.S.S.R. North American Contribution, National Academy of Science Press, Washington, D.C., pp. 71-100.

Buech, R.R., and Rugg, D.J. 1995. Biomass relations for components of five Minnesota shrubs, research paper NC-325. Forest Service, United States Department of Agriculture, St. Paul, Minnesota.

Burn, C.R. 1997. Cryostratigraphy, paleogeography, and climate change during the early Holocene warm interval, western arctic coast, Canada. Canadian Journal of Earth Sciences, **34**: 912-925.

Burn, C.R. 2002a. Mackenzie Delta. *In* Natural History of the Western Arctic, Part 1, Land and Water. *Edited by* S. Black and A. Fehr. Western Arctic Handbook Committee, Inuvik, N.W.T. pp. 24-29.

Burn, C.R. 2002b. Tundra lakes and permafrost, Richards Island, western arctic coast, Canada. Canadian Journal of Earth Sciences, **39**: 1281-1298.

Burn, C.R. 2004. The thermal regime of cryosols. *In* Cryosols: permafrost affected soils. *Edited by* J.M. Kimble. Springer, New York. pp. 391-413.

Burn, C.R., and Smith, C.A.S. 1988. Observations of the "thermal offset" in near-surface annual ground temperatures at several sites near Mayo, Yukon Territory, Canada. Arctic, **41**: 99-104.

Burn, C.R., and Nelson, F.E. 2006. Comment on "A projection of severe near-surface permafrost degradation during the 21st century" by David M. Lawrence and Andrew G. Slater. Geophysical Research Letters, **33**: L21503.

Burn, C. R., Barrow, E., and Bonsal, B. 2004. Climate change scenarios for the Mackenzie River Valley. *In* 57th Canadian Geotechnical Conference, Quebec City, Session 7A, pp. 2-8.

Carslaw, H.S., and Jaeger, J.C. 1959. Conduction of heat in solids. 2nd edition. Oxford University Press, Oxford.

Carson, M.A., Jasper, J.N., and Conly, F.M. 1998. Magnitude and sources of sediment input to the Mackenzie Delta, Northwest Territories, 1974-94. Arctic, **51**: 116-124.

Chen, J.M., Rich, P.M., Gower, S.T., Norman, J.M., and Plummer, S. 1997. Leaf area index of boreal forests: theory, techniques, and measurements. Journal of Geophysical Research, **10**: 429-444.

Cordes, L.D., McLennan, D., and Pearce, C.M. 1985. Alluvial ecosystems on the Mackenzie Delta, Northwest Territories. Environment and Socio-economic Services, B.C. Hydro, Vancouver, B.C.

Crawford, C.B., and Jonhston, G.H. 1971. Construction on permafrost. Canadian Geotechnical Journal, **8**: 236-251.

Dyke, L.D. 2000. Climate of the Mackenzie River valley. *In* The physical environment of the Mackenzie Valley, Northwest Territories: a base line for the assessment of environmental change. *Edited by* L.D. Dyke and G.R. Brooks. Geological Survey of Canada, Bulletin 547. pp. 21-30.

Eugster, W., Rouse, W.R., Pielke, R.A. Sr., McFadden, J.P., Baldocchi, D.D., Kittel, T.G.F., Chapin III, F.S., Liston, G.E., Vidale, P.L., Vaganov, E., and Chambers, S. 2000. Land-atmosphere energy exchange in Arctic tundra and boreal forest: available data and feedbacks to climate. Global Change Biology, **6**: 84-115.

Evans, B.M., Walker, D.A., Benson, C.S., Nordstrand, E.A., Petersen, G.W. 1989. Spatial interrelationships between terrain, snow distribution and vegetation patterns at an arctic foothills site in Alaska. Holarctic Ecology, **12**: 270-278.

Gill, D. 1971. Vegetation and environment in the Mackenzie River Delta: a study in subarctic ecology. Ph.D. thesis, Department of Geography, The University of British Columbia, Vancouver, B.C.

Gill, D. 1972. The point bar environment in the Mackenzie River delta. Canadian Journal of Earth Sciences, **9**: 1382-1393.

Gill, D. 1973. A spatial correlation between plant distribution and unfrozen ground within a region of discontinuous permafrost. *In* Proceedings, 2nd International Conference on Permafrost, 13-28 July 1973, Yakutsk, U.S.S.R., North American Contribution. National Academy of Science Press, Washington, D.C., pp. 105-113.

Goodrich, L. E. 1982. The influence of snow cover on the ground thermal regime. Canadian Geotechnical Journal, **19**: 421-432.

Greig-Smith, P. 1983. Quantitative plant ecology. Blackwell Scientific, Oxford.

Hallet, B. 1978. Solute redistribution in freezing ground. In Proceedings, 3rd International Conference on Permafrost, 10-13 July, Edmonton, Alberta. National Research Council, Ottawa, Ontario, pp. 85-91.

Heginbottom, J.A., Dubreuil, M-A., and Harker, P.A. 1995. Canada – Permafrost. Ottawa, Canada: Natural Resources Canada, National Atlas of Canada, 5th edition, Plate 2.1 (MCR No. 4177; scale 1:7500 000) [online]. Available from http://atlas.gc.ca/site/english/maps/archives/5thedition/environment/land/mcr4177 [cited 20 February 2007].

Heeler, R.M., and Day, G.S. 1975. A supplementary note on the use of cluster analysis for stratification. Applied Statistics, **24**: 342-344.

Hirst, S.M., Miles, M., Blachut, S.P., Goulet, L.A., and Taylor, R.E. 1987. Quantitative synthesis of the Mackenzie Delta ecosystems. Inland Waters Directorate, Environment Canada, Ottawa.

Hotelling, H. 1933. Analysis of a complex of statistical variables into principal components. Journal of Educational Psychology, **24**: 417-441, 498-520.

Johnston, G.H., and Brown, R.J.E. 1964. Some observations of permafrost at an arctic lake in the Mackenzie Delta, N.W.T., Canada. Arctic, **17**: 163-175.

Johnston, G.H., and Brown, R.J.E. 1966. Occurrence of permafrost at an arctic lake. Nature, **211**: 952-953.

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

Kokelj, S.V., and Burn, C.R. 2004. Tilt of spruce trees near ice wedges, Mackenzie delta, Northwest Territories. Arctic, Antarctic and Alpine Research, **36**(4): 615-623.

Kokelj, S.V., and Burn, C.R. 2005a. Near-surface ground ice in sediments of the Mackenzie Delta, Northwest Territories, Canada. Permafrost and Periglacial Processes, **16**: 291-303.

Kokelj, S.V., and Burn, C.R. 2005b. Geochemistry of the active layer and near-surface permafrost, Mackenzie delta region, Northwest Territories, Canada. Canadian Journal of Earth Sciences, **42**: 37-48.

Lachenbruch, A.H. 1957. Three-dimensional heat conduction beneath heated buildings. U.S. Geological Survey Bulletin 1052-B. U.S. Geological Survey.

Lachenbruch, A.H., Brewer, M.C., Greene, G.W., and Marshall, B.V. 1962. Temperatures in permafrost. *In* Temperature: its measurement and control in science and industry. Vol. 3, Part 1. *Edited by* C.M. Herzfeld. Reinhold, New York. pp. 791-803.

Lesack, L.F.W., Marsh, P., and Hecky, R.E. 1998. Spatial and temporal dynamics of major solute chemistry among Mackenzie Delta lakes. Limnology and Oceanography, **43** (7): 1530-1543.

Ling, F., and Zhang, T. 2003. Impact of the timing and duration of seasonal snow cover on the active layer and permafrost in the Alaskan Arctic. Permafrost and Periglacial Processes, **14**: 141-150.

Luthin, J.N. and Guymon, G.L. 1974. Soil moisture-vegetation-temperature relationships in central Alaska. Journal of Hydrology, **23**: 233-246.

Mackay, J.R. 1962. Pingos of the Pleistocene Mackenzie Delta area. Geographical Bulletin, **18**: 21-63.

Mackay, J.R. 1963. The Mackenzie Delta area, Northwest Territories, Geographical Branch, Memoir 8. Department of Mines and Technical Surveys, Ottawa.

Mackay, J.R. 1967. Permafrost depths, lower Mackenzie Valley, Northwest Territories. Arctic, **20**: 21-26.

Mackay, J.R. 1974. Seismic shot holes and ground temperatures, Mackenzie Delta area, Northwest Territories. *In* Geological Survey of Canada Paper 74-1, Part A, Report of Activities, April to October 1973. Geological Survey of Canada, Department of Energy, Mines and Resources, Ottawa, pp. 389-390.

Mackay, J.R., and Burn, C.R. 2002. The first 20 years (1978-1979 to 1998-1999) of ice-wedge growth at the Illisarvik experimental drained lake site, western Arctic coast, Canada. Canadian Journal of Earth Sciences, **39**: 95-111.

Mackay, J.R., and MacKay, D.K. 1974. Snow cover and ground temperatures, Garry Island, N.W.T. Arctic, **27**: 287-296.

Marsh, P., and Lesack, L.F.W. 1996. The hydrologic regime of perched lakes in the Mackenzie Delta: potential responses to climate change. Limnology and Oceanography, **41** (5): 849-856.

Meteorological Service of Canada. 2007. Canada climate data [online]. Ottawa, Canada: Environment Canada. Available from http://climate.weatheroffice.ec.gc.ca/climateData/canada_e.html [cited 25 March 2007].

Mitchell, J.E., and Popovich, S.J. 1997. Effectiveness of basal area for estimating canopy cover of ponderosa pine. Forest Ecology and Management, **95**: 45-51.

Mueller-Dombois, D., and Ellenberg, H. 1974. Aims and methods of vegetation ecology. John Wiley and Sons, New York.

Nelson, F.E., Outcalt, S.I., Goodwin, C.W., and Hinkel, K.M. 1985. Diurnal thermal regime in a peat-covered palsa, Toolik Lake, Alaska. Arctic, **38**: 310-315.

Nixon, F.M. 2000. Thaw-depth monitoring. *In* The physical environment of the Mackenzie Valley, Northwest Territories: a base line for the assessment of environmental change. *Edited by* L.D. Dyke and G.R. Brooks. Geological Survey of Canada, Bulletin 547. pp. 119-126.

Northwest Territories Centre for Geomatics. 2004. Mackenzie valley airphoto project [online]. Available from http://www.gnwtgeomatics.nt.ca/RemoteSensing/avhrr/Mackenzie ValleyPhotos.asp [cited 1 June 2007].

Oke, T.R. 1987. Boundary layer climates. 2nd edition. Methuen, London.

Oke, T.R. 1997. Surface climate processes. *In* The surface climates of Canada. *Edited by* W.G. Bailey, T.R. Oke, and W.R. Rouse. McGill-Queens University Press, Montreal. pp. 197-207.

Pearce, C.M. 1986. The distribution and ecology of the shoreline vegetation on the Mackenzie Delta, N.W.T. Ph.D. thesis, Department of Geography, The University of Calgary.

Pearce, C.M., McLennan, D., and Cordes, L.D. 1988. The evolution and maintenance of white spruce woodlands on the Mackenzie Delta. Holarctic Ecology, **11**: 248-258.

Pearce, C.M. 1994. Overbank sedimentation patterns on the Mackenzie Delta, Northwest Territories: Volume 2 (1993-1994), IWD-NOGAP Project C.11.4. Inland Waters Directorate, Environment Canada, Yellowknife.

Pearce, C.M. 1998. Vegetation patterns and environmental relationships in an arctic riparian wetland. *In* Ecology of wetlands and associated systems. *Edited by* S.K. Majumdar, E.W. Miller, and F.J. Brenner. The Pennsylvania Acadamy of Science. pp. 258-280.

Pomeroy, J., and Goodison, B. 1997. Winter and snow. *In* The surface climates of Canada. *Edited by* W.G. Bailey, T.R. Oke, and W.R. Rouse. McGill-Queens University Press, Montreal. pp. 208-221.

Rampton, V.N. 1988. Quaternary geology of the Tuktoyaktuk Coastlands, Northwest Territories, Memoir 423. Geological Survey of Canada, Energy Mines and Resources Canada, Ottawa.

Riedel, S.M., Epstein, H.E., Walker, D.A., Richardson, D.L., Calef, M.P., Edwards, E., and Moody, A. 2005. Spatial and temporal heterogeneity of vegetation properties among four tundra plant communities at Ivotuk, Alaska, USA. Arctic, Antarctic and Alpine Research, **37**: 25-33.

Rouse, W.R. 1984a. Microclimate of Arctic tree line, 1. Radiation balance of tundra and forest. Water Resources Research, **20**: 57-66.

Rouse, W.R. 1984b. Microclimate of Arctic tree line, 2. Soil microclimate of tundra and forest. Water Resources Research, **20**: 67-73.

Scheiner, S.M. 2001. Multiple response variables and multispecies interactions. *In* Design and analysis of ecological experiments, 2nd ed. *Edited by* S.M. Scheiner, and J. Gurevitch. Oxford University Press, New York. pp. 100-121.

Serreze, M.C., Walsh, J.E., Chapin III, F.S., Osterkamp, T., Dyurgerov, M., Romanovsky, V., Oechel, W.C., Morison, J., Zhang, T., and Barry, R.G. 2000. Observational evidence of recent change in the northern high-latitude environment. Climatic Change, **46**: 159-207.

Shaw, P.J.A. 2003. Multivariate statistics for the environmental sciences. Oxford University Press, New York.

Shippert, M.M., Walker, D.A., Auerbach, N.A., and Lewis, B.E. 1995. Biomass and leaf-area index maps derived from SPOT images for Toolik Lake and Imnavait Creek areas, Alaska. Polar Record, **31**: 147-154.

Smith, M.W. 1973. Factors affecting the distribution of permafrost, Mackenzie Delta, N.W.T. Ph.D. thesis, Department of Geography, The University of British Columbia, Vancouver, B.C.

Smith, M.W. 1975. Microclimate influences on ground temperatures and permafrost distribution, Mackenzie Delta, Northwest Territories. Canadian Journal of Earth Sciences, **12**: 1421-1438.

Smith, M.W. 1976. Permafrost in the Mackenzie Delta, Northwest Territories. Geological Survey of Canada Paper 75-28, Geological Survey of Canada, Department of Energy, Mines and Resources, Ottawa.

Smith, M.W. and Riseborough, D.W. 1996. Permafrost monitoring and detection of climatic change. Permafrost and Periglacial Processes, **7**: 301-309.

Smith, S., and Burgess, M. 2000. Ground temperature database for northern Canada. Open file 3954, Geological Survey of Canada, Natural Resources Canada, Ottawa.

Smith, S., and Burgess, M. 2004. Sensitivity of permafrost to climate warming in Canada. Geological Survey of Canada Bulletin 579, Geological Survey of Canada, Natural Resources Canada, Ottawa.

Smith, S.L., Burgess, M.M, Riseborough, D., and Nixon, F.M. 2005. Recent trends from Canadian permafrost thermal monitoring network sites. Permafrost and Periglacial Processes, **16**: 19-30.

Tarnocai, C. 1984. Characteristics of soil temperature regimes in the Inuvik area. *In* Northern Ecology and Resource Management. *Edited by* R. Olsen et al. The University of Alberta Press, Edmonton. pp. 19-37.

Thompson, C., Beringer, J., Chapin III, F.S., and McGuire, A.D. 2004. Structural complexity and land-surface energy exchange along a gradient from arctic tundra to boreal forest. Journal of Vegetation Science, **15**: 397-406.

Triola, M.F. 1994. Elementary statistics, 6th edition. Addison-Wesley, New York.

van Everdingen, R. 2005. Multi-language glossary of permafrost and related ground-ice terms. Boulder, CO: National Snow and Ice Data Center/World Data Center for Glaciology.

Viereck, L.A. 1970. Forest succession and soil development adjacent to the Chena River in interior Alaska. Arctic and Alpine Research, **2**: 1-26.

Ward, J.H. 1963. Hierarchical grouping to optimise an objective function. American Statistical Association Journal, **58**: 236-244.

Williams, P.J. 1968. Ice distribution in permafrost profiles. Canadian Journal of Earth Sciences, **5**: 1381-1386.

Williams, P.J. 1986. Pipelines and permafrost: science in a cold climate. Carleton University Press, Ottawa.

Williams, P.J. and Smith, M.W. 1989. The frozen earth: fundamentals of geocryology. Cambridge University Press, Cambridge.

Woo, M. 1997. A guide for ground based measurement of Arctic snow cover. Climate Research Branch, Atmospheric Environment Service, Environment Canada, Ottawa.

Zhang, T. 2005. Influence of the seasonal snow cover on the ground thermal regime: an overview. Reviews of Geophysics, **43**: 1-23.