Trends in permafrost conditions and ecology in northern Canada

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PREFACE

The Canadian Councils of Resource Ministers developed a Biodiversity Outcomes Framework[1] in 2006 to focus conservation and restoration actions under the *Canadian Biodiversity Strategy*.[2] *Canadian Biodiversity: Ecosystem Status and Trends 2010*[3] was a first report under this framework. It assesses progress towards the framework's goal of "Healthy and Diverse Ecosystems" and the two desired conservation outcomes: i) productive, resilient, diverse ecosystems with the capacity to recover and adapt; and ii) damaged ecosystems restored.

The 22 recurring key findings that are presented in *Canadian Biodiversity: Ecosystem Status and Trends 2010* emerged from synthesis and analysis of technical reports prepared as part of this project. Over 500 experts participated in the writing and review of these foundation documents. This report, *Trends in permafrost conditions and ecology in northern Canada*, is one of several reports prepared on the status and trends of national cross-cutting themes. It has been prepared and reviewed by experts in the field of study and reflects the views of its authors.

Acknowledgements

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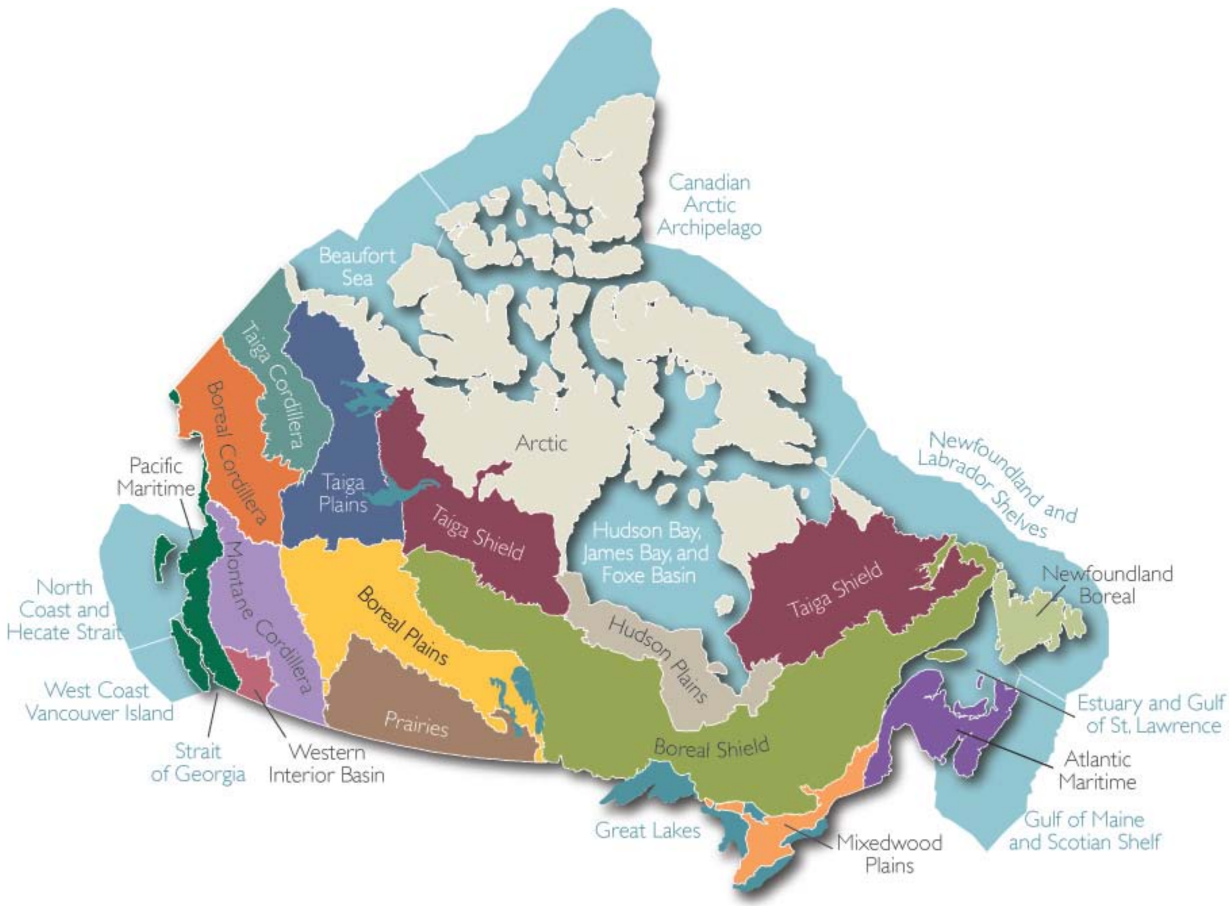
[1] Environment Canada. 2006. Biodiversity outcomes framework for Canada. Canadian Councils of Resource Ministers. Ottawa, ON. 8 p. http://www.biodivcanada.ca/default.asp?lang=En&n=F14D37B9-1

[2] Federal-Provincial-Territorial Biodiversity Working Group. 1995. Canadian biodiversity strategy: Canada's response to the Convention on Biological Diversity. Environment Canada, Biodiversity Convention Office. Ottawa, ON. 86 p. http://www.biodivcanada.ca/default.asp?lang=En&n=560ED58E-1

[3] Federal, Provincial and Territorial Governments of Canada. 2010. Canadian biodiversity: ecosystem status and trends 2010. Canadian Councils of Resource Ministers. Ottawa, ON. vi + 142 p. http://www.biodivcanada.ca/default.asp?lang=En&n=83A35E06-1

Ecological Classification System – Ecozones+

A slightly modified version of the Terrestrial Ecozones of Canada, described in the *National Ecological Framework for Canada*,[4] provided the ecosystem-based units for all reports related to this project. Modifications from the original framework include: adjustments to terrestrial boundaries to reflect improvements from ground-truthing exercises; the combination of three Arctic ecozones into one; the use of two ecoprovinces – Western Interior Basin and Newfoundland Boreal; the addition of nine marine ecosystem-based units; and, the addition of the Great Lakes as a unit. This modified classification system is referred to as "ecozones+" throughout these reports to avoid confusion with the more familiar "ecozones" of the original framework.[5]



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[4] Ecological Stratification Working Group. 1995. A national ecological framework for Canada. Agriculture and Agri-Food Canada, Research Branch, Centre for Land and Biological Resources Research and Environment Canada, State of the Environment Directorate, Ecozone Analysis Branch. Ottawa/Hull, ON. 125 p. Report and national map at 1:7 500 000 scale.

[5] Rankin, R., Austin, M. and Rice, J. 2011. Ecological classification system for the ecosystem status and trends report. Canadian Biodiversity: Ecosystem Status and Trends 2010, Technical Thematic Report No. 1. Canadian Councils of Resource Ministers. Ottawa, ON. http://www.biodivcanada.ca/default.asp?lang=En&n=137E1147-1

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INTRODUCTION

Permafrost is soil, rock, or sediment that remains at or below a temperature of 0°C for at least two consecutive years. Permafrost has an important influence on the biophysical environment and processes largely because it can contain ice as pore ice, ice lenses, ice wedges, and other massive ice bodies (Mackay, 1972). The permafrost region covers about half the Canadian landmass (Figure 1). In the northern portion of the permafrost region, permafrost is continuous and may be several hundred metres thick and have temperatures colder than -5°C (Heginbottom et al., 1995; Smith et al., 2001a). Further south, permafrost becomes discontinuous and patchy, is only a few metres thick and persists at temperatures approaching 0°C (for example Smith et al., 2008).

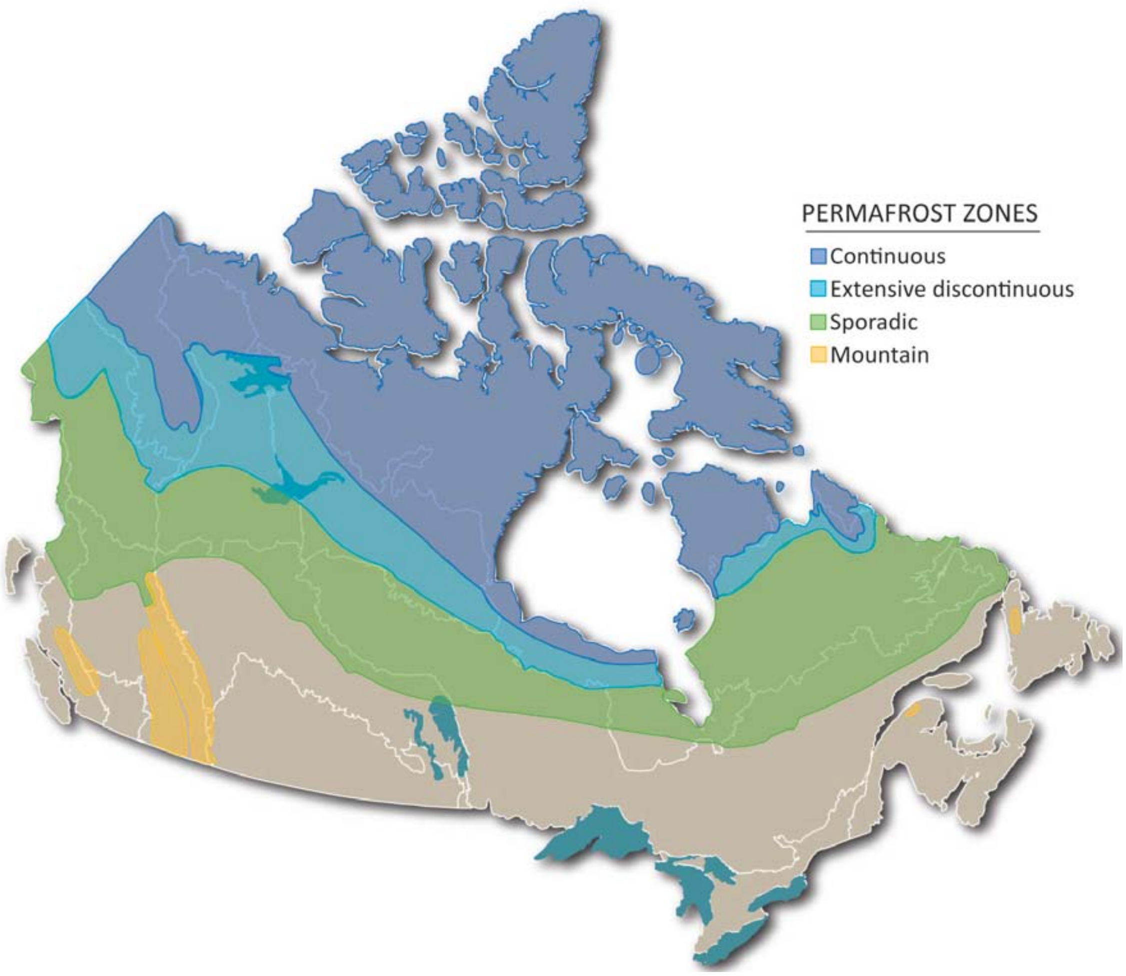

Figure 1. Permafrost map for Canada.
Source: adapted from Heginbottom et al. (1995)

The active layer is the upper part of the ground that thaws each summer and refreezes in the winter. The active layer overlies permafrost and its thickness is influenced by a number of factors, including climate and local factors such as snow cover, vegetation, presence of an organic layer, soil moisture conditions, and surficial materials (Smith et al., 2001a). Active layer thickness can vary from less than 0.5 metres in vegetated organic terrain to several metres in areas of exposed bedrock (Smith et al., 2001a). Moisture and gas fluxes are generally confined to the seasonally-thawed active layer. Permafrost and the characteristics of the active layer therefore can influence both physical and chemical processes. These processes interact and, along with climate, they shape the landscape, vegetative communities, and ecosystems from the boreal forests to the tundra (for example Mackay, 1995; Walker et al., 2004; Kokelj and Burn, 2005; Lewkowicz and Harris, 2005; Kokelj et al., 2007a).

Changes in both the areal extent and thickness of permafrost have occurred in the past in response to changes in climate occurring at scales of decades to centuries to millennia. Permafrost increases in areal extent and thickens under a cooling climate, while a warming climate results in thickening of the active layer and thinning or even disappearance of permafrost. Changes in permafrost conditions over the past several thousand years are discussed by Smith and Burgess (2004) and Smith et al. (2001a). Under warmer conditions during the mid-Holocene, 6,000 to 9,000 years ago, the southern limit of permafrost was north of its present position and active layers were generally thicker where permafrost was present (for example Burn et al., 1986; Zoltai, 1995). Following the mid-Holocene Warm Period, cooler conditions about 3,700 to 5,000 years ago resulted in an increase in permafrost extent (for example Zoltai, 1993; Vardy et al., 1998).

During the Little Ice Age between 1550 AD and 1850 AD, air temperatures were about 1°C colder and permafrost occurred farther south than at present (for example Vitt et al., 1994). At the southern fringes of the discontinuous permafrost zone, some of this permafrost persists in organic terrain, in particular *Sphagnum*-dominated peatlands (Halsey et al., 1995). Permafrost has been preserved under warmer present day climate conditions by a thick layer of insulating peat. More recently over the past two to three decades, warming of permafrost has been observed across the permafrost regions. Further discussion of more recent changes in permafrost conditions is found below.

Changes in permafrost conditions are expected over the next century in response to climate warming. Warmer and thinner permafrost in the southern portion of the discontinuous permafrost zone may ultimately disappear under anticipated climate warming, while in areas of thicker and colder permafrost, warming will likely result in thickening of the active layer and a decrease in permafrost thickness (Smith and Burgess, 2004). Simulations at a circumpolar scale project increases in active layer thickness of 20 to 60% over the next century (ACIA, 2005). However, models at these scales often use generalized representations for vegetation conditions and characteristics of earth materials which are important influences on the thermal response of permafrost. Results of modeling studies in the boreal and tundra environments of the Mackenzie Valley region, an area where recent increases in air temperature have been the greatest, indicate that thaw depths will increase 15 to 40% over the next century in response to climate warming, with smaller increases occurring where a thick organic layer is present (Woo et al., 2007).

IMPLICATIONS OF CHANGES IN PERMAFROST CONDITIONS

Permafrost is an important feature of the northern Canadian landscape and has impacts on the biophysical environment. Important inter-relationships exist between permafrost conditions, hydrological processes, soil conditions, and vegetation (Jorgenson et al., 2001; Hinzman et al., 2005). Permafrost and the ice-rich soil associated with it essentially provide the physical foundation for vegetation communities and ecosystems. Changes in permafrost conditions resulting from natural processes, climate change, or human activity can therefore have implications for both aquatic and terrestrial ecosystems.

A number of recent publications (for example Woo et al., 1992; Brown et al., 2004; Smith and Burgess, 2004; Mackenzie River Basin Board, 2004; ACIA, 2005) provide reviews of the linkages between permafrost conditions, hydrology, and vegetation including the implications of warming and thawing permafrost for aquatic and terrestrial ecosystems. Large quantities of moisture in permafrost are locked up as ground ice with only a thin layer (often less than one metre thick) of the overlying ground, the active layer, thawing and refreezing on an annual basis. Where permafrost is present, moisture and gas exchanges and biological processes are largely restricted to the seasonally-thawed active layer. Frozen ground plays an important role in northern hydrology through its influence on infiltration, runoff, and groundwater storage and flow (Woo et al., 1992).

Frozen ground and active layer thickness can influence rooting zone depth and soil moisture conditions which are important for vegetation succession and growth and also indirectly affect the hydrologic cycle through the influence on evapotranspiration (Woo et al., 1992; Hinzman et al., 2005).

Changes in the surface energy balance resulting from, for example, changes to vegetation cover due to natural processes (such as fire) or human activity (such as clearing for infrastructure construction) or changes in climate (air temperature and precipitation) can result in increases in ground surface temperature, and warming and thaw of permafrost (for example Mackay, 1995; Burgess and Smith, 2003; Smith et al., 2008). Ground surface settlement may occur as ice-rich permafrost thaws, a process referred to as thermokarst development (Jorgenson et al., 2008). Since ground ice conditions vary spatially, differential settlement may occur resulting in irregular topography. The impact of thermokarst development depends on ground ice and drainage conditions. Ponding (thermokarst ponds) may occur where settlement of ice-rich terrain occurs if drainage is poor.

In subarctic and boreal regions, flooding of tree roots may occur where drainage is poor, resulting in a change in the ecosystem structure as forests are replaced by wet sedge meadows, bogs, and thermokarst ponds and lakes (Jorgenson et al., 2001; Hinzman et al., 2005; Jorgenson and Osterkamp, 2005). The change in subsurface conditions and shift in ecosystem will be accompanied by changes in biological productivity, biomass, gas exchange, nutrient cycling, vegetation patterns and biodiversity (Racine et al., 1998; Lloyd et al., 2003; Lantz et al., 2009). In peatland areas, frozen peat plateaus that are normally forested may be replaced by ponds or sedge wetlands as ice-rich peat and underlying mineral soil thaws and collapses (Burgess and Tarnocai, 1997; Smith et al., 2008). Forested peatlands may therefore become fens (Aylsworth and Kettles, 2000; Christensen et al., 2004; Hinzman et al., 2005). The overall result of thermokarst development may be a new ecosystem that favours aquatic birds and other species instead of a forested ecosystem that supported land-based birds and mammals (Hinzman et al., 2005). Thermokarst processes, including expansion of lakes due to thaw slumping (Kokelj et al., 2009a), have also been found to alter the chemistry of tundra lakes which may have implications for aquatic ecosystems (Kokelj et al., 2009b).

Frozen peatlands store significant amounts of carbon. Climate warming in permafrost regions can therefore affect the carbon cycle through changes in greenhouse gas sources and sinks associated with thawing or burning of permafrost-affected peatlands (for example Robinson and Moore, 2000).

As thaw deepens over time, infiltration of water into the ground is less limited and may increase. Depending on precipitation and soil conditions, and therefore drainage characteristics, the upper layers of the soil may become drier which may impact ecosystem dynamics (Yoshikawa and Hinzman, 2003). These drier conditions may make vegetation more susceptible to forest fires (Hinzman et al., 2004; Hinzman et al., 2005).

Deepening of the active layer and breaching of the permafrost can facilitate drainage to the subsurface leading to drainage of wetlands, ponds, and lakes (Smith et al., 2005a). A number of studies have reported a drying trend in thermokarst lakes and other water bodies in various regions, such as the Old Crow Flats area of the Yukon (Labrecque et al., 2001), Alaska (Yoshikawa and Hinzman, 2003), and Siberia (Smith et al., 2005a). Where ground ice contents are high, thawing and erosion of drainage channels may result in catastrophic drainage of lakes, such as has occurred in northwest Canada (Marsh and Neumann, 2001; Marsh, 2008; Marsh et al., 2009).

Changes in permafrost causing transitions to drier conditions, such as shrub and forest tundra, can result in the loss of aquatic ecosystems. Plant communities that are unable to successfully colonize cold, poorly drained soils underlain by permafrost could expand under warmer drier conditions. Drier conditions associated with better drainage along thermokarst pond banks, for example, could support trees and large shrubs (Lloyd et al., 2003; Hinzman et al., 2004; Hinzman et al., 2005). It should also be noted that growth of shrubs and trees may, in turn, affect the ground thermal regime and permafrost conditions by catching snow which leads to warmer subsurface conditions in the winter and further promoting permafrost degradation (Smith, 1975).

In the polar desert of the high Arctic, the maintenance of a high water table is critical for the existence of patchy wetlands which provide hydrological and ecological conditions important to plants, insects, birds, and rodents (Woo and Young, 1998). A shallow active layer restricts drainage and maintains the high water table. Increases in active layer thickness resulting from warming of the ground will improve drainage and lower the water table. In addition, thawing of ice-rich permafrost beneath the wetland followed by slumping and erosion can lead to its demise and thermokarst processes may dissect the landscape leading to wetland drainage (Woo et al., 2006; Woo and Young, 2006). Loss of these wetlands can cause alterations in plant species and potential loss of wildlife habitat (Woo et al., 2006) especially for muskoxen which use the wetlands in summer.

Streamflow normally exhibits a quick response to snowmelt and rainfall events where permafrost is present as the active layer is easily saturated and most water travels to the stream as overland flow (Woo, 1976). Drainage basins in the permafrost region will therefore have a high runoff-to-rainfall ratio and once the precipitation or snowmelt event is over streamflow quickly declines as permafrost restricts groundwater flow (i.e. baseflow) to the stream (Kane et al., 1998; Lilly et al., 1998). As permafrost degrades and active layers thicken, subsurface flow will become more important leading to a more uniform distribution of streamflow throughout the year (Woo et al., 1992; Michel and Vaneverdingen, 1994; Hinzman et al., 2005). In many streams in the permafrost region there is often no or very little winter flow, but with permafrost degradation (particularly in the discontinuous permafrost zone), which may lead to talik (unfrozen zones) formation, winter base flow will increase which will sustain winter streamflow (Hinzman and Kane, 1992; Yoshikawa and Hinzman, 2003; Janowicz, 2008). Summer peak streamflows are also expected to decrease as permafrost degrades due to increased infiltration (and reduction in runoff) and subsurface flow (Yoshikawa and Hinzman, 2003; Hinzman et al., 2005).

These alterations in streamflow and water levels may lead to changes in aquatic ecosystems and fish habitat. In addition, the increased contribution of subsurface and groundwater flow to surface water bodies can lead to changes in water chemistry as dissolved load content increases, which may also affect fish and other aquatic life (Hinzman and Kane, 1992; Michel and Vaneverdingen, 1994; Hinzman et al., 2005; Frey and McClelland, 2009). Slope failures and erosion along rivers and streams associated with thaw of ice-rich permafrost and resulting loss of strength can result in increased siltation as well as damming of rivers and associated changes in the river course and possible upstream flooding (Aylsworth et al., 2000; Lamoureux and Lafreniere, 2009), all of which can effect aquatic habitats.

Loss of bearing strength, settlement of soils, and increased soil permeability that can accompany thawing of ice-rich permafrost also have important implications for northern infrastructure (for example Smith et al., 2001a; Couture et al., 2003). Of particular concern is the loss of integrity of containment structures, including, sumps and tailings ponds and piles and other waste storage sites, which often depend on the presence of permafrost to isolate contaminants from the surrounding environment. The inability to maintain frozen conditions can lead to increased soil permeability, loss of integrity of containment dams, and mobilization of contaminants which may have implications for both terrestrial and aquatic ecosystems (for example Dyke, 2001; Hayley and Horne, 2008; Furgal et al., 2008).

TRENDS IN PERMAFROST CONDITIONS IN EACH ECOZONE+

Recent results from permafrost thermal monitoring sites indicate that warming of permafrost is occurring across the permafrost region (for example Smith et al., 2005b), although the magnitude of this warming varies regionally. Since the 1980s, warming of shallow permafrost of 0.3 to 0.6°C per decade has occurred in the central and northern Mackenzie region in response to a general increase in air temperature. Warming of shallow permafrost has been observed in the eastern and high Arctic but this mainly occurred in the late 1990s. Further evidence of permafrost warming and thawing in recent decades, in particular the southern portions of permafrost zone, is provided by investigations of loss of frozen peatlands. A summary of observed recent changes in permafrost conditions for each ecozone+ is provided below.

Taiga Plains Ecozone+

An extensive permafrost monitoring network in the Mackenzie Valley region of western Canada provides records of permafrost temperature in the upper 20 to 30 m. Some of these records are over 20 years long. In the central Mackenzie Valley (near Norman Wells), where permafrost is up to 50 m thick and at temperatures of about -1°C, warming of 0.3°C per decade since the mid-1980s at a depth of 10 m has been observed, as shown in Figure 2 (Smith et al., 2005b; Romanovsky et al., 2007). Similar rates of permafrost temperature increases of 0.1 to 0.2°C per decade at a depth of 15 m have occurred since the 1960s in colder permafrost (-2 to -3°C) at spruce forested sites in the northern portion of the ecozone+ in the Mackenzie Delta (Kanigan et al., 2008). Kokelj et al. (2007b) found that ice wedges were inactive in spruce forests of the eastern Mackenzie Delta, suggesting that winter conditions have become warmer.

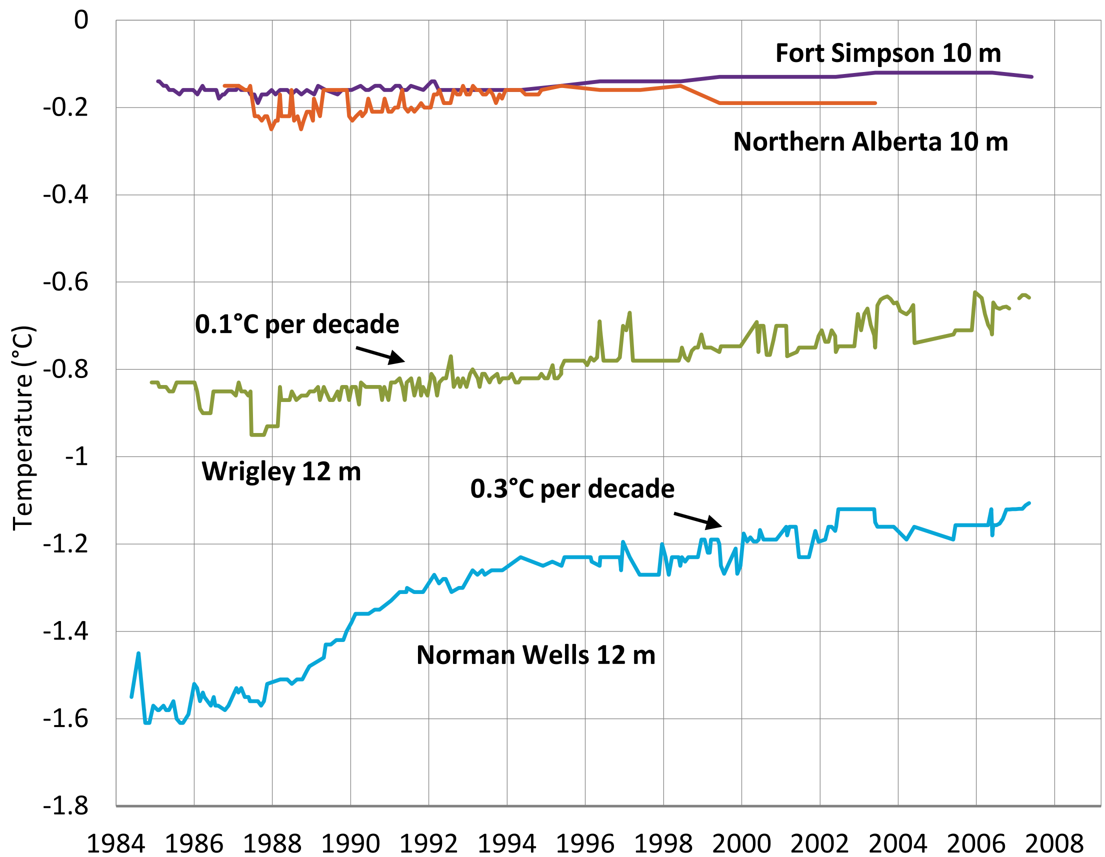

Figure 2. Ground temperatures between 1984 and 2007 at depths near 10 metres in the Mackenzie valley south of Norman Wells.
Note that the frequency of measurements was reduced in the mid-1990s at the two most southern sites.
Source: adapted and updated from Smith et al. (2005b)

In the southern Mackenzie Valley (near Fort Simpson) and northern Alberta where permafrost becomes patchy and warmer (temperatures close to 0°C), increases in permafrost temperatures have been much less (Figure 2). This absence of a trend or reduced increase in permafrost temperature in warm permafrost is probably due to the large amount of latent heat required for phase change in the ice-rich unconsolidated sediments (Smith et al., 2005b). In the southern portion of the ecozone+, permafrost is largely confined to organic terrain. Much of this permafrost likely formed during the Little Ice Age and has been preserved under warmer climatic conditions by a thick layer of insulating peat (for example Halsey et al., 1995). Since permafrost in these peatlands is generally ice-rich, ground temperatures at depth become isothermal as temperatures approach 0°C (Smith et al., 2008). Increases in thaw depth have been observed (Burgess and Smith, 2003), and some sites with thin permafrost (<5 m thick) have completely degraded over the last one to two decades (Figure 3) (Burgess and Smith, 2003).

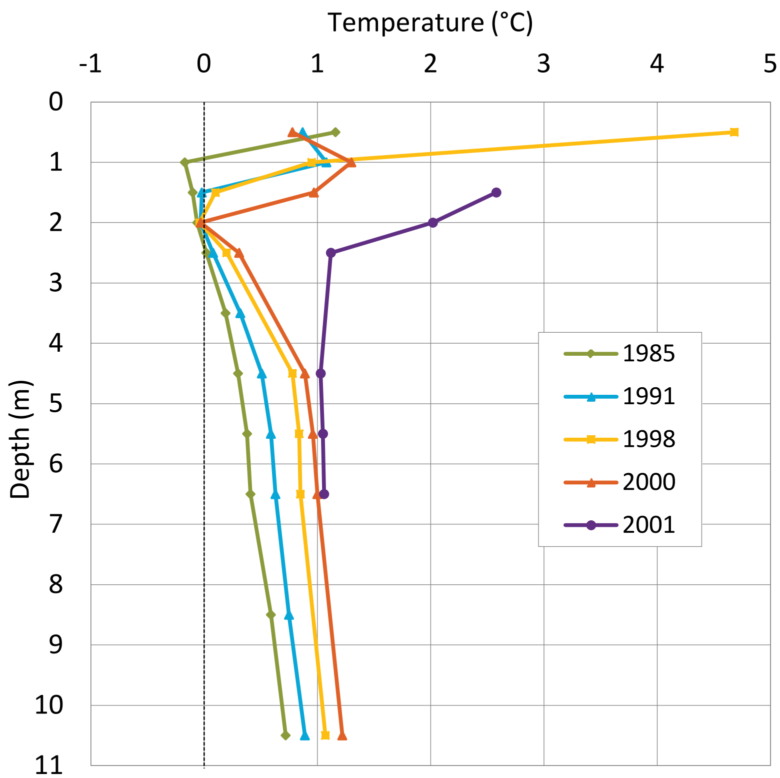

Figure 3. September ground temperature profiles between 1985 and 2001 for a site in a degrading peatland near Fort Simpson Northwest Territories.
Source: adapted from Smith et al. (2008)

Other evidence of changes in permafrost conditions in the southern Taiga Plains comes from analysis of air photos to determine the change in the area of frozen peatlands over time. Beilman and Robinson (2003) examined four sites in the southern Mackenzie Valley and found that over the latter half of the 20th century, the area of frozen peatlands decreased by 10 to 50%, with an average of 22% of the peat plateaus degrading over this period.

While these changes in permafrost distribution and thermal state within the Taiga Plains are consistent with changes in air temperature over the last few decades, changes in snow cover are also important in determining the response of permafrost to a warming climate. Snow cover acts as an insulator and reduces heat loss from the ground during winter resulting in warmer winter ground temperatures compared to areas of minimal snow cover (for example Goodrich, 1982; Burgess and Smith, 2000; Burn et al., 2009). Also, frozen peatlands progress through a natural evolution from an early stage of permafrost development to a mature stable stage and an overmature stage during which thermal degradation results in thawing of permafrost and collapse of peatland surfaces (Burgess and Tarnocai, 1997). Wildfires within the region may also result in changes in permafrost conditions (Mackay, 1995). Where burning is severe, damage to the surface organic layer may occur in addition to removal of vegetation. This reduction in surface insulation together with an increase in surface albedo can result in warming and thawing of the ground such as that observed in organic terrain of northern Alberta following fires in 2004 (Smith et al., 2008).

Taiga Shield Ecozone+

A quantification of changes in the distribution of frozen peatlands of northern Quebec on the east coast of Hudson Bay is presented by Payette et al. (2004). Air photos were utilized to characterize the changing patterns of permafrost and thermokarst ponds between 1957 and 2003. Their results show that permafrost has degraded since 1957 with the rate of loss of frozen peatland area being greater after 1993 (5.3% per year) as shown in Table 1. Surface subsidence of 1 to 1.5 m has occurred in response to melting of ground ice. Payette et al. (2004) concluded that the main driver for the accelerated rate in permafrost thawing was increases in snow precipitation and air temperature. An increase in thermokarst ponds is also found over this period (Beaulieu and Allard, 2003; Vallee and Payette, 2007). Fortier and Aubé-Maurice (2008) report, based on analysis of air photos and satellite imagery, that this loss of permafrost is continuing in this region with a decrease in permafrost extent between 1957 and 2005 of 40% near Umiujaq and an increase in thermokarst of 175%. Additional evidence of changing permafrost conditions in northern Quebec is provided by observations of shallow permafrost temperatures that indicate warming since 1993 (Allard et al., 2007).

Table 1. Permafrost decay rates for frozen peatlands in northern Quebec.

Period	Rate of permafrost loss
1957-1983	2.5% per yr
1983-1993	2.8% per yr
1993-2003	5.3% per yr

Source: Payette et al. (2004)

Boreal Plains Ecozone+

In the Boreal Plains, permafrost is patchy and confined to peatlands. Permafrost within this zone has been highly dynamic over the last millennium (Vitt et al., 2000). Permafrost likely formed during the colder climate of the Little Ice Age and has persisted due to the insulation provided by the peat. Through analysis of air photos, Beilman et al. (2001) and Beilman and Robinson (2003) have concluded that in some locations permafrost has completely thawed over the last century especially at the southern limit of the permafrost zone. Beilman and Robinson (2003) found that 32 to 70% of the frost mound area at field sites in Alberta has degraded over the last 100 to 150 years.

Boreal Shield Ecozone+

Similar to the permafrost distribution in the Boreal Plains, permafrost in this zone is also largely confined to organic terrain. Air photo analysis and measurements of rates of peatland collapse provide evidence that thawing has occurred over the last 50 to 100 years (Beilman et al., 2001; Beilman and Robinson, 2003; Camill, 2005) in northern Saskatchewan and Manitoba. Beilman and Robinson (2003) found that 53 to 64% of the frost mound area at field sites in Saskatchewan and Manitoba degraded over the last 100 to 150 years. This permafrost degradation has been attributed to changes in climate, although frozen peatlands go through a natural cycle of permafrost formation and thawing (see Taiga Plains section).

Boreal Cordillera Ecozone+

Limited information is available to characterize trends in permafrost in the southern Yukon and northern British Columbia. Some information however is available for sites along the Alaska Highway corridor. In the Takhini River Valley, Yukon, records of shallow permafrost temperatures collected between 1983 and 1996 showed no clear trend (Burn, 1998). In the central Yukon at Mayo, measurements of thaw depths collected in the 1990s at a forested site have showed no increase in thaw depth (Haeberli and Burn, 2002).

Preliminary results of field investigations in 2007 along the Alaska Highway corridor between Whitehorse, Yukon and Fort St. John, British Columbia of depths to the top of permafrost (James et al., 2008), indicate greater thaw depths than were measured in 1964 by Brown (1967). The results also indicate that some degradation of permafrost has occurred over four decades at more than half of the observation points.

Arctic Ecozone+

Information on recent trends in permafrost temperatures in the Arctic Ecozone+ comes from a number of monitoring sites from the western Arctic to the eastern Arctic and the high Arctic. In general, changes in shallow permafrost temperatures over the last decade are greater in the Arctic compared to those areas below the treeline (Taiga and Boreal) due to the lack of a buffer layer provided by vegetation and thick snow covers. The presence of colder permafrost also means that phase change and the presence of unfrozen water do not obscure the climate signal. There is therefore a more direct link between changes in air temperature and changes in permafrost temperature.

In the western Arctic, permafrost temperature data collected since the late 1990s from the northern Mackenzie Basin indicate that warming of permafrost has occurred since the early 1990s. On the Tuktoyaktuk Peninsula for example, at a depth of 28 m, permafrost temperatures increased between 1990 and 2002 at a rate between 0.02 and 0.06°C per year (Smith et al., 2005b). Analysis by Burn and Kokelj (2009) indicates that near surface ground temperatures in the tundra uplands of the Mackenzie Delta region have increased 1 to 2°C from the early 1970s to 2007. Modelling analysis conducted for a permafrost monitoring site at Herschel Island in the Yukon indicate that permafrost temperature at a depth of 20 m has increased by 1.9°C over the past 100 years (Burn and Zhang, 2009). Recent field observations at this monitoring site also indicate an increase in active layer thickness since 1985.

In the central southern portion of the Arctic Ecozone+, permafrost temperatures to 3 m depth have been collected since 1997 at Baker Lake, Nunavut. Between 1997 and 2007, a general increase in thaw depth (Figure 4) has been observed although there is some interannual variability within the short record (Smith et al., 2005b; Throop et al., 2008). The largest increase in thaw depth occurred between 1997 and 1998 and this was related to the longer thaw season in 1998 (Smith et al., 2001b).

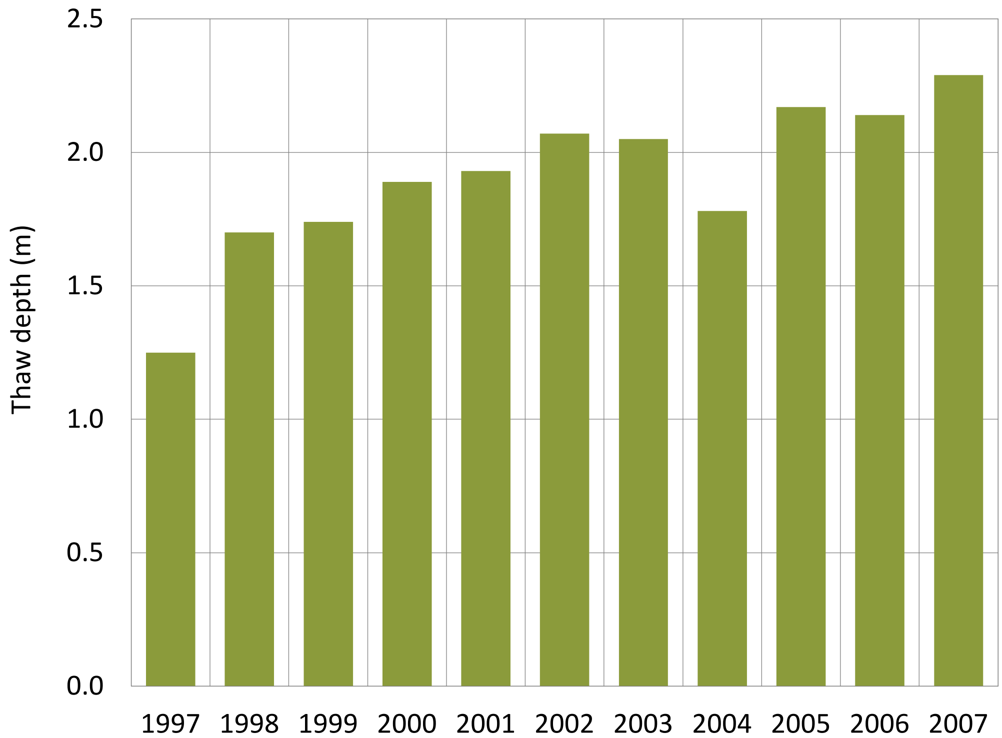

Figure 4. Maximum summer thaw depth for a site (BH4) at Baker Lake, 1997 to 2007. Source: adapted and updated from Smith et al. (2005b) and Throop et al. (2008)

Permafrost temperature data collected since 1978 at CFS Alert, Nunavut can be used to characterize trends in permafrost in the high Arctic. Although a general increase in air temperatures has been observed since the 1980s, distinct warming in shallow permafrost temperatures has only been observed since the mid-1990s. Between 1994 and 2001, an increase in permafrost temperatures of about 0.15°C per year occurred at a depth of 15 m (Smith et al., 2005b). Although some cooling of permafrost was observed between 2000 and 2002, recent data collected from the site indicates that warming of permafrost is continuing at an overall rate of approximately 0.1°C per year since 1994 (Figure 5). Recent increases in shallow ground temperatures have also been observed in other Arctic regions such as Scandinavia and Svalbard (Isaksen et al., 2007a; Isaksen et al., 2007b; Harris and Isaksen, 2008). Although snow cover is generally thin at these high Arctic sites, its variability can be an important factor affecting the response of permafrost temperatures to changes in air temperature (Smith et al., 2003). Changes in snow cover may counteract changes in air temperature occurring over the same period such that permafrost temperatures may increase in the high Arctic during periods of higher snow cover but lower air temperature (Taylor et al., 2006).

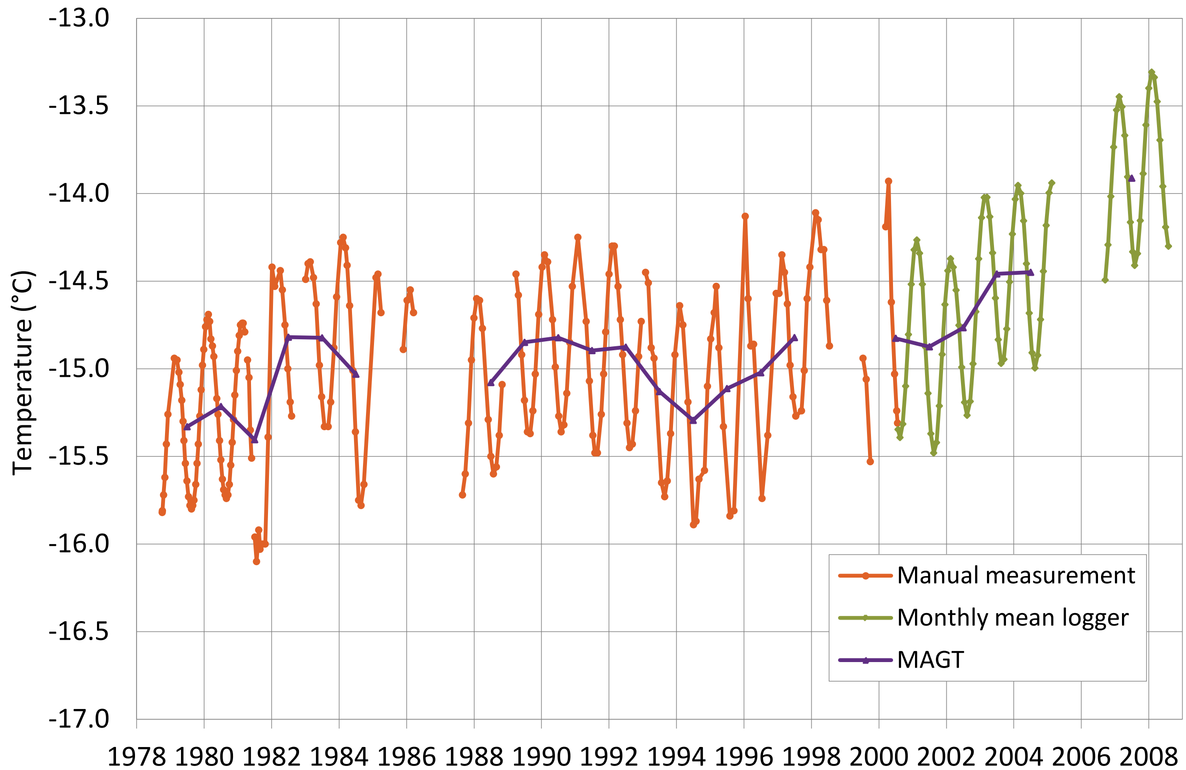

Figure 5. Observed and mean annual ground temperatures (MAGT) at a depth of 15 metres at Alert (BH5), 1978 to summer 2008.
Note that prior to July 2000, measurements were made manually at approximately monthly intervals. After July 2000, monthly mean temperatures were determined from data logger records.
Source: adapted and updated from Smith et al. (2005b)

In the eastern Arctic, cooling of shallow permafrost was observed until the early 1990s in response to the general decrease in air temperature that occurred until 1992. An increase in air temperatures began in 1993. Shallow (5 m) permafrost temperatures at Iqaluit also began to warm in 1993 with warming continuing through the 1990s (Figure 6). Temperatures at a depth of 5 m increased at a rate of 0.4°C per year between 1993 and 2000. A similar trend has been observed in northern Quebec, where cooling of about 0.1°C per year was observed between the mid-1980s and mid-1990s at a depth of 10 m (Allard et al., 1995). An increase in air temperatures commencing in 1993 in northern Quebec has been associated with warming of permafrost since 1993 to depths of 20 m (Allard et al., 2002; Ouranos, 2004; Chouinard et al., 2007) and an increase in active layer thickness (Brown et al., 2000).

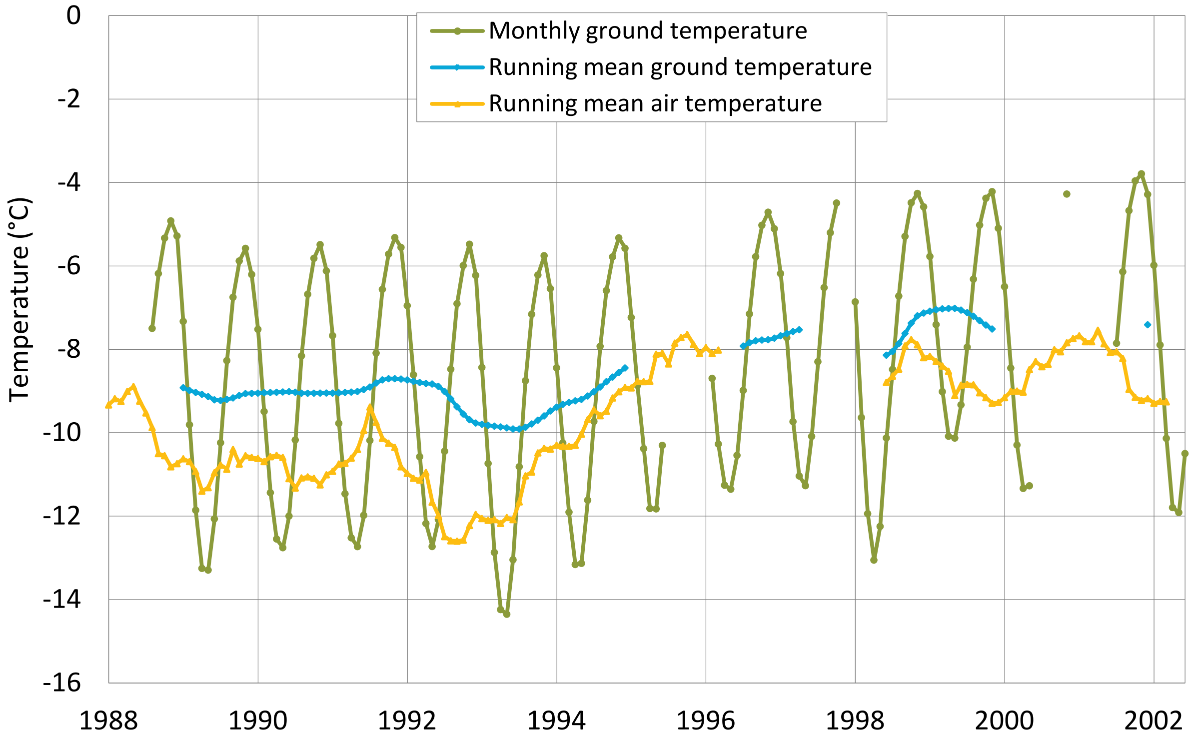

Figure 6. Monthly ground temperatures at a depth of 5 metres at Environment Canada's borehole at Iqaluit, 1988 to 2002.
The 12-month running mean for both ground and air temperature is also shown.
Source: adapted from Smith et al. (2005b)

Taiga Cordillera Ecozone+

Limited information is available on changes in permafrost conditions in this ecozone+. Analysis of sequential air photos beginning in the early 1940s and field surveys by Kershaw (2003) have facilitated an examination of permafrost landform degradation. A reduction in the area covered by frozen peat plateaus and palsas of greater than 1% per year has been determined for the Macmillan Pass area of the Northwest Territories. This permafrost degradation has been accompanied by the formation of thermokarst ponds. Temperatures measured near the top of the permafrost between 1991 and 2000 have also shown an increase of about 0.1°C per year (Kershaw, 2003).

References

ACIA. 2005. Arctic climate impact assessment. Cambridge University Press. New York, NY. 1042 p.

Allard, M., Fortier, R., Duguay, C. and Barrette, N. 2002. A trend of fast climate warming in northern Quebec since 1993. Impacts on permafrost and man-made infrastructures. *In* Submitted for Eos Transactions, American Geophysical Union, Fall Meeting 2002. Abstract #B11E-03. American Geophysical Union. San Francisco. Vol. 83(47).

Allard, M., Fortier, R., Sarrazin, D., Calmels, F., Fortier, D., Chaumont, D., Savard, J.P. and Tarussov, A. 2007. L'impact du réchauffement climatique sur les aéroports du Nunavik : caractéristiques du pergélisol et caractérisation des processus de dégradation des pistes. Rapport remis à Transports Québec, Ouranos et Ressources naturelles Canada. Université Laval, Centre d'études nordiques. QC. xii + 184 p.

Allard, M., Wang, B.L. and Pilon, J.A. 1995. Recent cooling along the southern shore of Hudson Strait, Quebec, Canada, documented from permafrost temperature-measurements. Arctic and Alpine Research 27:157-166.

Aylsworth, J.M., Duk-Rodkin, A., Robertson, T. and Travnor, J.A. 2000. Landslides of the Mackenzie Valley and adjacent mountainous and coastal regions. *In* The physical environment of the Mackenzie Valley, Northwest Territories: a baseline for the assessment of environmental change. Edited by Dyke, L.D. and Brooks, G.R. Geological Survey of Canada, Bulletin 547. pp. 167-176.

Aylsworth, J.M. and Kettles, I.M. 2000. Distribution of peatlands. *In* The physical environment of the Mackenzie Valley, Northwest Territories: a baseline for the assessment of environmental change. Edited by Dyke, L.D. and Brooks, G.R. Geological Survey of Canada, Bulletin 547. pp. 49-55.

Beaulieu, N. and Allard, M. 2003. The impact of climate change on an emerging coastline affected by discontinuous permafrost: Manitounuk Strait, northern Quebec. Canadian Journal of Earth Sciences 40:1393-1404.

Beilman, D.W. and Robinson, S.D. 2003. Peatland permafrost thaw and landform type along a climate gradient. *In* Proceedings of the 8th International Conference on Permafrost. Zurich, Switzerland, 21-25 July, 2003. Edited by Phillips, M., Springman, S.M. and Arenson, L.U. Swets & Zeitlinger. Lisse, Netherlands. Vol. 1, pp. 61-65.

Beilman, D.W., Vitt, D.H. and Halsey, L.A. 2001. Localized permafrost peatlands in western Canada: definition, distributions, and degradation. Arctic, Antarctic, and Alpine Research 33:70-77.

Brown, J., Hinkel, K.M. and Nelson, F.E. 2000. The Circumpolar Active Layer Monitoring (CALM) program: research designs and initial results. Polar Geography 24:166-258.

Brown, R.D., Demuth, M.N., Goodison, B.E., Marsh, P., Prowse, T.D., Smith, S.L. and Woo, M. 2004. Climate variability and change -- cryosphere. *In* Threats to water availability in Canada. Environment Canada, National Water Research Institute. NWRI Scientific Assessment Report Series No. 3 and ACSD Science Assessment Series No. 1. Burlington, ON. Chapter 14. pp. 107-116.

Brown, R.J.E. 1967. Permafrost investigations in British Columbia and Yukon Territory. Division of Building Research Technical Paper No. 253. National Research Council of Canada.

Burgess, M.M. and Smith, S.L. 2000. Shallow ground temperatures. *In* The physical environment of the Mackenzie Valley, Northwest Territories: a baseline for the assessment of environmental change. Edited by Dyke, L.D. and Brooks, G.R. Geological Survey of Canada, Bulletin 547. pp. 89-103.

Burgess, M.M. and Smith, S.L. 2003. 17 years of thaw penetration and surface settlement observations in permafrost terrain along the Norman Wells pipeline, Northwest Territories, Canada. *In* Proceedings of the 8th International Conference on Permafrost. Zurich, Switzerland, 21-25 July, 2003. Edited by Phillips, M., Springman, S.M. and Arenson, L.U. Swets & Zeitlinger. Lisse, Netherlands. pp. 107-112.

Burgess, M.M. and Tarnocai, C. 1997. Peatlands in the discontinuous permafrost zone along the Norman Wells pipeline, Canada. *In* Proceedings of the International Symposium on Physics, Chemistry, and Ecology of Seasonally Frozen Soils, Special Report 97-10. Fairbanks, AK, 10-12 June, 1997. Edited by Iskandar, I.K., Wright, E.A., Radke, J.K., Sharratt, B.S., Groenevelt, P.H. and Hinzman, L.D. U.S. Army Cold Regions Research and Engineering Laboratory. Hanover, NH. pp. 417-424.

Burn, C.R. 1998. The response (1958-1997) of permafrost and near-surface ground temperatures to forest fire, Takhini River Valley, southern Yukon Territory. Canadian Journal of Earth Sciences 35:184-199.

Burn, C.R. and Kokelj, S.V. 2009. The environment and permafrost of the Mackenzie Delta area. Permafrost and Periglacial Processes 20:83-105.

Burn, C.R., Mackay, J.R. and Kokelj, S.V. 2009. The thermal regime of permafrost and its susceptibility to degradation in upland terrain near Inuvik, N.W.T. Permafrost and Periglacial Processes 20:221-227.

Burn, C.R., Michel, F.A. and Smith, M.W. 1986. Stratigraphic, isotopic, and mineralogical evidence for an early holocene thaw unconformity at Mayo, Yukon Territory. Canadian Journal of Earth Sciences 23:794-803.

Burn, C.R. and Zhang, Y. 2009. Permafrost and climate change at Herschel Island (Qikiqtaruq), Yukon Territory, Canada. Journal of Geophysical Research-Earth Surface 114.

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

Chouinard, C., Fortier, R. and Mareschal, J.C. 2007. Recent climate variations in the subarctic inferred from three borehole temperature profiles in northern Quebec, Canada. Earth and Planetary Science Letters 263:355-369.

Christensen, T.R., Johansson, T.R., Akerman, H.J., Mastepanov, M., Malmer, N., Friborg, T., Crill, P. and Svensson, B.H. 2004. Thawing sub-Arctic permafrost: effects on vegetation and methane emissions. Geophysical Research Letters 31.

Couture, R., Smith, S., Robinson, S.D., Burgess, M.M. and Solomon, S. 2003. On the hazards to infrastructure in the Canadian north associated with thawing of permafrost. Proceedings of Geohazards 2003, 3rd Canadian Conference on Geotechnique and Natural Hazards. Edmonton, AB, 8-10 June, 2003. The Canadian Geotechnical Society. pp. 97-104.

Dyke, L.D. 2001. Contaminant migration through the permafrost active layer, Mackenzie Delta area. Polar Record 37:215-228.

Fortier, R. and Aubé-Maurice, B. 2008. Fast permafrost degradation near Umiujaq in Nunavik (Canada) since 1957 assessed from time-lapse aerial and satellite photographs. *In* Proceedings of the 9th International Conference on Permafrost. Fairbanks, AK, 29 June to 3 July, 2008. Edited by Kane, D.L. and Hinkel, K.M. Institute of Northern Engineering, University of Alaska Fairbanks. Vol. 1, pp. 457-462.

Frey, K.E. and McClelland, J.W. 2009. Impacts of permafrost degradation on arctic river biogeochemistry. Hydrological Processes 23:169-182.

Furgal, R., Prowse, T.D., Bonsal, B., Chouinard, R., Dickson, C., Edwards, T., Jackson, F., Melling, H., Milburn, D., Nickels, S., Nuttall, M., Ogden, A., Peters, D., Reist, J.D., Smith, S., Westlake, M. and Wrona, F. 2008. Northern Canada. *In* Impacts to adaptation: Canada in a changing climate 2007. Edited by Lemmen, D.S., Warren, F.J., Lacroix, J. and Bush, E. Government of Canada. Ottawa, ON. Chapter 3. pp. 57-118.

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

Haeberli, W. and Burn, C.R. 2002. Natural hazards in forests: glacier and permafrost effects as related to climate change. *In* Environmental change and geomorphic hazards in forests. Edited by Sidle, R.C. CABI Publishing. Wallingford, NY. pp. 167-202.

Halsey, L.A., Vitt, D.H. and Zoltai, S.C. 1995. Disequilibrium response of permafrost in boreal continental western Canada to climate change. Climatic Change 30:57-73.

Harris, C. and Isaksen, K. 2008. Recent warming of European permafrost: evidence from borehole monitoring. *In* Proceedings of the 9th International Conference on Permafrost. Fairbanks, AK, 29 June to 3 July, 2008. Edited by Kane, D.L. and Hinkel, K.M. Institute of Northern Engineering, University of Alaska Fairbanks. Vol. 1, pp. 655-661.

Hayley, D.W. and Horne, B. 2008. Rationalizing climate change for design of structures on permafrost: a Canadian perspective. *In* Proceedings of the 9th International Conference on

Permafrost. Fairbanks, AK, 29 June to 3 July, 2008. Edited by Kane, D.L. and Hinkel, K.M. Institute for Northern Engineering, University of Alaska Fairbanks. Vol. 1, pp. 681-686.

Heginbottom, J.A., Dubreuil, M.A. and Harker, P.A.C. 1995. Permafrost, 1995. *In* The national atlas of Canada. Edition 5. National Atlas Information Service, Geomatics Canada and Geological Survey of Canada. Ottawa, ON. Map.

Hinzman, L.D., Bettez, N.D., Bolton, W.R., Chapin, F.S., Dyurgerov, M.B., Fastie, C.L., Griffith, B., Hollister, R.D., Hope, A., Huntington, H.P., Jensen, A.M., Jia, G.J., Jorgenson, T., Kane, D.L., Klein, D.R., Kofinas, G., Lynch, A.H., Lloyd, A.H., McGuire, A.D., Nelson, F.E., Oechel, W.C., Osterkamp, T.E., Racine, C.H., Romanovsky, V.E., Stone, R.S., Stow, D.A., Sturm, M., Tweedie, C.E., Vourlitis, G.L., Walker, M.D., Walker, D.A., Webber, P.J., Welker, J.M., Winker, K. and Yoshikawa, K. 2005. Evidence and implications of recent climate change in northern Alaska and other Arctic regions. Climatic Change 72:251-298.

Hinzman, L.D. and Kane, D.L. 1992. Potential response of an arctic watershed during a period of global warming. Journal of Geophysical Research-Atmospheres 97:2811-2820.

Hinzman, L.D., Toniolo, H.A., Yoshikawa, K. and Jones, J.B. 2004. Thermokarst development in a changing climate. *In* Arctic Climate Impact Assessment, AMAP Report 2004:4, Extended abstracts. The ACIA International Scientific Symposium on Climate Change in the Arctic. Reykjavik, Iceland, 9-12 November, 2004. Arctic Monitoring and Assessment Program. Oslo, Norway. 3 p.

Isaksen, K., Benestad, R.E., Harris, C. and Sollid, J.L. 2007a. Recent extreme near-surface permafrost temperatures on Svalbard in relation to future climate scenarios. Geophysical Research Letters 34.

Isaksen, K., Sollid, J.L., Holmlund, P. and Harris, C. 2007b. Recent warming of mountain permafrost in Svalbard and Scandinavia. Journal of Geophysical Research-Earth Surface 112.

James, M., Lewkowicz, A.G., Smith, S.L. and Lipovsky, P. 2008. Historic change in permafrost distribution in northern British Columbia and southern Yukon. *In* Proceedings of the 9th International Conference on Permafrost, Extended Abstracts. Fairbanks, AK, 29 June to 3 July, 2008. Edited by Kane, D.L. and Hinkel, K.M. Institute of Northern Engineering, University of Alaska Fairbanks. Vol. 1, pp. 115-116.

Janowicz, J.R. 2008. Recent changes in hydrologic response observed in permafrost regions of northwest Canada. *In* Proceedings of the 9th International Conference on Permafrost. Fairbanks, AK, 29 June to 3 July, 2008. Edited by Kane, D.L. and Hinkel, K.M. Institute of Northern Engineering, University of Alaska Fairbanks. Vol. 1, pp. 827-831.

Jorgenson, M.T. and Osterkamp, T.E. 2005. Response of boreal ecosystems to varying modes of permafrost degradation. Canadian Journal of Forest Research/Revue canadienne de recherche forestière 35:2100-2111.

Jorgenson, M.T., Racine, C.H., Walters, J.C. and Osterkamp, T.E. 2001. Permafrost degradation and ecological changes associated with a warming climate in central Alaska. Climatic Change 48:551-579.

Jorgenson, M.T., Shur, Y. and Osterkamp, T.E. 2008. Thermokarst in Alaska. *In* Proceedings of the 9th International Conference on Permafrost. Fairbanks, AK, 29 June to 3 July, 2008. Edited by Kane, D.L. and Hinkel, K.M. Institute of Northern Engineering, University of Alaska Fairbanks. Vol. 1, pp. 869-876.

Kane, D.L., Soden, D.J., Hinzman, L.D. and Gieck, R.E. 1998. Rainfall runoff of a nested watershed in the Alaskan Arctic. *In* Proceedings of the 7th International Conference on Permafrost. Yellowknife, NT, 23-27 June, 1998. Centre d'études nordiques, Université Laval, Collection Nordicana No. 55. pp. 539-543.

Kanigan, J.C.N., Burn, C.R. and Kokelj, S.V. 2008. Permafrost response to climate warming south of treeline, Mackenzie Delta, Northwest Territories, Canada. *In* Proceedings of the 9th International Conference on Permafrost. Fairbanks, AK, 29 June to 3 July, 2008. Edited by Kane, D.L. and Hinkel, K.M. Institute of Northern Engineering, University of Alaska Fairbanks. Vol. 1, pp. 901-906.

Kershaw, G.P. 2003. Permafrost landform degradation over more than half a century, Macmillan/Caribou Pass region, NWT/Yukon, Canada. *In* Proceedings of the 8th International Conference on Permafrost. Zurich, Switzerland, 21-25 July, 2003. Edited by Phillips, M., Springman, S.M. and Arenson, L.U. Swets & Zeitlinger. Lisse, Netherlands. pp. 543-548.

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

Kokelj, S.V., Burn, C.R. and Tarnocai, C. 2007a. The structure and dynamics of earth hummocks in the subarctic forest near Inuvik, Northwest Territories, Canada. Arctic, Antarctic, and Alpine Research 39:99-109.

Kokelj, S.V., Lantz, T.C., Kanigan, J., Smith, S.L. and Coutts, R. 2009a. Origin and polycyclic behaviour of tundra thaw slumps, Mackenzie Delta region, Northwest Territories, Canada. Permafrost and Periglacial Processes 20:173-184.

Kokelj, S.V., Pisaric, M.F.J. and Burn, C.R. 2007b. Cessation of ice-wedge development during the 20th century in spruce forests of eastern Mackenzie Delta, Northwest Territories, Canada. Canadian Journal of Earth Sciences 44:1503-1515.

Kokelj, S.V., Zajdlik, B. and Thompson, M.S. 2009b. The impacts of thawing permafrost on the chemistry of lakes across the subarctic boreal-tundra transition, Mackenzie Delta region, Canada. Permafrost and Periglacial Processes 20:185-199.

Labrecque, S., Duguay, C.R. and Hawkings, J. 2001. Étude de la dynamique spatio-temporelle récente des lacs thermokarstiques de la plaine Old Crow Flats, Yukon, par télédétection. *In*

Proceedings of the 23rd Canadian Symposium on Remote Sensing/10e Congrès de l'Association québécoise de télédétection. Quebec, QC, 21-24 August, 2001. pp. 585-590.

Lamoureux, S.F. and Lafreniere, M.J. 2009. Fluvial impact of extensive active layer detachments, Cape Bounty, Melville Island, Canada. Arctic, Antarctic, and Alpine Research 41:59-68.

Lantz, T.C., Kokelj, S.V., Gergel, S.V. and Henry, G.H.R. 2009. Relative impacts of disturbance and temperature: persistent changes in microenvironment and vegetation in retrogressive thaw slumps. Global Change Biology 15:1664-1675.

Lewkowicz, A.G. and Harris, C. 2005. Morphology and geotechnique of active-layer detachment failures in discontinuous and continuous permafrost, northern Canada. Geomorphology 69:275-297.

Lilly, E.K., Kane, D.L., Hinzman, L.D. and Gieck, R.E. 1998. Annual water balance for three nested watersheds on the north slope of Alaska. *In* Proceedings of the 7th International Conference on Permafrost. Yellowknife, NT, 23-27 June, 1998. Centre d'études nordiques, Université Laval, Collection Nordicana No. 55. pp. 669-674.

Lloyd, A.H., Yoshikawa, K., Fastie, C.L., Hinzman, L. and Fraver, M. 2003. Effects of permafrost degradation on woody vegetation at arctic treeline on the Seward Peninsula, Alaska. Permafrost and Periglacial Processes 14:93-101.

Mackay, J.R. 1972. World of underground ice. Annals of the Association of American Geographers 62:1-22.

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

Mackenzie River Basin Board. 2004. Mackenzie River Basin state of the aquatic ecosystem report 2003. Mackenzie River Basin Board Secretariat. Fort Smith, NT. 213 p.

Marsh, P. 2008. Modeling discharge during the rapid drainage of thaw lakes in the western Canadian Arctic. *In* Proceedings of the 9th International Conference on Permafrost. Fairbanks, AK, 29 June to 3 July, 2008. Edited by Kane, D.L. and Hinkel, K.M. Institute for Northern Engineering, University of Alaska Fairbanks. Vol. 2, pp. 1143-1147.

Marsh, P. and Neumann, N.N. 2001. Processes controlling the rapid drainage of two ice-rich permafrost-dammed lakes in NW Canada. Hydrological Processes 15:3433-3446.

Marsh, P., Russell, M., Pohl, S., Haywood, H. and Onclin, C. 2009. Changes in thaw lake drainage in the western Canadian Arctic from 1950 to 2000. Hydrological Processes 23:145-158.

Michel, F.A. and Vaneverdingen, R.O. 1994. Changes in hydrogeologic regimes in permafrost regions due to climatic change. Permafrost and Periglacial Processes 5:191-195.

Ouranos. 2004. Adapting to climate change. Montreal, QC. 83 p.

Payette, S., Delwaide, A., Caccianiga, M. and Beauchemin, M. 2004. Accelerated thawing of subarctic peatland permafrost over the last 50 years. Geophysical Research Letters 31:L18208.

Racine, C.H., Jorgenson, M.T. and Walters, J.C. 1998. Thermokarst vegetation in lowland birch forests on the Tanana Flats, interior Alaska, U.S.A. *In* Proceedings of the 7th International Conference on Permafrost. Yellowknife, NT, 23-27 June, 1998. Edited by Lewkowicz, A.G. and Allard, M. Centre d'études nordiques, Université Laval, Collection Nordicana No. 55. pp. 927-933.

Robinson, S.D. and Moore, T.R. 2000. The influence of permafrost and fire upon carbon accumulation in high boreal peatlands, Northwest Territories, Canada. Arctic, Antarctic, and Alpine Research 32:155-166.

Romanovsky, V.E., Gruber, S., Instanes, A., Jin, H., Marchenko, S.S., Smith, S.L., Trombotto, D. and Walter, K.M. 2007. Frozen ground. *In* Global outlook for ice and snow. Edited by Eamer, J. United Nations Environment Programme. Chapter 7. pp. 181-200.

Smith, L.C., Sheng, Y., MacDonald, G.M. and Hinzman, L.D. 2005a. Disappearing arctic lakes. Science 308:1429-1429.

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

Smith, M.W. and Burgess, M.M. 2004. Sensitivity of permafrost to climate warming in Canada. Geological Survey of Canada, Bulletin 579. 24 p.

Smith, S.L., Burgess, M.M. and Heginbottom, J.A. 2001a. Permafrost in Canada, a challenge to northern development. *In* A synthesis of geological hazards in Canada. Edited by Brooks, G.R. Geological Survey of Canada, Bulletin 548. pp. 241-264.

Smith, S.L., Burgess, M.M. and Nixon, F.M. 2001b. Response of active-layer and permafrost temperatures to warming during 1998 in the Mackenzie Delta, Northwest Territories and at Canadian Forces Station Alert and Baker Lake, Nunavut. Current Research 2001-E5. Geological Survey of Canada. 12 p.

Smith, S.L., Burgess, M.M. and Riseborough, D. 2008. Ground temperature and thaw settlement in frozen peatlands along the Norman Wells pipeline corridor, NWT Canada: 22 years of monitoring. *In* Proceedings of the 9th International Conference on Permafrost. Fairbanks, AK, 29 June to 3 July, 2008. Edited by Kane, D.L. and Hinkel, K.M. Institute of Northern Engineering, University of Alaska Fairbanks. Vol. 2, pp. 1665-1670.

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

Smith, S.L., Burgess, M.M. and Taylor, A.E. 2003. High Arctic permafrost observatory at Alert, Nunavut -- analysis of a 23 year data set. *In* Proceedings of the 8th International Conference on Permafrost. Zurich, Switzerland, 21-25 July, 2003. Edited by Phillips, M., Springman, S.M. and Arenson, L.U. Swets & Zeitlinger. Lisse, Netherlands. pp. 1073-1078.

Taylor, A.E., Wang, K.L., Smith, S.L., Burgess, M.M. and Judge, A.S. 2006. Canadian Arctic permafrost observatories: detecting contemporary climate change through inversion of subsurface temperature time series. Journal of Geophysical Research-Solid Earth 111.

Throop, J.L., Smith, S.L. and Lewkowicz, A.G. 2008. Effect of a snow fence on the shallow ground thermal regime, Baker Lake, Nunavut, Canada. *In* Proceedings of the 9th International Conference on Permafrost, Extended Abstracts. Fairbanks, AK, 29 June to 3 July, 2008. Edited by Kane, D.L. and Hinkel, K.M. Institute of Northern Engineering, University of Alaska Fairbanks. Vol. 1, pp. 313-314.

Vallee, S. and Payette, S. 2007. Collapse of permafrost mounds along a subarctic river over the last 100 years (northern Quebec). Geomorphology 90:162-170.

Vardy, S.R., Warner, B.G. and Aravena, R. 1998. Holocene climate and the development of a subarctic peatland near Inuvik, Northwest Territories, Canada. Climatic Change 40:285-313.

Vitt, D.H., Halsey, L.A. and Zoltai, S.C. 1994. The bog landforms of continental western Canada in relation to climate and permafrost patterns. Arctic and Alpine Research 26:1-13.

Vitt, D.H., Halsey, L.A. and Zoltai, S.C. 2000. The changing landscape of Canada's western boreal forest: the current dynamics of permafrost. Canadian Journal of Forest Research/Revue canadienne de recherche forestière 30:283-287.

Walker, D.A., Epstein, H.E., Gould, W.A., Kelley, A.M., Kade, A.N., Knudson, J.A., Krantz, W.B., Michaelson, G., Peterson, R.A., Ping, C.L., Raynolds, M.K., Romanovsky, V.E. and Shur, Y. 2004. Frost-boil ecosystems: complex interactions between landforms, soils, vegetation and climate. Permafrost and Periglacial Processes 15:171-188.

Woo, M., Mollinga, M. and Smith, S.L. 2007. Climate warming and active layer thaw in the boreal and tundra environments of the Mackenzie Valley. Canadian Journal of Earth Sciences 44:733-743.

Woo, M.K. 1976. Hydrology of a small Canadian High Arctic basin during the snowmelt period. CATENA 3:155-168.

Woo, M.K., Lewkowicz, A.G. and Rouse, W.R. 1992. Response of the Canadian permafrost environment to climatic change. Physical Geography 13:287-317.

Woo, M.K. and Young, K.L. 1998. Characteristics of patchy wetlands in a polar desert environment, Arctic Canada. *In* Proceedings of the 7th International Conference on Permafrost. Yellowknife, NT, 23-27 June, 1998. Edited by Lewkowicz, A.G. and Allard, M. Centre d'études nordiques, Université Laval, Collection Nordicana No. 55. pp. 1141-1146.

Woo, M.K. and Young, K.L. 2006. High Arctic wetlands: their occurrence, hydrological characteristics and sustainability. Journal of Hydrology 320:432-450.

Woo, M.K., Young, K.L. and Brown, L. 2006. High Arctic patchy wetlands: hydrologic variability and their sustainability. Physical Geography 27:297-307.

Yoshikawa, K. and Hinzman, L.D. 2003. Shrinking thermokarst ponds and groundwater dynamics in discontinuous permafrost near Council, Alaska. Permafrost and Periglacial Processes 14:151-160.

Zoltai, S.C. 1993. Cyclic development of permafrost in the peatlands of northwestern Alberta, Canada. Arctic and Alpine Research 25:240-246.

Zoltai, S.C. 1995. Permafrost distribution in peatlands of west-central Canada during the holocene warm period 6000 years BP. Géographie physique et Quaternaire 49:45-54.