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Potential changes in thaw depth and thaw settlement for three locations in the Mackenzie valley

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Abstract: Locations near Tuktoyaktuk, Norman Wells, and Fort Simpson in the Mackenzie valley are analyzed to determine how quickly permafrost would degrade if the climate warms. The warming predicted by Canada Climate Centre modelling of climate under a doubled concentration of atmospheric carbon dioxide (5°C for Tuktoyaktuk, 4.2°C for both Norman Wells and Fort Simpson) was applied at different rates over a 50 year period. The effects of both and increase and decrease of snowfall were examined. After 50 years, the warming only produces an increase in active layer thickness at Tuktoyaktuk. At Norman Wells, thaw of permafrost to a depth approaching 10 m occurs for low ice content ground. At Fort Simpson, almost all permafrost disappears. Thaw subsidence associated with the modelled 50 year degradation of ice-rich permafrost ranges from 0.5 m at Norman Wells to more than 1.5 m in the Fort Simpson region.

Résumé : On a analysé des sites situés près de Tuktoyaktuk, Norman Wells et Fort Simpson dans la vallée du Mackenzie pour déterminer la rapidité à laquelle le pergélisol se dégraderait s'il y avait un réchauffement climatique. Le réchauffement prévu par le Centre canadien de climatologie, si la concentration de dioxyde de carbone atmosphérique devait doubler (5 °C pour Tuktoyaktuk; 4,2 °C pour Norman Wells et Fort Simpson), a été appliqué à différents taux sur une période de 50 ans. Étant donné que ce modèle climatique prévoit également une légère augmentation des précipitations, on a également analysé les effets d'une neige plus abondante. Après 50 ans, le réchauffement n'augmenterait l'épaisseur du mollisol qu'à Tuktoyaktuk. À Norman Wells, le dégel du pergélisol jusqu'à une profondeur pouvant atteindre 10 m aurait lieu dans les sols à faible teneur en glace. À Fort Simpson, le pergélisol disparaîtrait presque complètement. Selon le modèle de la dégénérescence d'un pergélisol riche en glace échelonnée sur 50 ans, la subsidence due au dégel varierait de 0,5 m à Norman Wells à plus de 1,5 m à Fort Simpson.

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INTRODUCTION

This paper discusses how climate warming due to doubling atmospheric carbon dioxide in 50 years may affect permafrost at specific locations in the Mackenzie valley. Three locations in the Mackenzie valley are examined: Richards Island near Tuktoyaktuk, Norman Wells, and Fort Simpson (Fig. 1). At each of these, an ice-poor and an ice-rich site are considered. The response of temperature in the ground to temperature in the air is predicted using a mathematical simulation of heat flow between the air and the ground (geothermal model). These simulations apply a prescribed change in air temperature over the 50 year period and show how ground temperatures change and permafrost thickness decreases. The ground ice content is an important factor in determining how quickly permafrost disappears. The amount of ice melted is then combined with data on soil type to calculate potential thaw settlement. Performing simulations for different initial climates (i.e. different regions), different soil conditions, and different degrees of climate change provides some indication of the potential range in permafrost response throughout the Mackenzie valley.

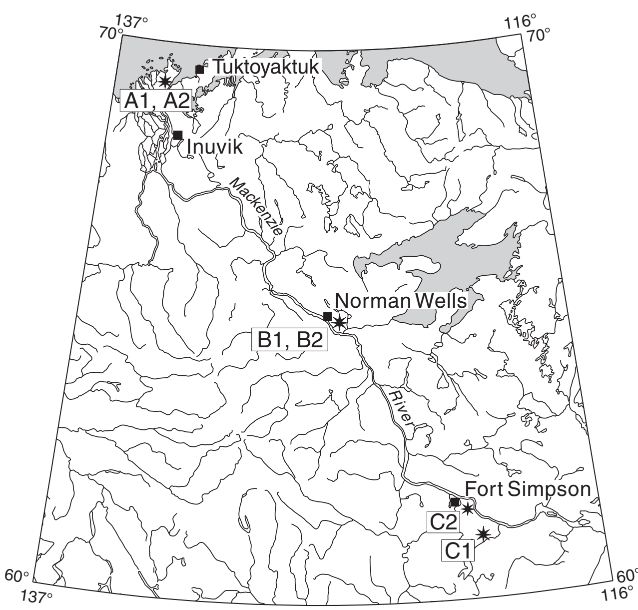

Figure 1. *Location of study sites. Permafrost boundaries are* modified from *Heginbottom et al. (1995).*

To carry out the simulation, detailed information is required for each site: borehole data (sediment type, physical and thermal properties), ground temperature measurements, surface condition, ice content, and climate data (air temperature and precipitation). There is no unique method to undertaking this modelling and the approach used here is briefly outlined. A more detailed discussion of procedures can be found in GSC Open File 3017 (Geo-Engineering (M.S.T.) Ltd., 1994).

CLIMATE DATA

The 1951–1980 climate normals for mean monthly air temperature and snow cover at the nearest Atmospheric Environment Service (AES) climate stations, i.e. Tuktoyaktuk, Norman Wells, and Fort Simpson, were adopted as the initial climate conditions corresponding to the present day carbon dioxide CO_2 concentration (i.e. 1 x CO_2 conditions). Atmospheric Environment Service's General Circulation Model (GCM) of mean monthly air temperature and mean monthly total precipitation under a doubled CO_2 concentration (i.e. 2 x CO_2 conditions) were then obtained (Atmospheric Environment Service, pers. comm., 1992) for each of these stations. Table 1 summarizes the present and predicted annual climate conditions for each site. The change from 1 x CO_2 to 2 x CO_2 conditions represents a 4°C to 5°C increase in mean annual air temperature, and increases of 9–16% in total annual precipitation.

Ground temperature in permafrost regions is greatly influenced by thickness and duration of snow cover (Goodrich, 1982). A discussion of observed trends in air temperature and snow depths at climate stations in the Mackenzie valley during the 20th century and their relationship to permafrost stability is presented in Stuart et al. (1991). Snow cover changes associated with the changing climate should therefore be incorporated in the geothermal simulation. Since the 2 x CO_2 climate prediction provided only total water-equivalent precipitation data, a means to estimate future snowfall and snow depth from the monthly precipitation data was therefore required. A method was developed based on the current relationship between temperature and snowfall. The fraction of total precipitation that falls as snow for each month, based on climate data from 1951–1980, is related to the monthly mean temperature for each Atmospheric Environment Service station (Fig. 2a shows the result for Norman Wells). This links snowfall to available parameters that are predicted by the climate change model. With Figure 2a, the amount of future snowfall can be estimated using the new mean monthly temperature provided by the climate model. To determine the

Table 1. Summary of mean annual climate conditions at start of simulation (1951–1980 climate normals) and end of climate warming (2 x CO_2 conditions).

	MEAN ANNUAL AIR TEMPERATURE (°C)			TOTAL ANNUAL PRECIPITATION (mm)		
LOCATION	30 year normals (1951–1980)	2XCO$_2$ scenario	Difference	30 year normals (1951–1980)	2XCO$_2$ scenario	Difference
Tuktoyaktuk	-10.9	-5.9	+5.0	138	157	+19
Norman Wells	-6.4	-2.2	+4.2	328	356	+28
Fort Simpson	-4.2	-0.0	+4.2	355	411	+56

actual depth of snow throughout the year, an additional step to relate snowfall to depth of snow on the ground for each month that snow accumulates or ablates is necessary. This is done in Figure 2b for accumulation and Figure 2c for ablation; these figures are also based on 1951–1980 climate data. With these correlations, snowpack history under the changed climate can be constructed.

Plots of 1951–1980 monthly climate data and the 2 x CO_2 monthly air temperatures and derived mean monthly snow depths are given for each region in Figure 3. Note that at all three locations, although there is an increase in total annual

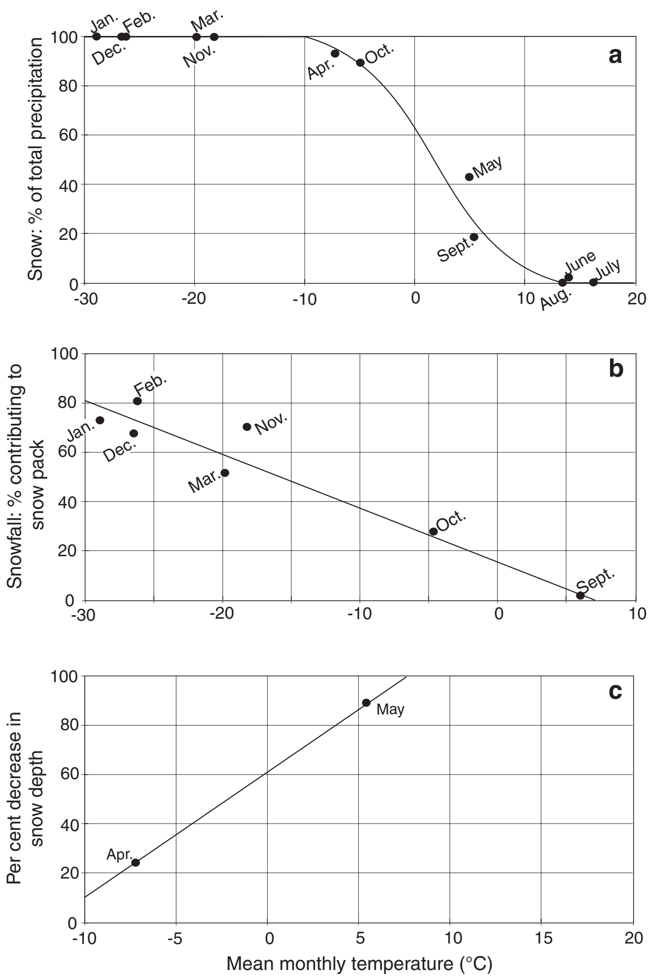

Figure 2. Correlations established for Norman Wells climate data to allow conversion of precipitation predicted by climate change models into snowfall and snow cover, based on monthly mean air temperature and precipitation data from the 1951–1980 climate data. ***a)*** *Percentage of total precipitation that falls as snow for each month as a function of mean monthly temperature.* ***b)*** *Percentage of monthly snowfall that accumulates in the snowpack, i.e. conversion factor for snowfall into depth of snow on the ground, as a function of mean monthly temperature.* ***c)*** *Ablation rate of the snowpack in spring as a function of mean monthly temperature.*

precipitation under 2 x CO_2 conditions, mean monthly snow depths have decreased under the warming scenario. This is due in part to warmer air temperatures causing more precipitation to fall as rain rather than snow. For the purpose of modelling the response of permafrost, these changes in mean monthly air temperature and snow cover are allowed to occur over the 50 year time interval during which the CO_2 doubling is assumed to take place. Figure 4 shows possible paths to reach the 2 x CO_2 conditions that were examined in the simulations: 1) linear case with a linear increase in temperature and linear decrease in snow cover, and 2) exponential increase in temperature and exponential decrease in snow depth. Since there is considerable uncertainty in climate model precipitation predictions and how these are translated into snow cover estimates, an additional scenario was included; 3) a linear increase in temperature with a 10% linear increase in snow cover (subsequently referred to as linear+10%). Scenario 3 thus allows an examination of the sensitivity of permafrost to an increase in snow cover.

SITE SELECTION

The three study areas were selected to provide a transect from cold continuous permafrost along the Beaufort Sea coast to warm discontinuous permafrost near Fort Simpson. Area A is located along a borehole transect established by the GSC to study massive ground ice in the Mackenzie Delta. At site A1 a massive ice layer underlies a thin glaciofluvial layer of silt and sand. Site A2 represents a relatively ice-poor glaciofluvial deposit. Average ground surface temperatures are -6 to -7°C at these sites and permafrost is several hundred metres deep in this region (*see* Taylor et al., 2000).

Sites in area B, near Norman Wells, were selected from numerous geotechnical boreholes drilled for design purposes by Interprovincial Pipeline Inc. (IPL), and by both IPL and the federal government for permafrost research along the Norman Wells pipeline corridor. Site B1 is located near Norman Wells on an ice-rich lacustrine plain (IPL borehole 80-1). Site B2 is located 19 km south of Norman Wells along the pipeline, near Canyon Creek, on a low-ice content till plain (pipeline study site 84-2A; Pilon et al., 1989). Permafrost is 25–50 m thick at these sites and mean annual ground surface temperatures are -1°C to -2°C.

Area C is located in the discontinuous permafrost region of Fort Simpson. The two sites here are approximately 50 km apart. Both are located along the Norman Wells pipeline and have very detailed geotechnical and geothermal data (Patterson and Riseborough, 1988; Patterson et al., 1988; Pilon et al., 1989). For a discussion of other aspects of Norman Wells Pipeline permafrost and terrain data, *see* Burgess and Lawrence (2000). Site C1 (pipeline study site 85-12B) is situated in an ice-rich peat plateau; permafrost is around 5.6 m thick. Site C2 is ice-poor in the near surface, but has an ice-rich clay at depth; permafrost is approximately 12 m thick. At both sites the mean annual ground surface temperature is between -1°C and 0°C.

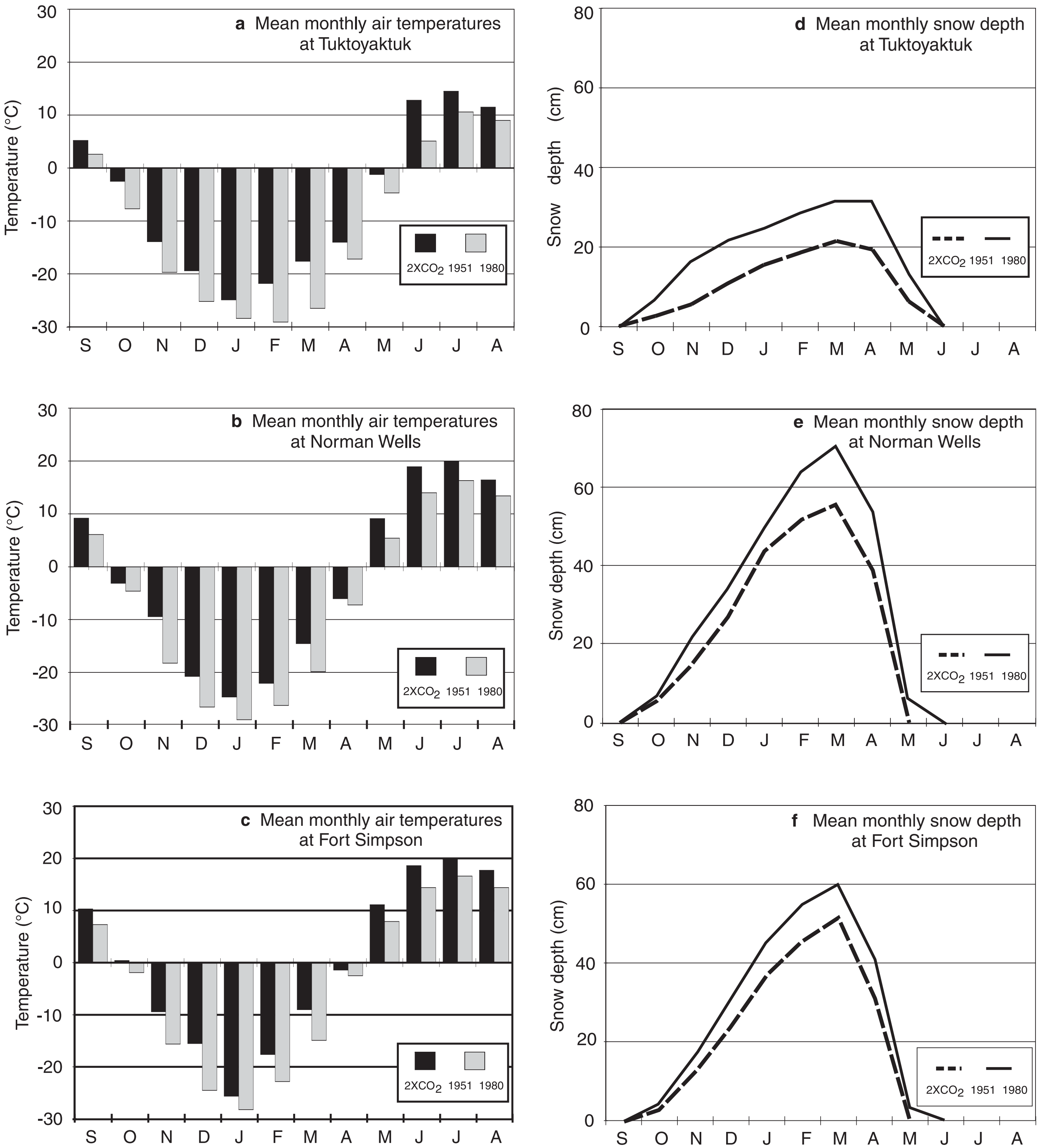

Figure 3. a), b), c) *Mean monthly air temperatures and* ***d), e), f)*** *snow depths from 1951–1980 climate normals and predicted 2 x CO_2 conditions at the Tuktoyaktuk, Norman Wells, and Fort Simpson climate stations, respectively.*

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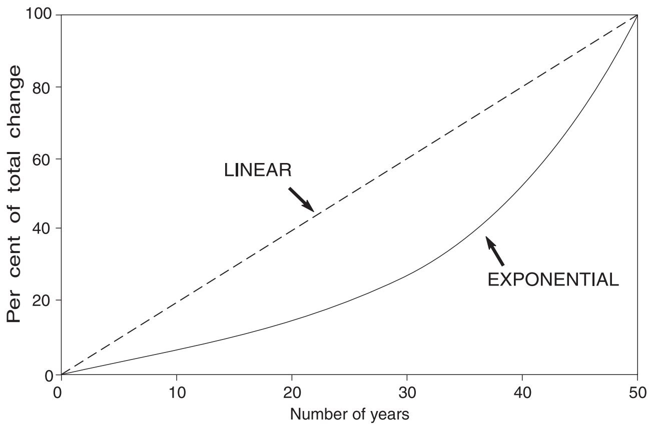

Figure 4. *Paths of change used to reach the 2 x CO_2 climate over a 50 year interval. The y-axis represents the per cent change, with 1 x CO_2 conditions equal to 0% and 2 x CO_2 conditions equal to 100%.*

Figure 5 presents for each borehole, logs of the lithology, moisture content or ice content, and temperature envelope (annual minimum and maximum) used in the geothermal simulations. Thaw strains, also included in these figures, will be discussed separately in "Potential thaw settlement" section.

GEOTHERMAL MODEL

The geothermal analyses were performed using a computer model (the one-dimensional model described in Nixon (1983)) that predicts depth of thawing using air temperature and snow depth data (i.e. the climate histories developed above). The model requires soil moisture content, soil density, and frozen and thawed thermal conductivity, determined when possible from borehole samples. Details on procedures to ensure that the model's initial ground thermal conditions were stable (i.e. in equilibrium with the model's initial climate conditions) are provided in GSC Open File 3017. Air temperatures were applied to the top of the snowpack in winter and to the ground surface in summer. An empirical relationship between air temperature and the actual temperature experienced at the ground surface (the n-factor, *see* Taylor (2000)) was used to account for the attenuation of air temperature caused by surface-layer conditions such as vegetation and snow.

THAW-DEPTH PREDICTIONS

Predicted thaw depths are plotted as a function of time for the three climate change regimes (linear, exponential, and linear+10%) in Figure 6. These plots show the rate of increase in maximum annual thaw depth over the 50 year simulation period. At the Beaufort Sea coast sites, only small increases in active layer (<0.5 m) are observed, regardless of the scenario, with the smallest increase occurring at the ice-rich site. The bulk of the energy reaching the ground during the 50 year climate warming in this region is directed towards increasing the permafrost ground temperatures (as shown for site A1 in Fig. 7), rather than in melting ground ice.

At Norman Wells, increases in thaw depth for the ice-rich site (B1) are very slight for the linear and exponential case, 0.5 m and 0.7 m respectively, but about 2.5 m for the linear+10% case. For the low-ice site B2, increases in thaw depth are much larger for all scenarios, ranging from about 2 m for the linear case to almost 7 m for the linear+10% case. The rates of increase in thaw depth are less at the ice-rich site because of the latent heat required to melt the additional ground ice. After 50 years of warming, thaw depths could range from about 1.5 m to 8 m in this region depending on warming scenario and soil profile. With time, allowing ground temperatures to return to equilibrium under the 2 x CO_2 conditions, permafrost would likely completely disappear at these sites, as can be deduced from an examination of the ground-temperature profiles shown for site B2 in Figure 7. Norman Wells permafrost occurrence would resemble conditions presently encountered farther south in the sporadic zone.

At Fort Simpson, changes in thaw depth are even more dramatic and complete degradation of permafrost may well occur in 50 years or less. At the peat plateau site C1, where permafrost initially was 5.6 m thick, both the linear and linear+10% scenarios caused permafrost to degrade in less than 50 years. At site C2, the 12 m of permafrost would degrade in about 50 years under the linear +10% scenario, and likely within 100 years for the other two scenarios. Of note, the rate of retreat of the base of permafrost is slower in the C2 case due to the presence of higher ice content at depth at this site.

It is interesting to note that in all simulations for Norman Wells and Fort Simpson (where impacts on thaw depths are the greatest), the rate of change in thaw depth is very slow in the first 10–20 years of the simulations. This observation suggests that detection of the early impacts of warming by monitoring thaw depth (*see* Nixon, 2000) may be difficult, particularly when allowing for seasonal variations and when dealing with permafrost temperatures near 0^{o}C where heat associated with phase change plays an important role in the ground thermal regime (Burgess and Riseborough, 1990; Riseborough, 1990). The simulations undertaken here support the need for long-term observations to clearly define trends.

POTENTIAL THAW SETTLEMENT

The potential for settlement of the ground surface as frozen ground thaws at each site is determined using the calculated thaw strain for each soil layer. The total thaw strain is a measure of the per cent change in height or thickness of a soil unit upon thaw (i.e. per cent settlement), and is a function not only of the volume change involved in melting frozen ground but also of the compressibility of the soil layer. The compressibility component is generally one to two orders of magnitude smaller than that due to thaw, particularly for the thin layer (less than 10 m) of overlying material under consideration here, and therefore it has not been included in the

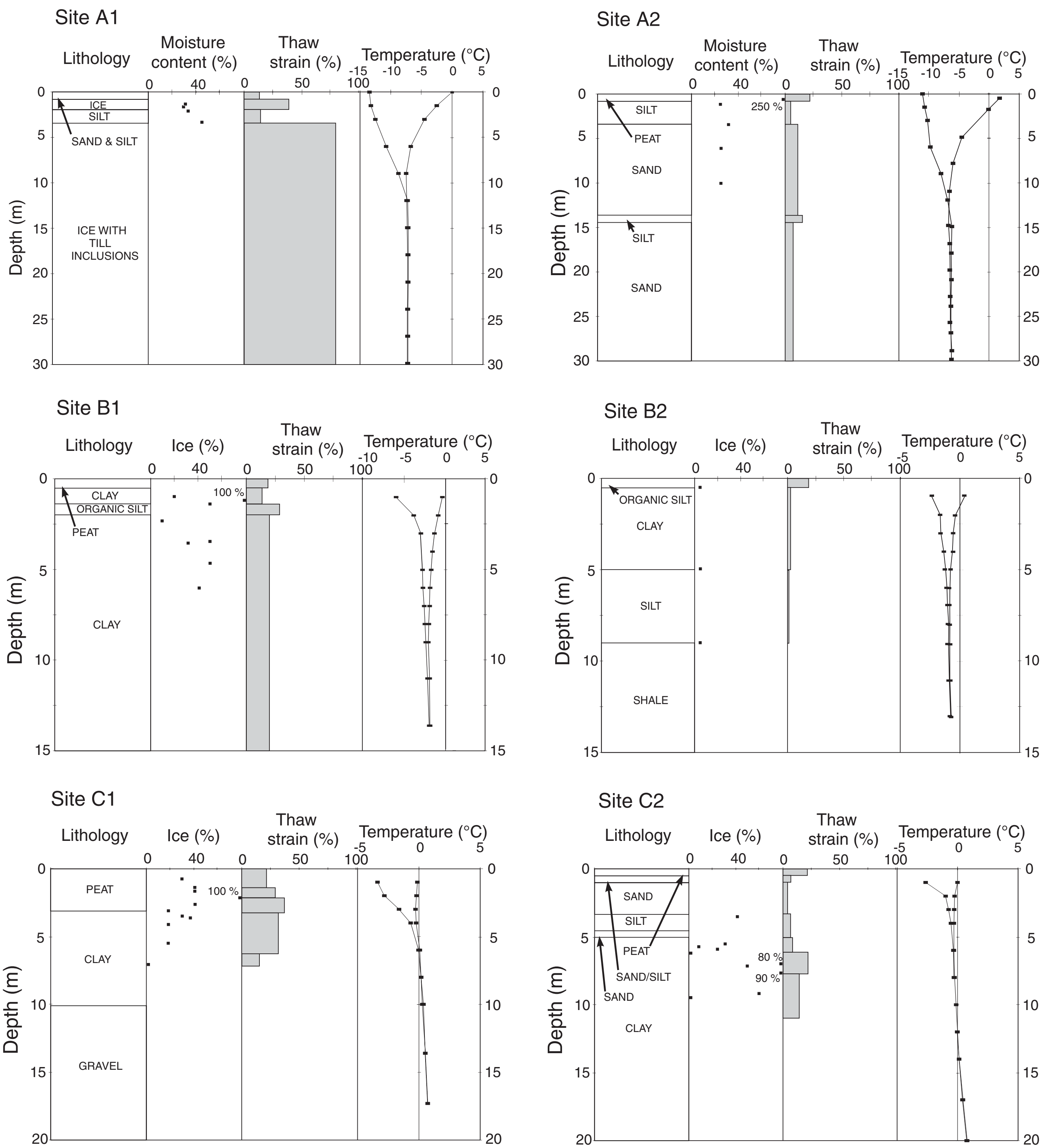

Figure 5. Stratigraphy, moisture content, thaw strain in the case of complete melting of ground ice, and ground temperature envelopes for each borehole used in the study.

calculations. Thaw relationships reported in the literature for major soil groups (Speer et al., 1973; McRoberts et al., 1978a, b; Hardy Associates Ltd.,, 1982;) were used to determine thaw strain. These require a knowledge of sediment type, and of one of the following properties: total moisture content, ice content, or frozen bulk density. Generally the geotechnical property most readily available for these determinations is the moisture content. Calculated thaw-strain values for each soil layer are included in the borehole data plotted in Figure 5.

The calculated thaw strains were then used to determine the thaw settlement resulting from the simulated increase in thaw depth at each site for each scenario. Thaw settlements after 10 and 50 years are tabulated in Table 2. Sites and scenarios which have complete permafrost degradation over the 50 years are shaded in the table and the predicted settlements for these cases are the ultimate settlement for the site. Elsewhere, since complete permafrost degradation has not occurred during the 50 years, the potential for additional thaw settlement obviously remains.

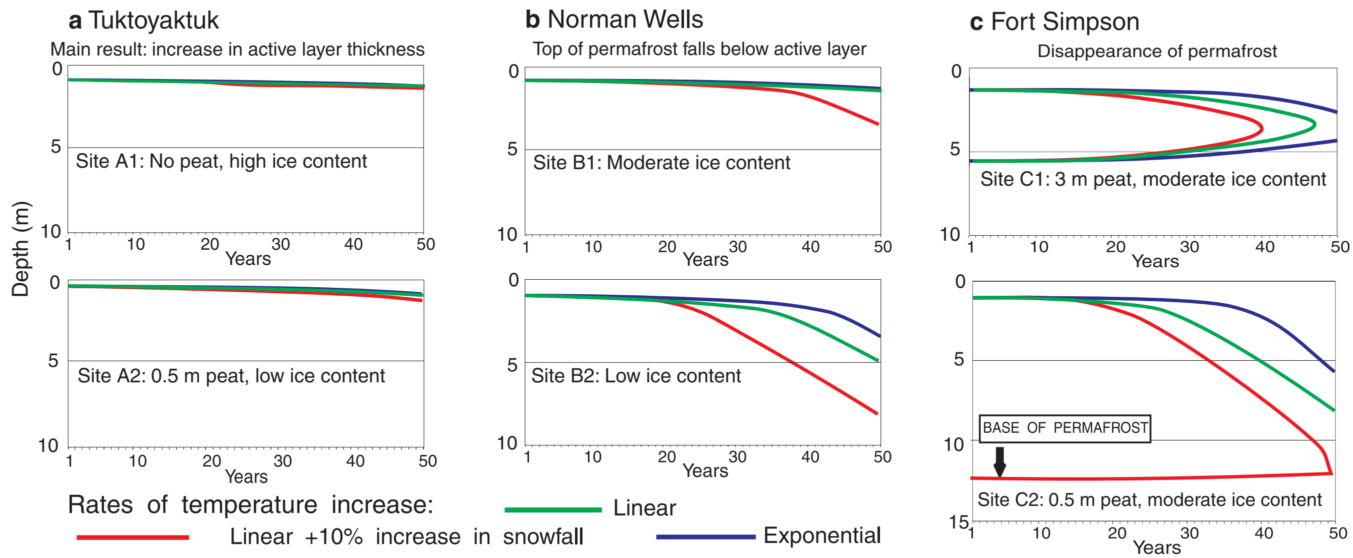

Figure 6. Predicted maximum annual thaw depth for each site, under linear, exponential, and linear+10% temperature change regimes.

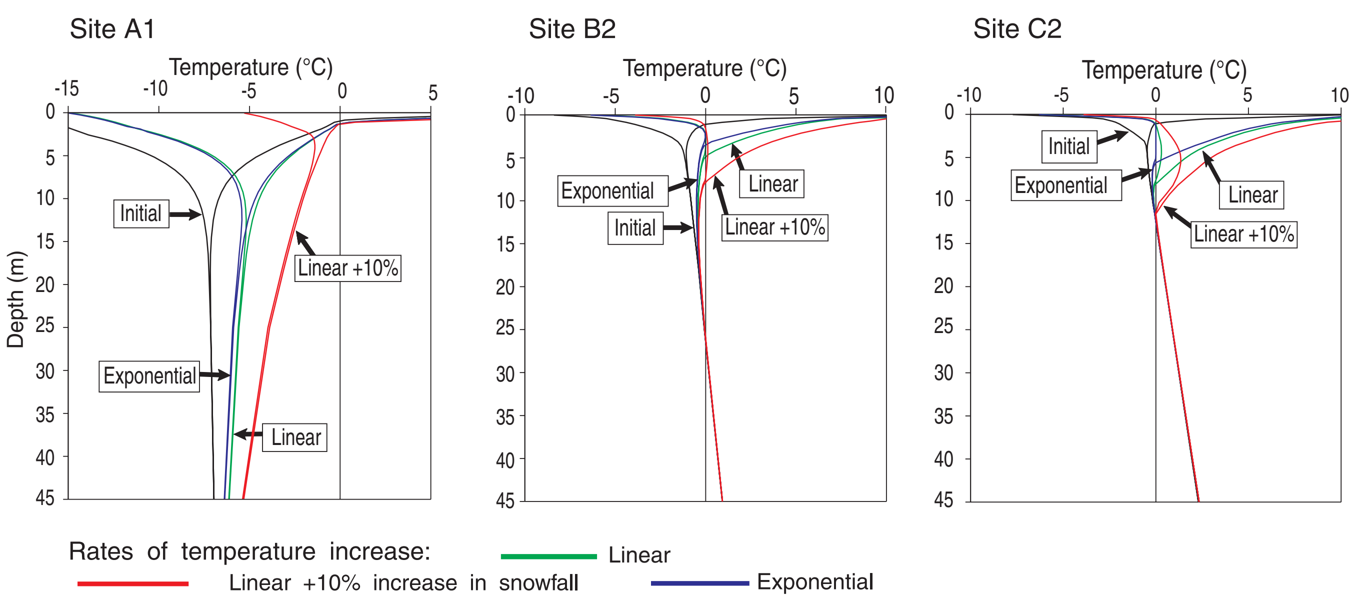

***Figure 7.** Ground temperature profiles predicted after 50 years for site A1, B2, and C2 under the temperature change regimes shown in Figure 5. Profiles used as the start-up conditions at these sites are also shown (initial case).*

Table 2. Predicted thaw depths and calculated thaw settlements after 10 years and 50 years at each site for each climate-change history. Shaded areas indicate that complete permafrost degradation and maximum thaw settlement have occurred.

Site	Surface function	Active layer thickness (m)		Cumulative thaw settlement (m)	
		t=10 years	t=50 years	t=10 years	t=50 years
A1	Exponential	0.9	1.2	0.00	0.12
	Linear	1.0	1.2	0.02	0.12
	Linear +10%	1.0	1.3	0.02	0.16
A2	Exponential	0.4	0.6	0.00	0.03
	Linear	0.4	0.6	0.00	0.03
	Linear +10%	0.4	0.7	0.00	0.06
B1	Exponential	0.9	1.3	0.00	0.12
	Linear	1.0	1.4	0.03	0.14
	Linear +10%	1.0	3.1	0.03	0.50
B2	Exponential	1.1	3.5	0.00	0.01
	Linear	1.3	4.7	0.04	0.06
	Linear +10%	1.3	7.8	0.04	0.08
C1	Exponential	0.9	2.3	0.00	0.38
	Linear	1.0	5.6	0.01	1.44
	Linear +10%	1.0	5.6	0.01	1.44
C2	Exponential	1.1	6.0	0.00	0.50
	Linear	1.2	8.0	0.01	1.06
	Linear +10%	1.2	12.6	0.01	1.77

At the Beaufort Sea sites, where increases in thaw depths are small, thaw settlement is at most a few centimetres. In the Norman Wells region, after 50 years, thaw settlements range from less than 0.15 m for all scenarios at the low-ice site B2 to 0.5 m at the ice-rich site B1 for the linear+10% case. At Fort Simpson, where permafrost degrades completely at site C1 in less than 50 years for all cases except the exponential, this results in 1.44 m of settlement. At site C2, permafrost degrades completely in 50 years or less for the step and linear+10% cases, resulting in about 1.8 m of settlement. The exponential case for site C2, which produced the slowest increase in thaw depth, still results in 0.5 m of settlement.

In summary for the sites and approach selected for this analysis, thaw settlement over 50 years is negligible in the Tuktoyaktuk area, and could range from 0.01 m to 0.5 m in the Norman Wells region and from 0.4 m to 1.8 m in the Fort Simpson area.

The results of the modelling exercise presented in this chapter clearly indicate how permafrost response to climate warming can be expected to vary, depending on site-specific characteristics and the climate change history. A modelling approach that takes into account normal year-to-year climatic variability along with the predicted warming in the Fort Simpson region can be found in Riseborough and Smith (1993). For a discussion of mapping the response of permafrost to climate warming, *see* Wright et al. (2000).

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