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Permafrost and Peatland Evolution in the Northern Hudson Bay Lowland, Manitoba

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ABSTRACT. The northern Hudson Bay lowland includes the largest area of frozen peat plateau bog in Canada. Polar bear denning habitat, caribou forage, carbon storage, and wetland drainage control provided by peat plateaus will be affected if post-Little Ice Age warming continues. Mapping and thermal modeling of frozen peat plateau stability indicate that permafrost peatlands are stable at a mean annual air temperature as warm as -3.5˚C. In the peat plateaus of the northern lowland, permafrost can be absent at the peat plateau margins where peat plateaus border fens or lakes. Here, insulating snow accumulations permit thawed conditions at mean annual air temperatures colder than -3.5˚C. Continued warming will result in expansion of thawed zones, subsidence at plateau margins, and even collapse of plateau surfaces, resulting in conversion to fen. This process has already occurred across north-central Manitoba, Saskatchewan, and Alberta since the end of the Little Ice Age, and there are signs that it is extending into the northern Hudson Bay lowland. Wave erosion of subsiding plateau borders at lake shorelines is also resulting in loss of peat plateau bog.

Key words: fen, Hudson Bay lowland, lake, peat plateau, peatland, permafrost, polar bear, thawing, Wapusk National Park

RÉSUMÉ. Les basses-terres du nord de la baie d’Hudson comprennent la plus grande zone composée de tourbière oligotrophe de plateaux tourbeux du Canada. Advenant que le réchauffement du post-Petit Âge glaciaire se poursuive, l’habitat de tanières de l’ours polaire, les zones de fourrage du caribou, le stockage de carbone et la régulation du drainage des zones humides découlant de la présence de plateaux palsiques en subiront des conséquences. Le mappage et la modélisation thermique de la stabilité du plateau palsique gelé indiquent que les tourbières de pergélisol sont stables lorsque la température moyenne annuelle de l’air est aussi chaude que -3,5 ˚C. Dans les plateaux palsiques des basses-terres du Nord, le pergélisol peut être absent en marge des plateaux palsiques lorsque les plateaux palsiques bordent des tourbières basses ou des lacs. Ici, les accumulations de neige isolante donnent lieu à des conditions de décongélation moyennant des températures moyennes annuelles de l’air plus froides que -3,5 ˚C. Le réchauffement continu se traduira par l’agrandissement des zones de décongélation, l’affaissement à la hauteur des marges des plateaux et même l’effondrement des surfaces de plateaux, ce qui transformera ces zones en tourbières basses. Ce processus a déjà commencé à se produire dans le centre-nord du Manitoba, de la Saskatchewan et de l’Alberta depuis la fin du Petit Âge glaciaire, sans compter qu’il y a des signes indiquant que cela s’étend dans le nord des basses-terres de la baie d’Hudson. L’érosion par les vagues des bordures de plateaux subsidantes à la hauteur des littoraux de lacs se traduit également par la perte de tourbières oligotrophes de plateaux tourbeux.

Mots clés : tourbière basse, basses-terres de la baie d’Hudson, lac, plateau palsique, tourbière, pergélisol, ours polaire, décongélation, parc national Wapusk

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INTRODUCTION

The Hudson Bay lowland borders Hudson Bay from Churchill, Manitoba, to southern James Bay, Ontario, and comprises the largest region of thick peatland soils in Canada (Dredge and Nixon, 1992; Glooschenko et al., 1994) (Fig. 1). The northern part of the lowland, which includes Wapusk National Park, contains the most extensive area of polygonal peat plateau bog in Canada. The presence of permafrost has an important influence on the biological and hydrological functions of this terrain. Permafrost contributes to the elevation of peat plateaus, allowing the formation of peat banks that provide a denning habitat for polar bears, particularly by lakes (Richardson et al., 2005). The surfaces of the plateaus offer winter forage for caribou (Parks Canada, 2002). By restricting lateral flow, the plateaus also help to maintain water levels and the storage of carbon in the adjacent fen (Burton et al., 1996). The disappearance of permafrost would result in subsidence of the plateaus, compromising all of these functions.

Thawing of permafrost peatlands has been occurring in a band across north-central Alberta, Saskatchewan, and Manitoba since the end of the Little Ice Age (Vitt et al., 1994). Should this warming trend of the past century or so continue, permafrost peatland degradation will extend northward into the frozen peat plateau region of the Hudson Bay

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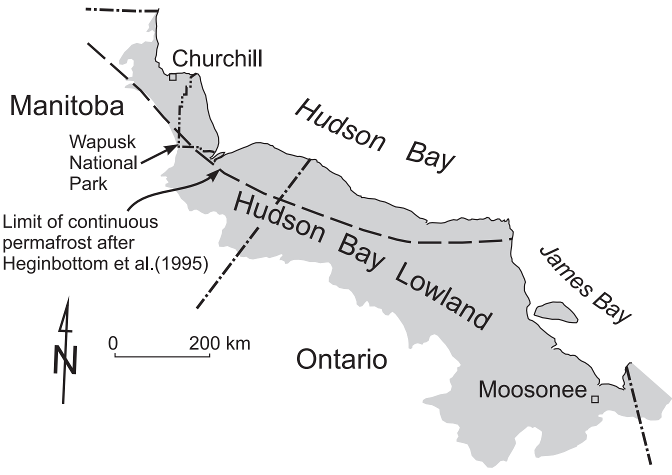

FIG. 1. The extent of the Hudson Bay lowland and the limit of continuous permafrost as mapped by Heginbottom et al. (1995).

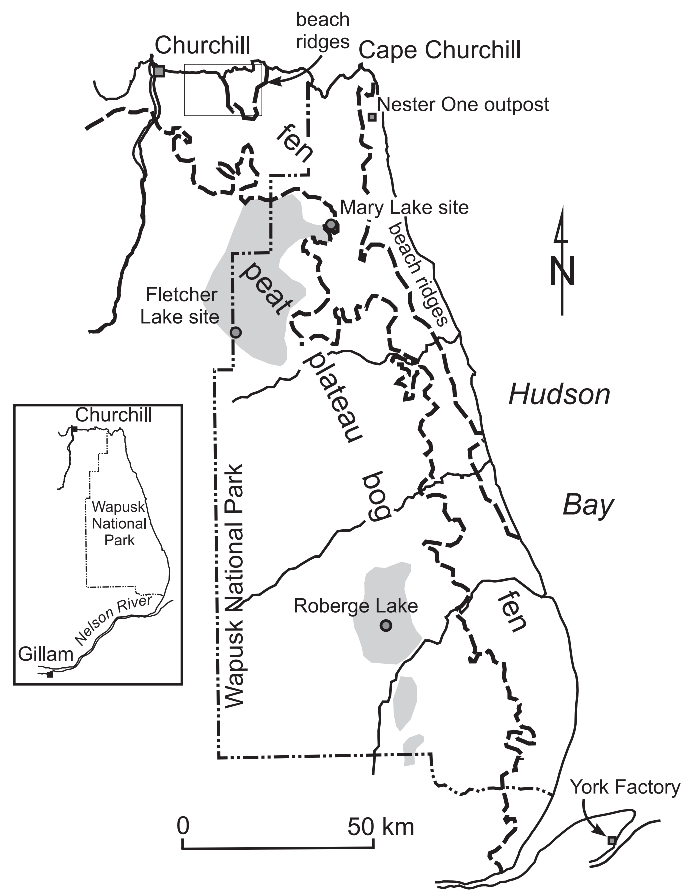

FIG. 2. The wetland types comprising the northern Hudson Bay lowland and the location of the ground and air temperature measurement sites referred to in the text. Shading indicates the areas with concentrations of lakes with largest dimensions of 1–2 km. The rectangle near Churchill represents the study area of Duguay and Lafleur (2003). The inset map shows the location of Gillam.

lowland. Snow accumulations along peat plateau edges are likely locations for the initiation of thaw. The abundant lakes in the northern lowland augment plateau degradation by providing shoreline peat banks as additional locations for snow accumulation and by exposing the peat to wave erosion.

In this paper, we investigate the sensitivity of peat plateau terrain in the northern Hudson Bay lowland to continued climate warming. We assess the importance of snow and shallow standing water as the environmental factors most likely to produce above-freezing ground temperatures in otherwise frozen peat plateau terrain. We also determine relationships between ground and air temperatures for these surface environmental conditions. These relationships are used with climate station air temperature records, which provide a measure of air temperature variability and long-term trend, to determine whether foreseeable climate warming will cause peat plateau thaw. In addition, we assess lakeshore erosion as another mechanism for the degradation of frozen peat plateau terrain.

RESEARCH AREA AND METHODS

The Northern Hudson Bay Lowland

The northern Hudson Bay lowland comprises a broad wetland sloping gently towards Hudson Bay on an average gradient of about 1 m/km. Peat covers the wetland, thickening inland in response to the increasing time available for peat accumulation following post-glacial emergence from Hudson Bay (Dredge and Nixon, 1992; Dredge and Mott, 2003). The dominant wetland classes are bog, defined as peatland with the water table at or below the surface but unaffected by mineral-rich groundwater, and fen, defined as peatland with the water table at or slightly above the surface and having mineral-rich water (National Wetlands Working Group, 1988). Near the coast, fen occupies the swales between beach rides, supporting primarily sedges. With distance inland, the beach ridge zone gives way to continuous fen. Bog, primarily in the form of polygonal peat plateaus, begins to appear about 10 km inland (Fig. 2). Along the western boundary of Wapusk National Park, about 80 km inland, the peat reaches thicknesses of 2–3 m.

The elevation of peat plateau bog above fen (typically 1–2 m, Fig. 3), in part produced by ice segregation in the mineral soil immediately beneath the peat (typically 50% excess ice in the top 0.5 m of mineral soil), allows summer drying of the surface peat layers. This drying lowers the peat thermal conductivity, insulating the deeper peat against thaw. Wetter conditions during fall freeze-back raise the peat thermal conductivity and, along with snow removal from the plateau surface by wind, accentuate the cooling in winter (Brown, 1963; Kershaw, 2003). Because of their surface water, fens transmit more heat downwards in summer than dry peat. In winter, freezing the surface water takes up some of the freezing that would extend into the ground below. The result is that fens have warmer ground temperatures than peat plateaus and are the type of peatland most likely to be permafrost-free in the discontinuous permafrost zone. The drifting snow that accumulates on the fen along plateau edges further raises the ground temperature because of the snow's insulating properties.

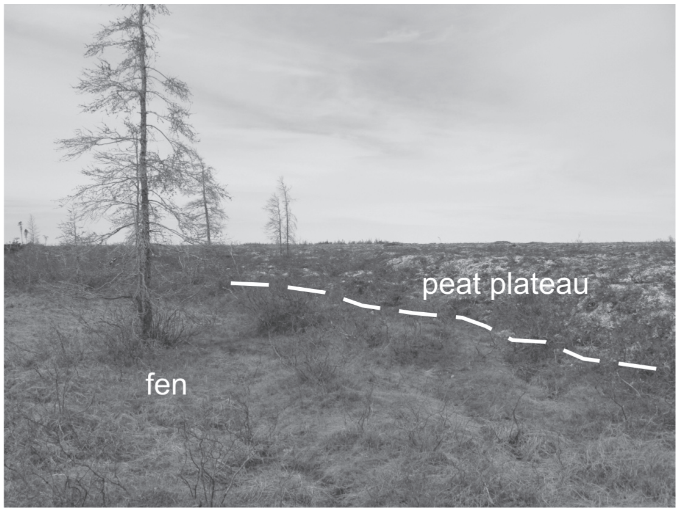

FIG. 3. A peat plateau exhibiting about 1.5 m of relief above a bordering fen near Fletcher Lake. The dashed line shows the boundary between the peat plateau and the adjacent fen.

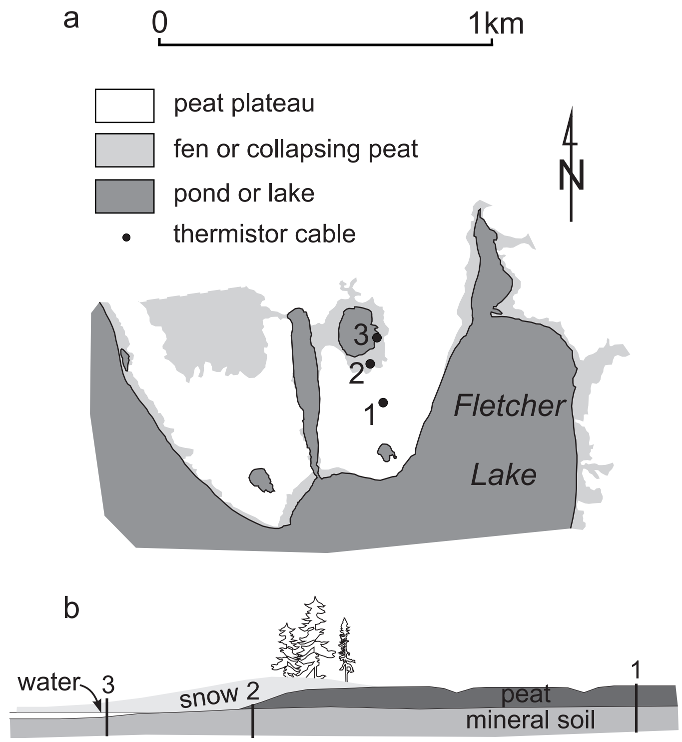

FIG. 4. The Fletcher Lake thermistor cables. a) Location of the cables (for the location of Fletcher Lake, see Fig. 2). b) Approximate cross-section showing the environment of each cable.

The small elevation differences between peat plateaus and fens are also important in controlling drainage. In particular, the elevation and frozen core of peat plateaus restrict lateral water flow. Detailed hydrological studies in the peatlands of the central Mackenzie River basin identify peat plateaus as contributing significant runoff to other adjacent bogs and fens (Quinton and Hayashi, 2004). The hydrologic function of peat plateaus in the northern Hudson Bay lowland is not as well understood. In the northern Hudson Bay lowland, peat plateaus typically extend continuously for kilometers. The plateau surfaces are often broken by myriad ponds with hydraulic connection only through the active layer. Thus, the contribution of runoff to the adjacent bog or fen is presumably low because of water detention in ponds and the very low hydraulic gradients toward the plateau edges. If thawing converts peat plateaus to fen in the northern Hudson Bay lowland, the contribution of runoff to streams draining into Hudson Bay may increase. The disappearance of permafrost and the improvement of the drainage may also alter the long-term carbon accumulation that is enabled by the present poor drainage (Rouse, 2000).

Ground Temperature Measurements

To assess the warming effect of snow and standing water on the peat plateau terrain of the northern Hudson Bay lowland, we installed temperature sensors in the ground at three sites near Fletcher Lake, about 70 km south of Churchill and 50 km inland. These sites represent three terrain types: an open peat plateau, the forested margin of the plateau where a 1.5 m deep snowdrift accumulates, and an adjacent pond with a 5–10 cm water depth (Fig. 4). An additional sensor was installed at a peat plateau site at Mary Lake, about 20 km inland (Fig. 2). Each installation consists of a series of thermistors placed in a one-inch diameter plastic casing extending to a depth of about 5 m. The plastic casing was placed inside steel casing that was diamond drilled to depth, then removed, leaving the plastic in place. Thermistors are spaced at intervals of 0.5 m, changing to 1.0 m toward the bottom of each installation. The thermistors are read by a data logger a few times daily, giving an essentially continuous record of ground temperature at each depth. The temperatures recorded are accurate to 0.1˚C.

Ground Surface and Air Temperature Measurements

Ground temperature measurements can characterize the ground thermal regime as records accumulate. However, air temperature records, decades in length, are now available and can be used to estimate ground temperature if the damping effect of the surface vegetation and snow between the air and the ground is known. A simple empirical way to determine this damping effect is to compare freezing and thawing indices between the air and the ground surface. The ratio between air and ground surface temperature indices for both freezing and thawing, respectively termed the freezing and thawing n-factors (Lunardini, 1981), can be used to predict mean annual ground temperatures (MAGT) for any yearly air temperature record. Thus statistical indices of warming, such as the warmest year or the interpolation of a warming trend, can be used to predict the associated ground temperature response. To determine n-factors, ground surface temperature records have been acquired from environments that represent the range of surface conditions that influence sub-surface temperature. Thermistors used to record the ground surface temperature are placed within 5 cm of the ground surface. Air

TABLE 1. Mean annual ground temperature (MAGT, ˚C) for the Fletcher Lake thermistor cables (Cables 1, 2, and 3) and Mary Lake peat plateau cable at each thermistor for the year following 1 July.

Thermistor depth (m)	MAGT, ˚C 2007–08 Cable 1 Peat plateau	MAGT, ˚C 2007–08 Cable 2 Plateau edge	MAGT, ˚C 2007–08 Cable 3 Pond	MAGT, ˚C 2008–09 Cable 2 Plateau edge	MAGT, ˚C 2008–09 Cable 3 Pond	MAGT, ˚C 2008–09 Mary Lake Peat plateau
0.4	–	–	-2.7	–	-1.1	–
0.5	-6.2	–	–	–	–	–
0.6	–	1.9	–	0.5	–	-4.1
0.9	–	–	-2.3	–	-0.7	–
1.0	-6.0	–	–	–	–	–
1.1	–	1.5	–	0.2	–	-4.0
1.4	–	–	-2.2	–	-0.8	–
1.5	-5.6	–	–	–	–	–
1.6	–	1.5	–	0.4	–	-3.9
1.9	–	–	-1.8	–	-0.7	–
2.0	-5.3	–	–	–	–	
2.1	–	1.3	–	0.3	–	-3.7
2.5	-5.1	–	–	–	–	–
2.6	–	1.1	–	0.2	–	-3.7
2.9	–	–	-1.5	–	-0.9	–
3.1	–	0.9	–	0.2	–	-3.7
3.5	-4.9	–	–	–	–	–
3.9	–	–	-1.2	–	-0.9	–
4.1	–	0.5	–	0.1	–	-3.5
4.5	-4.7	–	–	–	–	–
5.1	–	0.2	–	0.0	–	-3.7

temperatures are measured approximately 2–3 m above the ground surface.

Calculation of the Mean Annual Ground Temperature

We estimate the equilibrium MAGT by determining the freezing degree–days remaining once the active layer is frozen and converting that freezing index to a year-long temperature. Thus,

$$MAGT = (t_f - t_h)T_f / 365, \qquad (1)$$

where t_f is the time in days available for freezing at the ground surface, t_h is the time in days required to re-freeze the active layer, and T_f is the mean ground surface freezing temperature. If freezing is not sufficient to re-freeze the active layer, then the MAGT is greater than 0˚C, and the terms in the formula must be switched to the number of days with ground surface temperature above 0˚C, the number of days to thaw the frozen layer, and the mean ground surface thawing temperature, respectively. The active layer depth, h, is determined using the Neumann equation for freezing and thawing depth (Jumikis, 1977):

$$h = \alpha\, t^{1/2}, \qquad (2)$$

where α is a term incorporating ground surface temperature, thermal conductivity, and volumetric ice content and t is the time during which thawing temperatures are available. Equation 2 is recast to determine the time to re-freeze the active layer as required in equation 1:

$$t_h = (h)^2/(\alpha)^2.$$

To determine T_f, the freezing temperature at the ground surface, the freezing n-factor, n_f, can be used with, for instance, a 30-year climate normal to determine a MAGT. Using the air and ground surface temperature records available at the Mary, Roberge, and Fletcher Lake sites (Fig. 2), we calculate the n-factors and use them to calculate the MAGT for the Churchill 1971–2000 climate normal and for the mean annual air temperature (MAAT) for 2006, the warmest year for the Churchill period of record, i.e.,

$$n_f = FDD_g/FDD_a \text{ and}$$
$$T_f = FDD_a\, n_f/t_f, \qquad (3)$$

where FDD_g is freezing degree–days at the ground surface and FDD_a is freezing degree–days in the air. Equation 3 supplies the T_f term required in equation 1 for calculating the MAGT.

RESULTS

Ground Temperatures

In Table 1, we compare the MAGTs at all thermistor depths for the three installations at the Fletcher Lake site and for the Mary Lake installation. In Figure 5, we show monthly temperature with depth for the installations to define the annual temperature envelope and the active layer. These data show a wide variation in ground temperature between sites, which illustrates the influence of the local environment on the ground thermal regime. The peat plateau site (Cable 1 in Fig. 4 and Table 1) has well-established permafrost, with a MAGT for 2007–08 of -6.2˚C near the top of permafrost, warming to -4.7˚C at 4.5 m. This MAGT

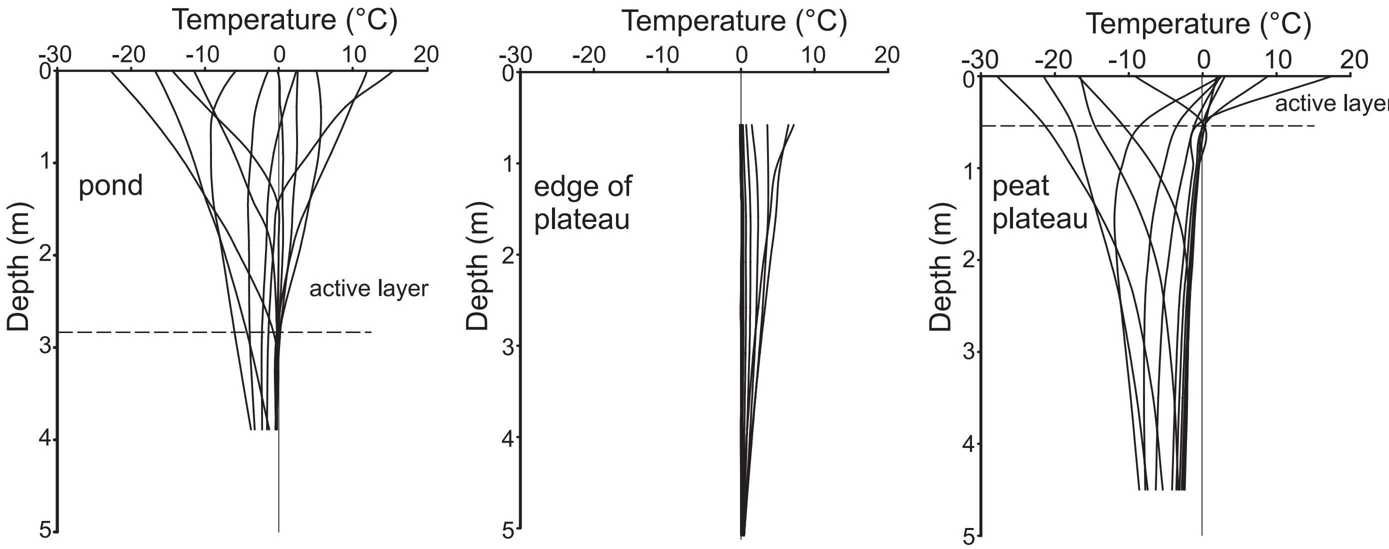

FIG. 5. Monthly temperature vs. depth graphs for the Fletcher Lake thermistor cables. The individual monthly records are not labeled, but together they approximate the envelope of temperature variation and the active layer.

is cold compared with the other MAGTs available in the Churchill area, although Dredge's (1979) unforested peat plateau with a MAGT of -4.5˚C is consistent with the tendency of peat plateaus to favour cold ground temperatures.

The warming in MAGT with depth at the Fletcher Lake peat plateau site suggests that the shallower ground temperatures reflect a short-term cooling. This cooling may be associated with less-than-normal snow accumulation because the MAAT (-6.5˚C) during the period of ground temperature measurement is near the Churchill MAAT normal of -6.9°C (Environment Canada 1971–2000 climate normal). The Mary Lake peat plateau cable gives a MAGT of -4.1˚C for 2008–09 near the top of permafrost, warming to -3.7˚C only at a depth of 5.1 m (Table 1). Records are available only from 2007–08 for the Fletcher Lake peat plateau and from 2008–09 for the Mary Lake site, so the two sites cannot be compared. However, all of the peat plateau sites discussed in this section suggest that peat plateau MAGTs in the Fletcher Lake to Mary Lake area are about -4˚C. All of these sites are free of trees, resulting in exposure to wind that prevents the accumulation of snow. This temperature contrasts with observations near the Nelson River, where forested peat plateaus trap the snow, resulting in MAGTs warmer than -1˚C (EBA Engineering Consultants Ltd., 1977).

The plateau edge site (Cable 2, Fig. 4, Table 1) shows no continuously sub-0˚C temperatures, indicating that permafrost is absent, at least to a depth of 5 m. A comparison of the MAGTs for 2007–08 and 2008–09 suggests that the water circulation during drilling in April 2007 hastened ground warming by thawing the frozen ground, which extended to a depth of 50 cm at the time. Ground temperatures for 2008–09, a year after the drilling, are distinctly cooler and presumably represent the thermal regime at this site more accurately.

At the pond site (Cable 3, Fig. 4, Table 1), warm ground temperatures result from the shallow water (typically < 10 cm deep). The MAGT for the depth of 3.9 m is -1.2 and -0.9˚C for the two successive years. The active layer at the pond site is unusually deep, between 2.5 and 3.0 m. Summer warming of the shallow water or the exposed rocky bottom is probably responsible for the excessive thaw.

In summary, unforested peat plateaus promote cold ground temperatures in part because the peat dries and insulates in summer, but also because exposure to wind minimizes the accumulation of an insulating cover of snow. However, environmental characteristics that elevate ground temperatures at the margin of peat plateaus are effective enough to either eliminate permafrost or promote permafrost temperatures that are much warmer than those beneath unforested peat plateaus.

Air Temperature

Air temperatures recorded by us at Fletcher Lake and Nester One outpost (for locations see Fig. 2) and by Kershaw (G.P. Kershaw, unpubl. data) at Mary and Roberge lakes (Fig. 2) confirm the inland summer warming documented by Rouse (1991). Comparisons for the summers of 2005–08 indicate that the inland sites at Fletcher, Mary, and Roberge lakes are all about 1.5˚C warmer than the coastal sites of Churchill or the Nester One outpost. Most of the temperature increase takes place within the first few kilometers inland (Rouse, 1991), indicating that in general the summer air temperatures are considerably warmer at these sites than is suggested by the average gradient derived from the regional climate station observations. Since the snow extends continuously across the coast in the winter, the air temperatures will show the strong inland warming gradient only in the summer. Thus, in general, the MAAT is probably about 1˚C warmer inland compared to Churchill.

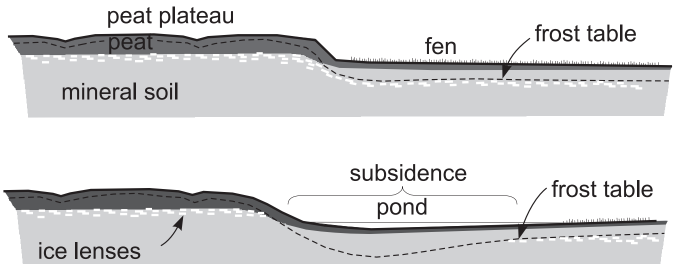

FIG. 6. A peat plateau border showing the subsidence and migration of the unfrozen zone towards the plateau center as a result of ground warming along the plateau edge.

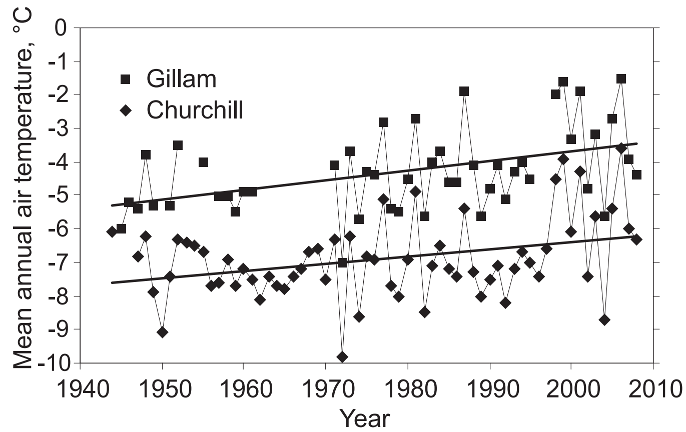

FIG. 7. Mean annual air temperatures for Churchill and Gillam for the Environment Canada period of record. A linear regression line is shown for each data set.

Predicted Mean Annual Ground Temperatures

The thermistor cables at Fletcher Lake show that peat plateau margins can be unfrozen under the present climate of this area. If the climate warms, then the unfrozen zone may expand toward the plateau center (Fig. 6). Recent warm years as recorded at Churchill and Gillam (Fig. 7) and degrading permafrost peatlands to the south suggest that peat plateaus in the northern lowland may begin to degrade in the near future. In this section, we use n-factors to determine the thermal response of frozen peat plateaus to a possible warmer MAAT than presently exists for Churchill. The MAGT associated with the Churchill 1971–2000 climate normal (-6.9˚C) is first calculated for comparison with the reported ground temperature measurements. Then the MAGT for the warmest MAAT of the 63-year climate record for Churchill, -3.6˚C in 2006, is determined. A summary of the calculated MAGTs is presented in Table 2.

The peat thermal conductivities required for the MAGT calculation are taken from the literature. Values listed in Dredge and Nixon (1992) agree generally with the nomograms for selecting peat conductivities given the unit weight and the degree of saturation published by Anderson and Andersland (1978) and with a detailed study of peat thermal conductivity in Finland (Kujala et al., 2008). We selected a value of 0.3 W/m˚C for unsaturated thawed peat, given that the plateau surfaces dry out in the summer. However, to simulate the saturated thawed peat that would occur in an adjacent fen, we also calculate the MAGT using a peat conductivity of 0.5 W/m˚C. The corresponding conductivities for frozen peat are 1.0 and 1.5 W/m˚C for dryer and wetter peat, respectively.

The peat plateau thermistor installation at Fletcher Lake records a MAGT for 2007–08 of -6.2˚C for the shallowest thermistor in permafrost, a value that probably results from thin snow cover, as discussed in our sub-section on ground temperatures. The n_f value of 0.83 for this site is consistent with much less snow cover than at the Roberge Lake peat plateau sites. Using this n-factor with the Churchill climate normal gives a MAGT of -7.5˚C. This cold temperature, although unusually low, emphasizes the tendency of a peat plateau to promote cold ground temperatures.

Two years of ground surface temperature records for two peat plateau sites are available from Roberge Lake (G.P. Kershaw, unpubl. data). These records give an average thawing n-factor, n_t, of 0.95 and an average n_f of 0.42. The n_f from Roberge Lake is considered to be more representative of peat plateau conditions than the n_f from our Fletcher Lake peat plateau site because of the low snow cover implied by our low ground temperature observations. Using the 1971–2000 Churchill MAAT with the Roberge Lake n_f gives a MAGT of -3.7˚C. It is implicitly assumed that the snow depth during the two years of record at Roberge Lake is representative of the 1971−2000 interval for the Churchill climate normal. For comparison, the peat plateau MAGT would rise to -1.8˚C if the 2006 warm year air temperatures persisted and the Roberge Lake n-factors applied.

The MAGT analysis for the peat plateaus suggests that this landscape component will remain stable even if the MAAT rises to the Churchill record maximum. For peat plateaus to thaw in the northern lowland, other factors must come into play. The Fletcher Lake thermistor cable located at the peat plateau margin indicates that snow accumulation there can restrict the winter ground cooling sufficiently to preclude permafrost. The ground surface temperatures associated with the snow depth measurements available for Mary Lake (G.P. Kershaw, unpubl. data) provide an additional opportunity to examine the insulating influence of snow depth. For the three successive winters between 2004 and 2007, snow depth reached 93, 40, and 166 cm, producing an n_f of 0.38, 0.52, and 0.30, respectively. The predicted MAGT for a peat plateau, using the n-factor for the greatest snow depth with the Churchill climate normal freezing index, is -2.2˚C. If we use the 2006 extreme warm year conditions, the predicted MAGT is -1.4˚C. Even with considerable snow depth and a particularly warm summer, enough cooling is still available to maintain a MAGT below 0˚C in a peat plateau.

Mineral soil will increase the MAGT because of the reduced ratio between the frozen and unfrozen thermal conductivity (for this analysis, the unfrozen thermal conductivity = 1.5 W/m˚C, and the frozen = 2.0 W/m˚C; values are for a silty sand). Permafrost is absent at the Fletcher Lake

TABLE 2. Summary of calculated mean annual ground temperatures (˚C) based on freezing and thawing indices determined from the 1971–2000 climate normal and the 2006 (extreme warm year) mean air temperature for Churchill. Because ground surface temperature records are not available for the plateau margin or fen wetland settings, n-factors are taken from available sites with suitable snow covers.

Wetland setting:	Peat plateau			Plateau margin	Fen
Source of n-factors All $n_t = 0.95$	Roberge Lake peat plateau $n_f = 0.42$	Fletcher Lake peat plateau $n_f = 0.83$	Mary Lake snow cover $n_f = 0.30$	Mary Lake snow cover $n_f = 0.30$	Roberge Lake peat plateau $n_f = 0.42$
Climate normal	-3.7	-7.5	-2.2	-0.5	-2.3
2006	-1.8	No data	-1.4	1.1	-0.1

peat plateau margin site because, in addition to the snow insulation, the margin probably has moister peat than a peat plateau surface, and the peat thickness over the underlying mineral soil is considerably reduced. Ground surface temperature data are not available for the plateau margin site, but the freezing n-factor for the maximum Mary Lake snow accumulation can be used to predict the influence of the mineral soil. Applying the Churchill climate normal gives a MAGT of -0.5˚C, while using the 2006 extreme warm year freezing and thawing indices gives a MAGT of 1.1˚C. Clearly the snow and the mineral soil are combining to favour the absence of permafrost. Our second year of ground temperature observations at the plateau margin site (Table 1) gives a MAGT of about 0.5˚C, suggesting that ground temperatures are responding to a climate warmer than the Churchill 1971 – 2000 climate normal.

Ground temperature measurements for fen are not yet available for comparison with a MAGT calculation. For the case of fen with the mineral soil essentially at the surface, the MAGT can be estimated using the Roberge Lake n-factors and the assumed mineral soil thermal properties. Fen gives MAGT values of -2.3˚C for the Churchill climate normal and -0.1˚C for the 2006 extreme warm year. Fen with deep snow would favour the same MAGT as the peat plateau margin, suggesting that where snow can accumulate on fen or shallow ponds, permafrost will be marginal or absent.

Accuracy of Calculated Mean Annual Ground Temperatures

The calculated MAGT of -3.7˚C for the Churchill climate normal on unforested peat plateau compares well with an observed MAGT for this environment of about -4˚C. The MAGT of -0.5˚C calculated for the snowbank ground surface temperature measurements from Mary Lake is colder than the observed thawed conditions for the Fletcher Lake plateau edge site (mean 2008 – 09 temperature of 0.0˚C for the deepest thermistor). However, the discrepancy is not large, considering that snow at the Fletcher lake site is probably deeper than at Mary Lake (because the Fletcher Lake site is close to a peat plateau edge), and the inland warming gradient in summer temperature probably raises the MAAT above the Churchill climate normal by about 1˚C. Although n-factors are subject to the variability of environmental controls, particularly snow depth, the comparability of our measured and calculated ground temperatures suggests that our inferences about peat plateau response to warmer temperatures are valid.

DISCUSSION

Permafrost Distribution in the Northern Hudson Bay Lowland

For peat plateaus to collapse, continuous permafrost must degrade, or permafrost in the discontinuous zone must decrease in extent. Ground temperatures in the vicinity of Churchill suggest that permafrost is close to continuous in this area. Observations recorded by Brown (1978), Dredge (1979), and Dyke (1988) show MAGTs ranging from -4.5˚C for a peat plateau to -0.9˚C for a forested palsa. However, Brown (1978) also recorded 0.4˚C for a peat depression, and Dyke (1988) recorded a temperature of 1.0˚C below extensive willows immediately above the tidal zone of the Churchill River estuary. These observations confirm that permafrost is widespread, but environmental factors can limit its distribution in the Churchill climatic setting. From modeling studies in the Mackenzie valley, Wright et al. (2003) found that the transition from discontinuous to continuous permafrost appears to require a MAAT of about -7˚C, assuming that ground temperatures are in equilibrium with climate. If equilibrium is also the case for the Churchill area, the -6.9˚C MAAT climate normal for Churchill is consistent with almost continuous permafrost.

Other Ground Temperatures Confirming Discontinuous Permafrost

The inland summer warming described under the subsection *Air Temperature* suggests that although permafrost is widespread in the vicinity of Churchill, it becomes increasingly discontinuous with both distance inland and distance south. The widespread distribution of peat plateaus in the northern Hudson Bay lowland is responsible for permafrost well inland from Churchill being mapped as continuous by Dredge and Nixon (1992). In fen, permafrost probably starts to disappear with distance toward Gillam. In the mid-1970s, two thermistor cables installed in peat plateaus near the Hudson Bay Railroad crossing of the Nelson River (230 km south of Churchill) both recorded MAGTs of -0.9˚C, while an adjacent fen recorded 1.1˚C (EBA Engineering Consultants Ltd., 1977). In the Fort Simpson area

(1971–2000 MAAT climate normal: -3.2˚C), permafrost is restricted to peat plateaus, which are degrading with MAGTs warmer than -1.0˚C, and permafrost is absent in fenlands (Ednie et al., 2008; Smith et al., 2008). Furthermore, modeling indicates that permafrost near Fort Simpson is not in equilibrium with the present climate but is still adjusting to warming since the Little Ice Age. Thus, if it were in equilibrium with the present Fort Simpson climate, permafrost would be even less extensive than at present. In the Hudson Bay lowland, therefore, permafrost is likely absent from fen in the vicinity of Gillam (MAAT 1971–2000 climate normal: -4.2˚C). This conclusion is supported by results from two thermistor cables installed in open forested fen about 0.5 km inland from the Hayes River at York Factory in 2007 (for location see Fig. 2). These installations give MAGTs for 2007–08 of 3.6 and 3.9˚C (Sladen et al., 2009).

Available ground temperature measurements for the northern Hudson Bay lowland suggest that most of its area is in the discontinuous permafrost zone. Therefore, rather than permafrost having first to degrade in fens before bogs can begin to degrade, unfrozen fen is probably already present and is likely to expand at the expense of bog in proportion to any amount of climate warming.

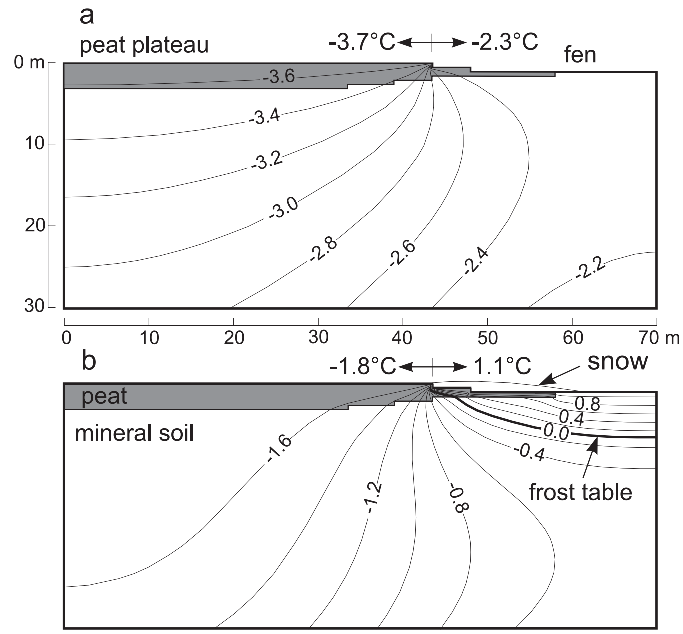

FIG. 8. A numerical model of the ground temperature distribution at the edge of a peat plateau. a) The ground temperatures in equilibrium with a MAGT (˚C) based on the 1971–2000 air temperature climate normal for Churchill and an assumed geothermal gradient of 1.0˚C/50 m. b) The thermal regime 20 years after increasing the MAGT to the value beneath snow produced by the 2006 MAAT, the warmest on record at Churchill.

Warming Trends

Eley (2000), who repeated the temperature measurements at two sites that Brown (1978) had measured in the early 1970s, found that the MAGT had warmed 1.0˚C at Brown's bedrock site and 0.3˚C at his fen site. These changes over 25 years are small and correspond with only a weak overall warming in MAAT at Churchill since the late 1940s (Fig. 7). Thus climate warming does not seem to have been pronounced for the past half-century or so in the Churchill area. However, abnormally warm MAATs have occurred roughly once or more a decade, and these extremes have also warmed slightly over the period of record. For the same period of record, Gillam shows a slightly stronger overall warming trend, as well as the same distribution of abnormally warm MAATs.

Peat Plateau Degradation: Historical Trends and Modeling

Halsey et al. (1995) have carried out a regional-scale assessment of permafrost distribution in the northern prairie provinces, south of the northern Hudson Bay lowland. Their work not only indicates a reduction of permafrost in bogs since the Little Ice Age, but also concludes that the remaining permafrost is in part relic. They determine a limiting MAAT for permafrost reduction of -3.5˚C, below which the permafrost in all peat plateaus will persist. Thus the permafrost in peat plateaus in the northern Hudson Bay lowland should also persist, even if the MAAT rises permanently to the -3.6˚C warmest value for the period of record at Churchill. Gillam records -1.5˚C for the warmest MAAT, suggesting that the peat plateaus somewhere between there and Churchill will begin to thaw first if the past warming trend in MAAT continues. Furthermore, if fen thawing can extend laterally to the bordering peat plateaus, then peat plateau degradation may begin at MAAT levels cooler than that suggested by Halsey et al. (1995). At present, excessive snow accumulation appears to be capable of achieving MAGTs above 0˚C where the peat overlying the mineral soil is thin and where MAATs are considerably cooler than -3.5˚C.

In Figure 8 we show a two-dimensional simulation of ground temperature distribution at a peat plateau–fen border for MAGTs produced by the Churchill 1971–2000 normal. We also show the frost table after 20 years of thawing under a sudden switch to the 2006 extreme warm year conditions. The simulation assumes that snow having a thermal effect equivalent to the Mary Lake snowdrift accumulates beside the peat plateau. The thawing penetrates the thinner peat at the edge of the plateau but does not proceed into the thick peat toward the plateau interior. Although the model confirms that the peat plateau remains frozen, the thawing at the plateau edge would be accompanied by subsidence, especially once the thawing penetrates the excess ice that is typically concentrated in the mineral soil immediately beneath the peat. Thus, the thermal conductivity of the peat at the edge of the plateau would increase, allowing the thawing to progress toward the plateau interior. An elongated pond parallel to the plateau edge may form in response to the subsidence and serve as a sign that plateau degradation is in progress. Elongated ponds bordering peat plateaus are present between Churchill and the Nelson River (Fig. 9), and a comparison of aerial images shows that the transformation of peat plateau to fen is occurring to a

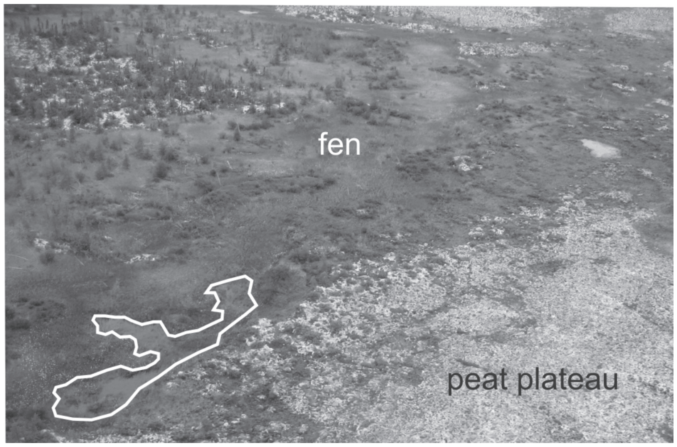

FIG. 9. A peat plateau–fen boundary near Mary Lake (see Fig. 2 for location). Note the possible subsidence pond outlined in white. The approximate distance across the bottom of the photo is 100 m.

limited extent in this area (Fig. 10). Carried on indefinitely, this process would ultimately lead to the collapse of the entire peat plateau.

Although the simulation of peat plateau thaw (Fig. 8) is for conditions that are unusual at present, the peat terrain closer to Gillam is more likely to experience the conditions similar to the Churchill 2006 extreme warm year. Furthermore, given the indicated warming in MAAT of approximately 1˚C that appears to occur only a few kilometers inland from Hudson Bay, the onset of peat plateau conversion to fen may occur farther north in the Hudson Bay lowland than would be suggested by the regional air temperature gradient. In Figure 11, we show a comparison between MAATs based on the 1971−2000 climate normal and the 2006 warm year for climate stations within or near the Hudson Bay lowland. The -3.5˚C MAAT isotherm has moved northward almost to Churchill under the 2006 conditions. If recent warming trends for the northern Hudson Bay lowland continue, MAATs warmer than -3.5˚C will occur with increasing frequency over most of this region.

Peatland Lakes

The susceptibility of frozen peat to thermokarst subsidence and erosion, the low topographic gradient, and subtle topographic rises formed by beach ridges buried by peat all contribute to the existence of the vast numbers of lakes and ponds that cover the northern Hudson Bay lowland. In addition to the peat plateau collapse induced by climate warming, lakes appear to act as an agent of peat plateau degradation. There are several areas of up to 100 km^2 where lakes with longest dimensions of 1 to 2 km constitute up to 50% of the terrain (Fig. 2). These larger lakes are all located in the polygonal peat plateau area of the northern lowland and appear to be enlarging by wave erosion of the peat bank shorelines (Fig. 12). Although a systematic analysis of lakeshore changes has not been made, a few comparisons between 1947 and 2005 aerial images of individual lakes in the peat plateau area indicate average erosion rates of as high as 2 m per year.

Lake formation in the peat plateau terrain may be initiated by thermokarst subsidence at ice wedge troughs (Dredge and Nixon, 1979). The lakes then enlarge to reach a critical fetch at which wave erosion becomes a significant contributor to their continued expansion. The sensitivity of these lake shorelines to erosion is probably controlled by permafrost. Where lakes are shallow enough to sustain permafrost, the sub-bottom permafrost is continuous with the adjacent shore permafrost, thereby maintaining resistance to erosion. If permafrost in the lake bottom degrades, subsidence at the shoreline will expose thawed peat to erosion. For lake-bottom permafrost to degrade, the lake depth must be great enough to ensure that lake-bottom cooling is less than that required for permafrost. Duguay and Lafleur

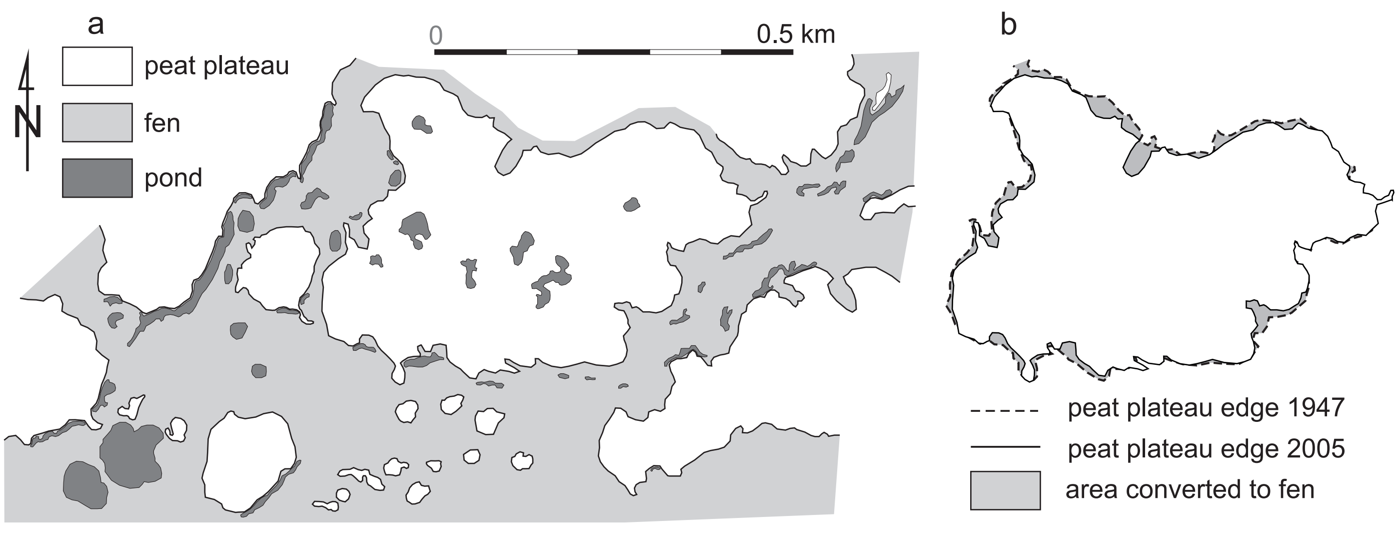

FIG. 10. a) A simplified map of the peat plateau and fen distribution approximately 25 km north of Roberge Lake (see Fig. 2 for location), interpreted from a 2005 Google Earth image. Note the elongated ponds bordering the peat plateaus. b) A comparison of the 1947 (interpreted from National Air Photo Library photo A14218–42) and the 2005 outlines of the central peat plateau in a). The grey bordering area is the part of the 1947 peat plateau that has been converted to fen.

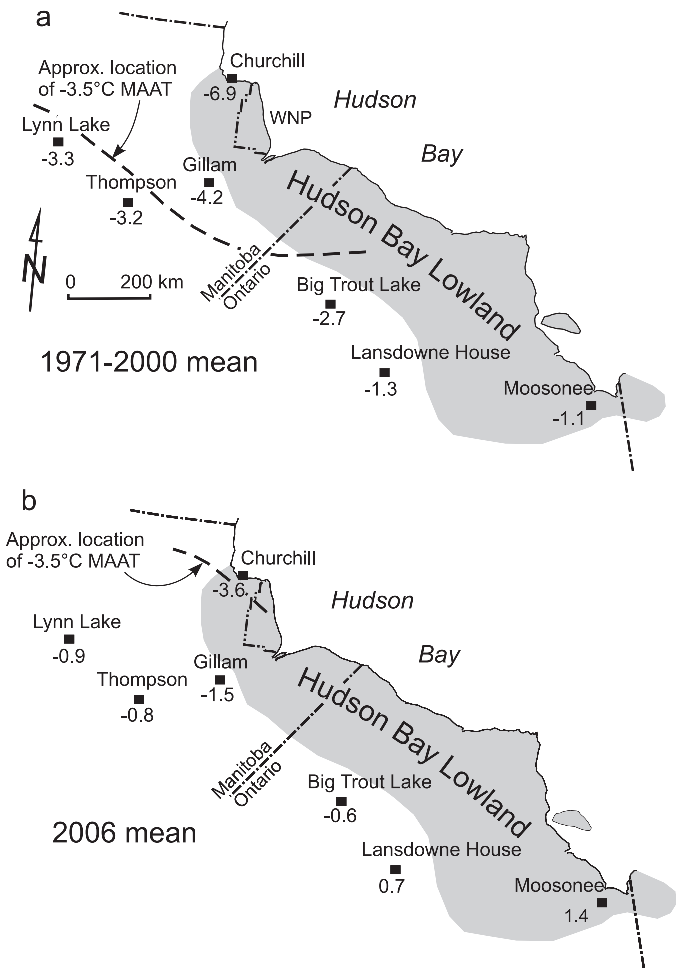

FIG. 11. a) Mean annual air temperatures for 1971–2000 for the available climate stations in the Hudson Bay lowland region. b) The same temperature for 2006, the year with the highest MAAT for the period of record at Churchill. The isotherm for -3.5˚C, the maximum temperature that ensures preservation of permafrost in peat plateaus (Halsey et al., 1995), is shown on both maps. WNP stands for Wapusk National Park.

(2003) note a maximum measured ice thickness of 1.6 m in lakes within 10 km of the Hudson Bay coast between Churchill and the Nestor One outpost (See Fig. 2 for the location of Duguay and Lafleur's study area). Thus the maximum lake depth that will allow the formation of permafrost is probably somewhat less than 1.6 m, given that sufficient freezing into the lake bottom is required to ensure that the lake bottom remains frozen after the subsequent summer thaw. The ground temperatures at our Fletcher Lake pond site show that even a very shallow pond produces significant warming.

Lake depths in the northern Hudson Bay lowland are poorly known save for the area examined by Duguay and Lafleur (2003). For lakes up to 1 km in diameter, the depths range up to about 1 m; for larger diameter lakes, the depths range to about 2 m. Raised beaches typically impound these lakes; hence, depths are probably limited to the relief of beach ridge crests above intervening swales. Inland lakes are incised into peat but probably lie on the same non-organic surface. Inland lakes would therefore have the same

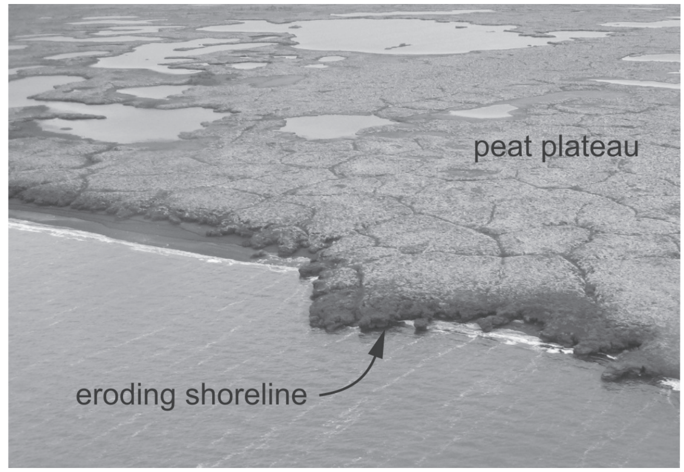

FIG. 12. The eroding shoreline of a lake in the peat plateau area of the northern Hudson Bay lowland. The shoreline segment is about 100 m long.

depth control as the lakes in the Duguay and Lafleur (2003) study area, with additional depth provided by the thicker peat. Therefore, it is unlikely that permafrost exists beneath the large lakes in the peat plateau area of the northern Hudson Bay lowland.

Ground electrical conductivity measurements using electromagnetic induction can distinguish frozen from unfrozen terrain and were used to confirm the sensitivity of permafrost occurrence to lake depth (Fig. 13). On the coast near the Nestor One outpost (Fig. 13a), where lakes are less than 1 m deep, the conductivities are typically lowest across lakes, suggesting freezing to the bottom and permafrost beneath. Using Fletcher Lake as an example of a deeper peat plateau area lake (Fig. 13b), the highest conductivities coincide with the lake, indicating the presence of unfrozen water. The conductivity response over Fletcher Lake is likely muted by the intervening ice and snow at the time of the survey, requiring a significant talik to produce the observed value. Hence permafrost is very likely absent beneath this lake bottom.

Consequences of Lake Enlargement

As lakes enlarge, the chances for lake drainage increase because of the intersection with fens, streams, or other lakes. A considerable number of lakes in both the Fletcher Lake and the Roberge Lake areas exhibit fen-like margins, suggesting partial drainage. An examination of aerial images shows that many lakes have developed enlarged fen-like margins over the same 58-year time interval used to detect shoreline erosion. These enlarging fen-like margins contrast with the margins of lakes in groupings of similar size in the southern part of the Hudson Bay lowland, where permafrost is only sporadic or absent. There, the lakeshores are typically sharply defined, lacking the fen-like fringes seen in Wapusk National Park. The difference in the lake appearance may relate to the role played by permafrost in allowing the lakes in permafrost peatland to expand by shoreline erosion and eventually to drain.

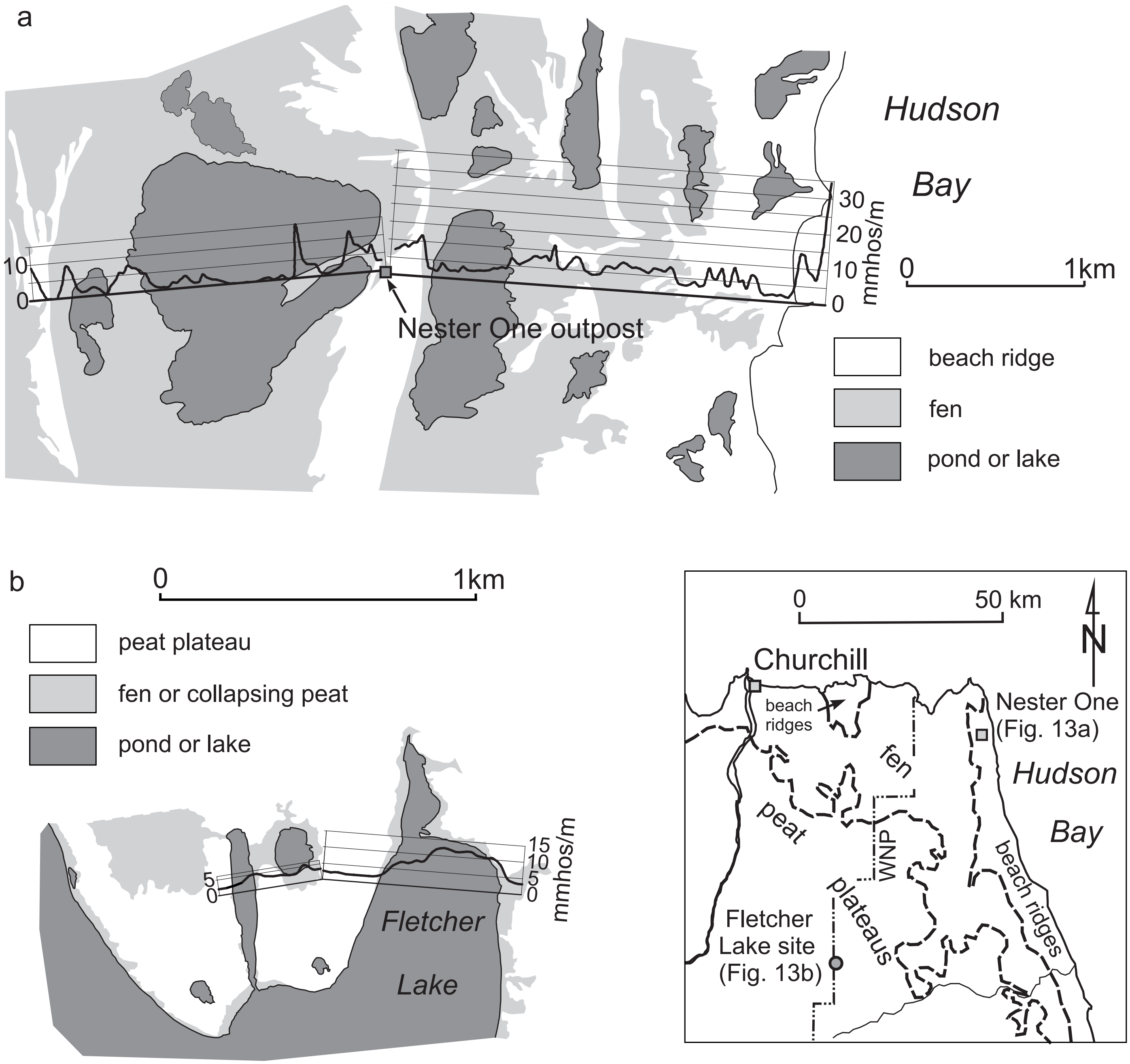

FIG. 13. The electrical conductivity profiles across lakes and intervening terrain for a) a coastal area of beach ridges and fen with lakes typically less than 1 m deep and b) an area dominated by peat plateaus, with the lakes typically deeper than 1 m. The inset map shows the profile locations. The unit of electrical conductivity is millimhos per meter (mmhos/m).

Lake enlargement becomes more likely as the peat layer thickens. This is because the increasing height of the lakeshore peat bank permits a deepening snowdrift, increasing the insulating effect of the snow. For the peatland lakes to enlarge, a lakeshore just high enough to accumulate snowbanks capable of initiating thaw (Fig. 14) may suffice. Eventual lake drainage may allow permafrost to re-establish and peat accumulation to resume. At present, lake enlargement is probably more effective in reducing peat plateau area than thawing at fen-peat plateau boundaries.

CONCLUSIONS

Permafrost is widespread in the Hudson Bay lowland near Churchill but becomes restricted to peat plateaus in the vicinity of the Nelson River estuary. The zone of peat plateau degradation and transformation to fen identified by Halsey et al. (1995) may already extend into areas north of the Nelson River. MAGT predictions suggest that thawing of fen adjacent to peat plateaus will occur for MAATs cooler than the -3.5˚C maximum MAAT that Halsey et al. (1995) determined is necessary to maintain bog permafrost. If the

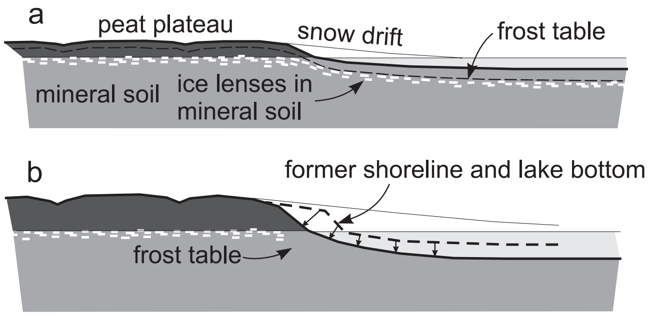

FIG. 14. An inferred cross-section of a peat plateau bordering a lake. a) The snowdrift in the lee of the shore is insufficiently deep to initiate thaw in the lake sub-bottom permafrost. b) A lake bordering thicker peat. The deeper snow has resulted in thawing and subsidence along the lakeshore (small arrows), which increase the exposure of the shore to wave erosion.

peat plateau to fen transition is taking place north of the zone mapped by Halsey et al. (1995), the thermal modeling suggests that under present climatic conditions, the process is slow. With continued warming, however, the modeling also suggests that subsidence at the plateau edges will become pronounced and accelerate the subsidence process. A threshold MAAT may even be reached at which thawing of peat plateau surfaces may begin. The myriad ponds that typically dot the plateau surfaces may be the initial sites of this thaw, augmenting the thaw that would be occurring at the plateau edges. Plateau edge collapse appears to be starting in the northern Hudson Bay lowland and will likely accelerate if abnormally warm years occur more frequently than at present. In the meantime, erosion along the windward shores of the larger lakes is at present providing a more effective mechanism of peat plateau degradation.

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