PERMAFROST THAW ACCELERATES IN BOREAL PEATLANDS DURING LATE-20TH CENTURY CLIMATE WARMING

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Abstract. Permafrost covers 25% of the land surface in the northern hemisphere, where mean annual ground temperature is less than 0°C. A 1.4–5.8 °C warming by 2100 will likely change the sign of mean annual air and ground temperatures over much of the zones of sporadic and discontinuous permafrost in the northern hemisphere, causing widespread permafrost thaw. In this study, I examined rates of discontinuous permafrost thaw in the boreal peatlands of northern Manitoba, Canada, using a combination of tree-ring analyses to document thaw rates from 1941–1991 and direct measurements of permanent benchmarks established in 1995 and resurveyed in 2002. I used instrumented records of mean annual and seasonal air temperatures, mean winter snow depth, and duration of continuous snow pack from climate stations across northern Manitoba to analyze temporal and spatial trends in these variables and their potential impacts on thaw. Permafrost thaw in central Canadian peatlands has accelerated significantly since 1950, concurrent with a significant, late-20th-century average climate warming of +1.32 °C in this region. There were strong seasonal differences in warming in northern Manitoba, with highest rates of warming during winter (+1.39 °C to +1.66 °C) and spring (+0.56 °C to +0.78 °C) at southern climate stations where permafrost thaw was most rapid. Projecting current warming trends to year 2100, I show that trends for north-central Canada are in good agreement with general circulation models, which suggest a 4–8 °C warming at high latitudes. This magnitude of warming will begin to eliminate most of the present range of sporadic and discontinuous permafrost in central Canada by 2100.

1. Introduction

Permafrost covers 25% of the land surface in the northern hemisphere, where mean annual ground temperature is less than 0 °C (Brown et al., 1998; Zhang et al., 1999). A 1.4–5.8 °C warming in mean annual air temperature by 2100 (IPCC, 2001) will dramatically impact regions underlain with permafrost. Inversions of borehole temperature profiles have documented 20th-century warming anomalies of 2–4 °C across Alaska, Canada, northern Europe, and Russia (Lachenbruch and Marshall, 1986; Beltrami and Mareschal, 1991; Majorowicz, 1996; Pollack et al., 1998; Majorowicz and Skinner, 2001; Zhang et al., 2001). At the southern boundary of permafrost in the boreal biome, warming will likely change the sign of mean annual air and ground temperatures over most of the zone of sporadic and discontinuous permafrost in the northern hemisphere, causing widespread permafrost thaw (Anisimov and Nelson, 1996; Nelson et al., 2002; Stendel and Christensen, 2002).

Understanding the potential impact of climate warming on permafrost is essential for the prediction of future responses and feedbacks in the land surface–climate

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system (IPCC, 2001; Zhuang et al., 2003), especially if responses to permafrost thaw differ between lowland versus upland ecosystems, as recent evidence suggests. In peatlands and low-lying tundra, permafrost thaw and attendant shifts to wetter conditions may induce regional and global cooling by increasing carbon sequestration by *Sphagnum* mosses and sedges in thaw pools (Trumbore and Harden, 1997; Waelbroeck et al., 1997; Camill, 1999a; Robinson and Moore, 2000; Turetsky et al., 2000; Camill et al., 2001), raising summer and winter albedo by reducing forest cover (Camill, 1999b; Lynch et al., 1999; Lloyd et al., 2003), and shifting net energy partitioning in summer from sensible to latent heat fluxes (Lynch et al., 1999; Baldocchi et al., 2000; Chapin et al., 2000a; Eugster et al., 2000). In contrast, if permafrost thaw in better-drained boreal and tundra uplands creates warmer and drier soil conditions, this may amplify climate warming through increased rates of afforestation (Lloyd et al., 2003) and lowered albedo in drier sites, reduced evapotranspiration and shifts to sensible heat fluxes (Baldocchi et al., 2000), decreased summer ground heat fluxes (Eugster et al., 2000), and increased decomposition and the release of soil C (Billings, 1987; Oechel et al., 1993; Goulden et al., 1998; Stieglitz et al., 2000), although nitrogen mineralization associated with increased decomposition may slow or reverse ecosystem C loss (Oechel et al., 2000; Stieglitz et al., 2000; Melillo et al., 2002).

Relating changes in mean annual air temperature to rates of permafrost warming and thaw is challenging because soil thermal conditions are also strongly controlled by a combination of lithology, vegetation, snow depth and duration, and disturbances (Brown and Péwé, 1973; Smith, 1975; MacKay, 1995; Smith and Riseborough, 1996, 2002; Harris et al., 2003; Stieglitz et al., 2003). To incorporate these effects, the relationship between mean annual air temperature and the temperature at the top of permafrost is often modeled using equations (n-factors) that explicitly scale air temperature by the effects of vegetation, snow depth, and lithological differences in thermal conductivity (Lunardini, 1978; Jorgensen and Kreig, 1988; Smith and Riseborough, 1996, 2002). Such models have proven to be a robust method for generalizing climate–permafrost relationships (Romanovsky and Osterkamp, 1995; Smith and Riseborough, 1996, 2002). Although permafrost is ultimately a climatic phenomenon (Zhang and Stamnes, 1998; Smith and Riseborough, 2002), these models suggest that lithological conditions (e.g., peat vs. mineral soil) exert a dominant control on permafrost temperatures followed by snow cover and vegetation. Notably, peatlands often support the southernmost extent of permafrost, in regions as warm as $+1.0$ to $+1.5$ °C mean annual air temperature because of the large thermal offset created by dry, insulating peat (Brown and Péwé, 1973; Smith and Riseborough, 2002). In contrast, mean annual air temperatures greater than -2.0 °C represent the threshold for the disappearance of permafrost in mineral soils (Smith and Riseborough, 2002). Other numerical models using fixed lithological conditions have shown the importance of snow depth and duration on active layer and permafrost temperatures (Goodrich, 1982; Ling and Zhang, 2003; Oelke et al., 2003; Stieglitz et al., 2003).

The disappearance of permafrost with climate warming will likely occur most rapidly in the regions of sporadic and discontinuous permafrost to the south (Osterkamp and Romanovsky, 1999). Boreal peatlands located throughout the northern hemisphere offer a unique method for monitoring rates of permafrost thaw and the potential impacts of climate in this region because thaw in peatlands causes a dramatic change in land cover that is easily detectible (Thie, 1974; Camill and Clark, 1998; Osterkamp et al., 2000; Jorgenson et al., 2001). Permafrost plateaus rise 1–3 m above the regional water table because of the volumetric expansion of frozen peat and are dominated almost exclusively by *Picea mariana* trees with a feathermoss understory (Camill, 1999b). Plateau thaw is initiated by fire and other physical disturbances that cause subsidence and the formation of wet thermokarst basins (collapse scars) not underlain by permafrost and dominated by a treeless cover of *Sphagnum* mosses and *Carex spp*.(Camill, 1999b). Because of the high heat capacity and substantial ground heat fluxes in thaw ponds during summer (Rouse, 2000; Harris, 2002), collapse scars and other types of unfrozen peatlands expand laterally through time by thawing surrounding permafrost plateaus, causing *Picea* trees to lean toward the thawing edge and eventually to subside and drown as the thawing margin passes. Rates of lateral thaw can be measured using aerial photography (Thie, 1974; Laberge and Payette, 1995; Beilman et al., 2001; Jorgenson et al., 2001), records of frost or compression rings in *Picea* trees (Englefield, 1994; Camill and Clark, 1998), or by direct measurement using permanent benchmarks surveyed through time, all of which provide direct, visual field evidence of permafrost thaw.

In this study, I analyzed changes in mean annual air temperature, mean seasonal differences in air temperature, snow depth and duration, and permafrost thaw across the discontinuous permafrost zone in northern Manitoba, Canada, to determine the magnitude of recent change in these variables and the likelihood that climate warming is impacting thaw rates.

2. Methods

2.1. GENERAL APPROACH AND STUDY REGION

Given the influences of lithology, snow cover, vegetation, and disturbance on the climate–permafrost relationship, I developed an approach to examine the effects of climate warming on permafrost thaw in peatlands by holding confounding variables roughly constant across climatic changes in space and time. I examined 21 peatland sites located in four study regions spanning a climatic gradient of $\sim$4 °C, including most of the sporadic and discontinuous permafrost zones, in northern Manitoba, Canada (Figure 1). Instrumented records of air temperature, mean winter snow depth (December–March), and duration of continuous snow pack were obtained from five climate stations (Environment Canada, 2002) in northern Manitoba, including

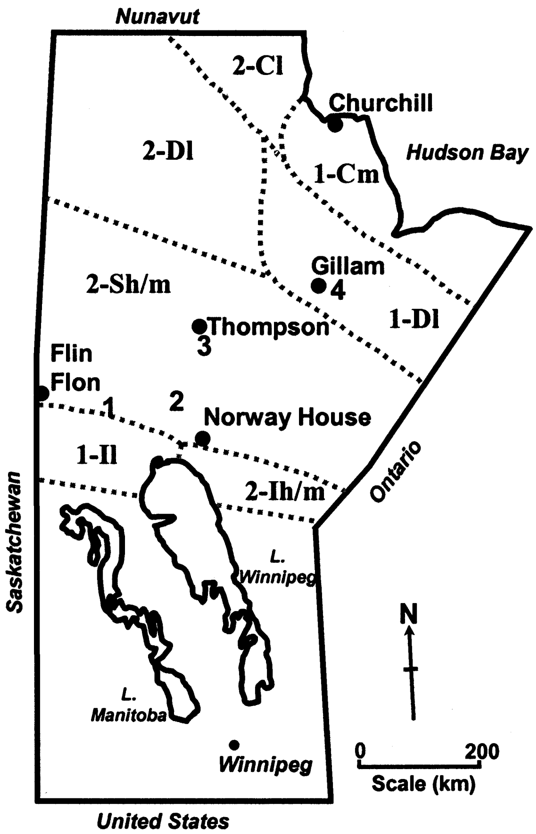

Figure 1. Location of climate stations (Flin Flon, Norway House, Thompson, Gillam, Churchill) and permafrost study regions (1 = Snow Lake, 2 = Wabowden, 3 = Thompson, 4 = Gillam) in northern Manitoba, Canada. Dotted lines represent permafrost coverage classification adapted from Brown et al. (1998): Surficial Geology: 1 = Lowlands, highlands, and intra- and intermontaine depressions characterized by thick overburden cover (>5–10 m), 2 = Mountains, highlands, ridges, and plateaus characterized by thin overburden cover (<5–10 m) and exposed bedrock; Permafrost extent: C = Continuous (90–100%), D = Discontinuous (50–90%), S = Sporadic (10–50%), I = Isolated Patches (0–10%); Ground Ice Content (visible ice in the upper 10–20 m of the ground; percent by volume): *h* = high (>20%), *m* = medium (10–20%), h/m = high to medium (>10%), l = low (0–10%).

Churchill in the continuous permafrost zone, located nearest to the four permafrost study regions (Figure 1). Climate records included the period AD ~1970–2000, the longest period for which continuous data existed at all five stations. The relatively uniform boreal bog vegetation cover (*P. mariana* monocultures) and lithology (*Sphagnum*/feathermoss peat 2–4 m in depth) minimized variability in ecosystem structure and soil properties across sites (Camill, 1999a, b). Fire disturbance was eliminated as a source of thaw variability by using macrofossil and charcoal analyses of ^{210}Pb-dated peat cores from these sites to show that late-20th Century permafrost degradation was not caused by fire (Camill, 1999a).

2.2. MEASURING PERMAFROST THAW RATES

Permafrost thaw rates were determined using two methods. The first method used compression rings formed in *P. mariana* trees (Camill and Clark, 1998). In general, thawing permafrost plateau margins slope from the relatively flat surface of the plateau to the thawed collapse scar below. The horizontal and vertical dimensions of the slope were not measured explicitly but were usually <2 m. Trees on permafrost plateaus are forced to lean along the slope as the thaw margin expands, and they die on reaching the thawed, inundated collapse scars at the bottom (Camill and Clark, 1998; Camill, 1999a, b). Only live trees currently on the thaw slope were analyzed in this study. Compressional growth rings formed as wide, lignified bands on the downslope side of the stem as a mechanism for restoring vertical growth, and the number of compression rings laid down indicated the number of years of leaning by each tree. Once trees began leaning along the thaw margin slope, compression wood formation was continuous, prominent, and directionally coherent among all trees along a thaw margin, indicating unambiguously that these outer compression rings were not formed by other processes. I measured the distance of each tree along the slope to the top margin of the permafrost plateau (cm), and dividing this distance by the number of compression rings yielded an estimate of thaw rate (cm yr^{-1}). Across the four study zones (Figure 1), a total of 75 trees were sampled in 21 sites (12 trees/4 sites in Snow Lake, 23 trees/5 sites in Wabowden, 29 trees/5 sites in Thompson, and 11 trees/7 sites in Gillam). Site-based mean values of thaw rate were also calculated by averaging the thaw rates recorded by individual trees for each site.

For the second method, I used a 2-m steel probe to identify the exact location of the permafrost plateau/collapse scar margin at each site in late August 1995, and I drove a permanent stake $\sim$75cm into the peat to mark the position of the 1995 margin. Between 1995–2002, I visited each site semi-annually to make sure the benchmarks had not been removed or damaged by animals. During late August 2002, I measured the distance from each benchmark to the permafrost plateau/collapse scar margin. I report thaw rates for each site during the median year of this 7-yr period (1999). This approach offers one of the most direct assessments of permafrost thaw across climatic changes in space (northern Manitoba) and time (AD 1941–2002).

2.3. STATISTICAL ANALYSIS OF THAW RATE AND CLIMATE DATA

Permafrost thaw rates were analyzed using three statistical tests. First, thaw rates were modeled as a linear function of calendar year using likelihood functions with normal error to generate maximum likelihood estimates for fitted slopes. To test whether the correlation coefficients, r, and slopes, B, of the permafrost thaw–time relationships were significantly different than zero, I developed a robust, nonparametric procedure based on bootstrap resampling (Efron and Tibshirani, 1993). For each study region, thaw data were resampled 1000 times to bootstrap 95% confidence intervals on r and B. Significant correlations and slopes that differed from zero were identified by values lying outside the confidence intervals. The bootstrapping method for testing significance was used instead of classical t-tests employed in linear modeling because the individual tree data were partially autocorrelated (some sites have more than one tree represented), which violated the assumption of data independence. To ensure the robustness of these results, I also averaged thaw rates for individual trees into site averages and repeated the linear modeling using these data. Slopes were consistently significant ($p < 0.05$) in all four study regions and indistinguishable from those based on individual trees (data not shown). Second, using mean values of thaw for the 21 sites based on tree rings (1941–1991) and benchmark surveys (1995–2002), I conducted a repeated-measured analysis of variance (ANOVA) to determine if thaw rate changed significantly in each study region. Third, I tested for significant differences in thaw acceleration among study regions (H_o: $B_1 - B_2 = 0$, H_a: $B_1 - B_2 \neq 0$) by calculating differences in B between all combinations of study regions for each of the 1000 bootstrapping simulations, and significant differences were identified by values lying outside a 95% confidence interval bounding zero.

Several analyses were conducted with instrumented temperature and snow data acquired from the five climate stations (Figure 1). Trends in mean annual air temperature, seasonal differences in mean air temperature, mean winter snow depth, and duration of continuous snowpack were analyzed using linear modeling with maximum likelihood estimation as described above. I tested for significant correlations using the bootstrapping procedure described above for permafrost thaw. Seasonal differences in mean air temperature warming have been documented previously for high latitudes (Chapman and Walsh, 1993; Serreze et al., 2000), indicating a large rise in winter and spring air temperature. Mean monthly air temperatures were grouped into four, three-month seasons following Chapman and Walsh (1993): winter (December–February), spring (March–May), summer (June–August), autumn (September–November). Seasonal changes in air temperature may significantly impact permafrost dynamics to the extent that frozen soil develops in winter and thaws in spring, when liquid water from snowmelt increases thermal conductivity of surface soils (Hinkel et al., 2001). To assess the potential for future thaw across the sporadic and discontinuous permafrost zone in Manitoba, I projected current trends in mean annual air temperature from year 1990 to 2100. For simplicity, the linear models developed for the instrumented records above were used in this analysis.

3. Results

Permafrost thaw rates have accelerated significantly across the sporadic and discontinuous zones over the past 50 years (Figure 2). Thaw rates between 1995–2002 rose 200–300% relative to rates from the period 1941–1991 measured using tree

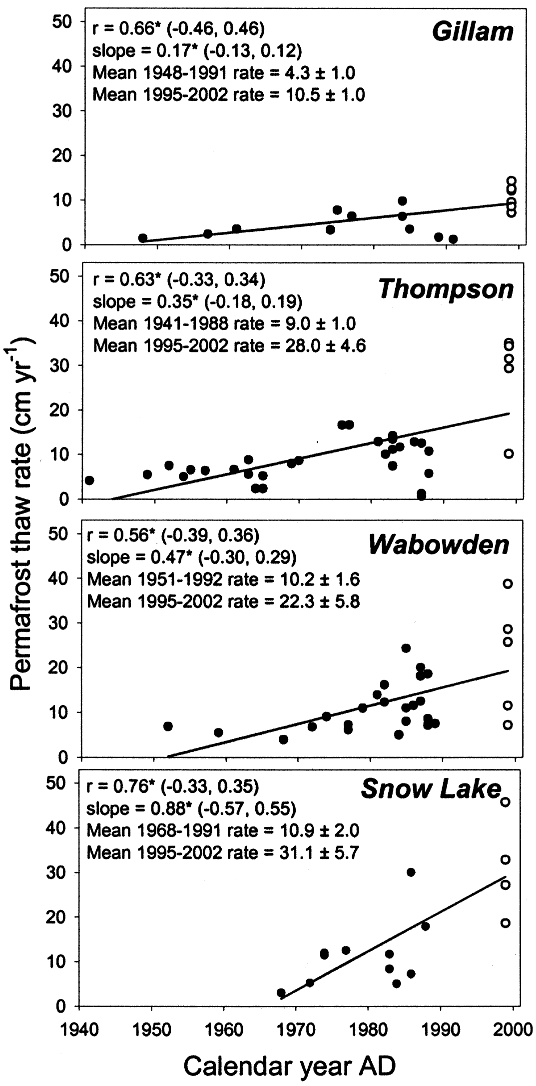

Figure 2. Permafrost thaw rate (cm yr^{-1}) plotted against time. Black dots represent thaw rate measured for the period 1941–1991 using compression rings laid down by individual leaning *P. mariana* trees. Open circles represent mean thaw rates measured using permanent benchmarks for the period 1995–2002 (plotted for the median year, 1999). Mean site thaw rates for the periods 1941–1991 and 1995–2002 are also shown. Correlation coefficients and fitted slopes with 95% confidence intervals in parentheses are also shown. Significant correlation coefficients and slopes are denoted with an asterisk.

rings. The repeated measures ANOVA indicated highly significant differences between these periods for all four study regions ($F = 26.4$, $p < 0.0001$). Individual t-tests comparing site-level thaw rates between periods 1941–1991 and 1995–2002 for each zone were all significant (Snow Lake $p = 0.02$, Wabowden $p = 0.05$, Thompson $p = 0.007$, Gillam $p = 0.0004$). Acceleration was significantly faster in Snow Lake compared to Gillam (Figure 2, $p < 0.05$) but was not significantly different among other sites.

Climate stations examined in this study revealed a large mean annual air temperature warming trend of 1.08–1.75 °C (mean = +1.32 °C) between ∼1970–2000 (Figure 3), which is consistent with rates of surface air warming in western Canada (Gullet and Skinner, 1992; Chapman and Walsh, 1993; Majorowicz and Skinner, 2001) that are more than double the globally averaged 20th-century warming of 0.6 ± 0.2 (IPCC, 2001). Annual warming trends were significant at Churchill, Gillam, and Flin Flon (Figure 3A, $p < 0.05$). Substantial warming caused the sign of mean annual air temperature to change at Flin Flon in 1990 (Figure 3), and the sign change will occur at Norway House by ∼2005. Tests for differences in slopes revealed no significant differences among the five climate stations ($p > 0.05$).

There were strong and significant seasonal differences in warming in northern Manitoba, including Thompson and Norway House, where mean annual air temperature increases were not significant (Table I). At the highest latitude climate station in Churchill, warming was significant only during summer (+0.66 °C per decade), but the highest rates of warming shifted to winter and spring at the more southerly stations (Fig. 1). At Gillam, warming was significant in winter (+1.23 °C per decade) and summer (+0.49 °C per decade), and it was significant in winter at Thompson (+0.84 °C per decade), Norway House (+1.68 °C per decade), and Flin Flon (+1.33 °C per decade). These warming trends are among the highest reported for boreal and arctic regions over the last four decades (Chapman and Walsh, 1993). Warming trends during spring months were also large, especially at the southern stations (Table I): Norway House (+0.78 °C per decade), and Flin Flon (+0.56 °C per decade). Warming rates were lowest in autumn, during which mean air temperature changed relatively little, or even declined (Norway House, Table I). It is important to note that the greatest warming rates in northern Manitoba over the past three decades occurred during winter and spring at the southern climate stations (Table I) where permafrost thaw was most rapid (Figure 2).

Analyses of snow data suggest that changes in mean snow depth and snow pack duration are not contributing to soil warming and acceleration of permafrost thaw (Figure 4). Mean winter snow depth has declined across the sporadic and discontinuous permafrost zones from ∼1970–2000, with significant declines in Thompson and Norway House (Figure 4A). Decreased snow cover should cool, rather than warm, permafrost in these regions for two reasons: Snow introduces a layer of low thermal conductivity between air and ground and, winter cooling waves are damped out by snow and have a reduced effect on ground thermal regimes (Gold, 1963; Smith, 1975; Majorowicz, 1996; Smith and Riseborough, 2002). In contrast to previous hypotheses (Majorowicz, 1996), the duration of continuous snow pack did not decline over the last three decades in this region and, in fact, increased significantly at Churchill (Figure 4B). In addition, higher mean snow depths in northern sites (Figure 4A, with the exception of Churchill) are counterbalanced by the lower mean annual air temperatures in these regions, producing similar

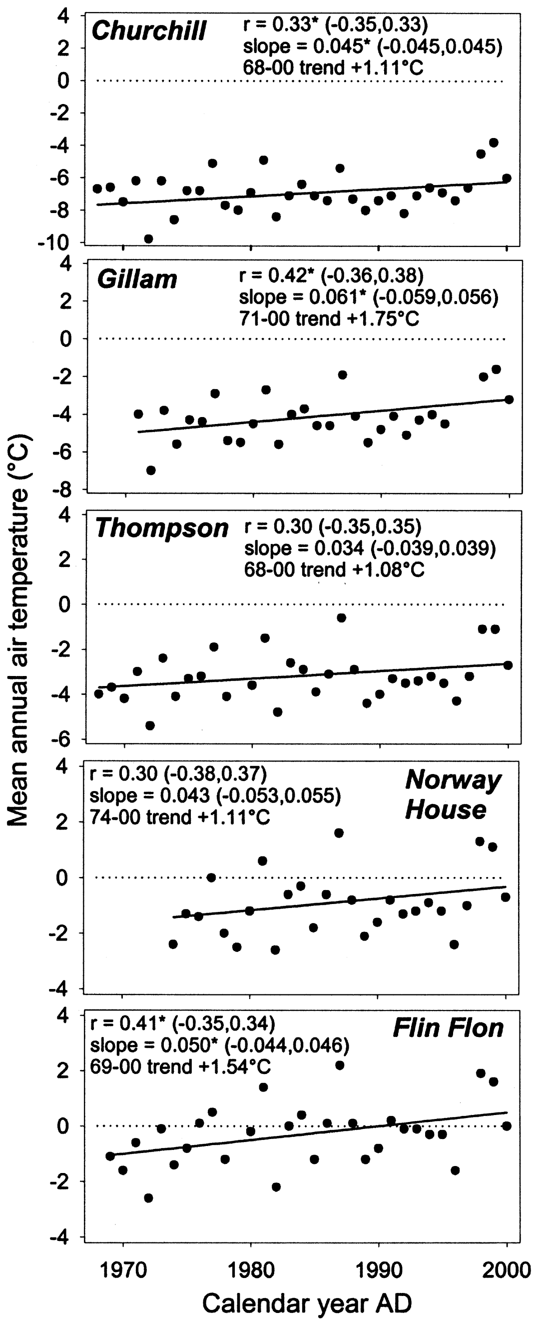

Figure 3. Changes in mean annual air temperature between ~1970–2000 for the five climate stations shown in Figure 1. The 0 °C mean annual air temperature is shown as a dotted line for reference. Correlation coefficients and fitted slopes with 95% confidence intervals in parentheses and the 1970–2000 warming trends are also shown. Significant correlation coefficients and slopes are denoted by an asterisk.

TABLE I

Trends in mean seasonal air temperature at the five climate stations over the period reported. The correlation coefficients (r) for the regressions of air temperature on time and 95% confidence intervals on r are also shown

Climate station and period	Mean seasonal air temperature trends[a]	Winter (Dec–Feb)	Spring (March–May)	Summer (June–Aug)	Autumn (Sep–Nov)
Churchill	Mean air temperature change over period	+1.34 °C	+0.73 °C	+2.11 °C	+0.01 °C
(1968–2000)	Trend per decade	+0.42 °C	+0.23 °C	+0.66 °C	∼0 °C
	r(95% CI)[b]	0.18 (−0.35, 0.33)	0.12 (−0.33, 0.33)	0.47[c] (−0.34,0.34)	0.001 (−0.34,0.34)
Gillam	Mean air temperature change over period	+3.58 °C	+1.32 °C	+1.43 °C	+0.70 °C
(1971–2000)	Trend per decade	+1.23 °C	+0.46 °C	+0.49 °C	+0.24 °C
	r(95% CI)[b]	0.45[c] (−0.35,0.36)	0.20 (−0.37,0.36)	0.36[c] (−0.34, 0.33)	0.12 (−0.32, 0.33)
Thompson	Mean air temperature change over period	+2.69 °C	+1.36 °C	+1.25 °C	+0.15 °C
(1968–2000)	Trend per decade	+0.84 °C	+0.42 °C	+0.39 °C	+0.05 °C
	r(95% CI)[b]	0.33[c] (−0.33, 0.31)	0.22 (−0.35,0.34)	0.32 (−0.34, 0.33)	0.03 (−0.34,0.34)
Norway House	Mean air temperature change over period	+4.37 °C	+2.04 °C	+1.03 °C	−0.09 °C
(1974–2000)	Trend per decade	+1.68 °C	+0.78 °C	+0.40 °C	−0.03 °C
	r(95% CI)[b]	0.38[c] (−0.36,0.36)	0.24 (−0.39,0.39)	0.22 (−0.38,0.40)	−0.013 (−0.40,0.40)
Flin Flon	Mean air temperature change over period	+4.12 °C	+1.74 °C	+0.99 °C	+1.01 °C
(1969–2000)	Trend per decade	+1.33 °C	+0.56 °C	+0.32 °C	+0.33 °C
	r(95% CI)[b]	0.42[c] (−0.35,0.35)	0.27 (−0.34, 0.33)	0.27 (−0.35, 0.33)	0.18 (−0.33, 0.35)

[a] A slight difference between mean annual temperature trends (Figure 3) and the average of mean seasonal trends exists because of the calculation of mean winter air temperature. Mean annual air temperature averages mean monthly temperature over a calendar year, whereas mean winter air temperature includes air temperature values for December of the previous year.

[b] Confidence intervals were determined using 1000 bootstrap simulations. Correlation coefficients that lie outside the confidence interval are significant at the $\alpha = 0.05$ level.

[c] Denotes significant correlation.

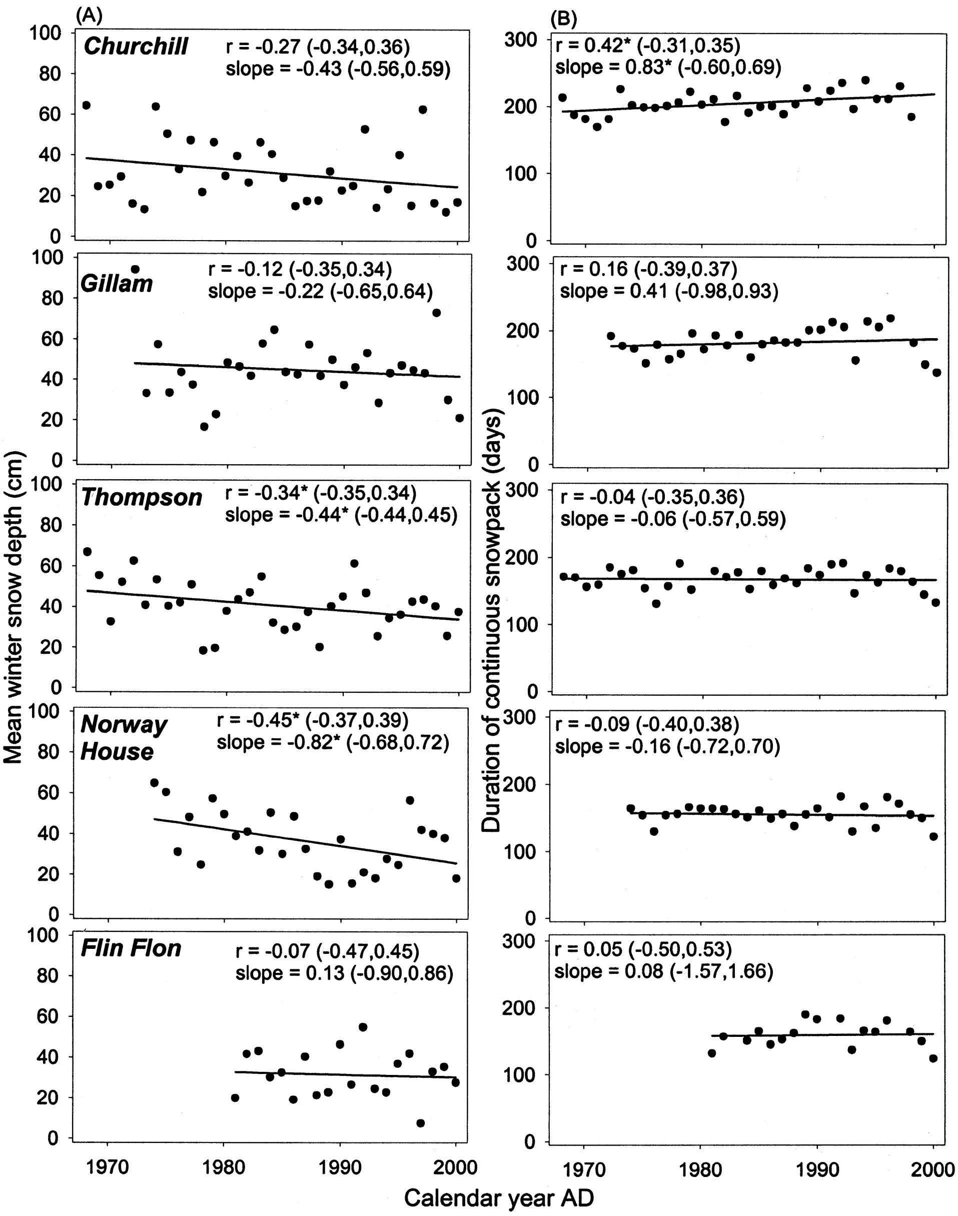

Figure 4. (A) Changes in mean winter snow depth (Dec–March) (cm) between ~1970–2000 for the five climate stations shown in Figure 1. Correlation coefficients and fitted slopes with 95% confidence intervals in parentheses are also shown. Significant correlation coefficients and slopes are denoted by an asterisk. (B) Changes in the duration of continuous snow pack (days) between ~1970–2000 for the five climate stations shown in Figure 1. Correlation coefficients and fitted slopes with 95% confidence intervals are also shown.

nival offsets across the sporadic and discontinuous permafrost zones based on the equations of Smith and Riseborough (2002). Collectively, these results indicate that changes in mean snow depth should have cooled permafrost temperatures between ~1970–2000 and that there were minimal effects on permafrost thaw as a result of regional differences in mean snow depth.

Projections of warming trends to year 2100 compared to 1990 baseline temperatures indicate that, if current warming trends continue, mean annual air temperatures in northern Manitoba will warm between 3.8–6.8 °C by 2100 (Figure 5), which is in good agreement with high latitude warming projections of 4–8 °C by general circulation models (IPCC, 2001). Assuming that a 0 °C to +1.5 °C mean annual temperature envelope represents the climatic threshold for the existence of permafrost in peatlands (Smith and Riseborough, 2002), permafrost will begin to thaw rapidly and possibly disappear across the sporadic and discontinuous permafrost zone by 2100, with significant thaw in Flin Flon between 1990–2020, Norway House between 2005–2040, Thompson between 2075–2100, and Gillam between 2050–2080. Permafrost will not disappear in Churchill, but the projected future mean annual air temperature of −2 °C (Figure 5) indicates that this region will become a zone of discontinuous permafrost, with probable widespread thaw in regions underlain with mineral soil (Smith and Riseborough, 2002). It is important to point out that these projections assume that permafrost thaw in peatlands occurs immediately on crossing the +1.5 °C mean annual air temperature threshold. Depending on the unfrozen water content and depth of the permafrost, additional time may be required for the permafrost to thaw.

4. Discussion

By eliminating the effects of snow, vegetation, lithology, and disturbance, I conclude that the significant acceleration of permafrost thaw across the sporadic and discontinuous permafrost zones in Manitoba, Canada, over the latter half of the 20th century (Figure. 2) has likely been caused by large increases in mean air temperature (Figure 3), which are especially significant in winter and spring (Table I). Significant winter warming will prohibit the formation of new permafrost, and large spring warming will accelerate thaw in this region (Hinkel et al., 2001), which may account for the greatest acceleration of permafrost thaw in southern regions experiencing the greatest warming during these seasons (Figure 2, Table I). The empirical results presented here suggest that current warming trends may eliminate most, if not all, peatland permafrost across this region by 2100 (Figure 5), supporting model predictions of large changes in discontinuous permafrost cover over the 21st century (Anisimov and Nelson, 1996; Nelson et al., 2002; Stendel and Christensen, 2002), but see Lunardini (1996).

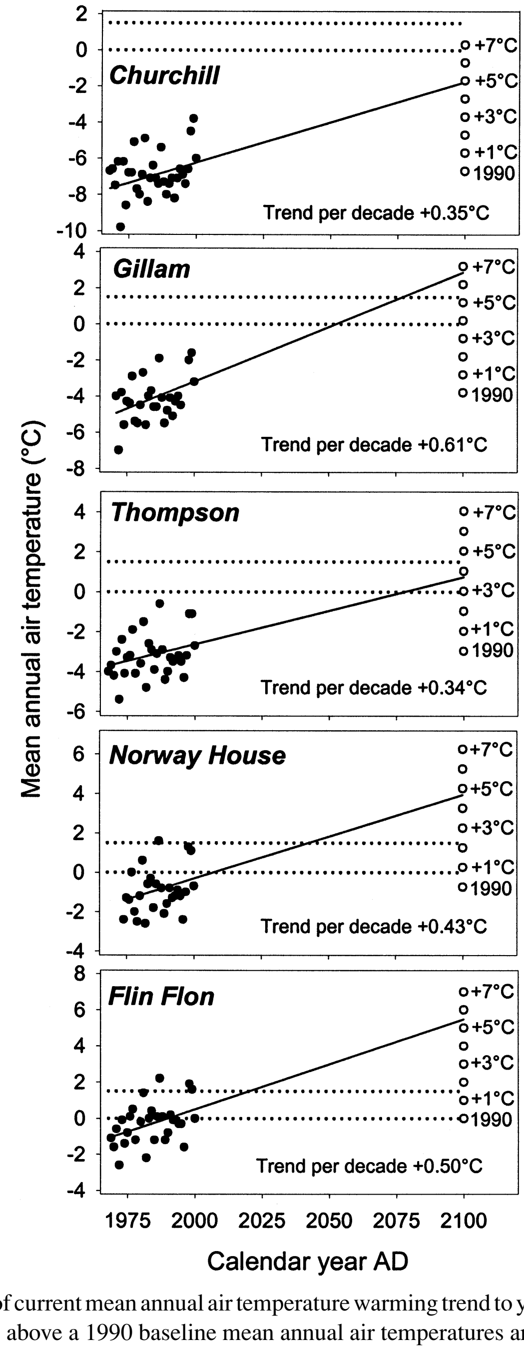

Figure 5. Projection of current mean annual air temperature warming trend to year 2100. For reference, temperature increases above a 1990 baseline mean annual air temperatures are shown along with the 0 °C to +1.5 °C climate envelope (dotted lines) representing the critical mean annual air temperatures for the disappearance of permafrost in peatlands (Smith and Riseborough, 2002).

Because of the low thermal conductivity of peat, boreal and subarctic peatlands are often viewed as ecosystems that will support the final remnants of discontinuous permafrost (Brown and Péwé, 1973; Halsey et al., 1995, Camill and Clark, 1998; Smith and Riseborough, 2002). Although permafrost thaw is generally expected to be large with climate warming (Anisimov and Nelson, 1996; Nelson et al., 2002; Stendel and Christensen, 2002), the rate of change in permafrost distribution has been debated (Halsey et al., 1995; Camill and Clark, 1998). Local factors, such as dry peat and azimuth, have been shown to slow permafrost thaw in peatlands (Camill and Clark, 1998), leading to the southernmost permafrost remnants that appear to exist out of equilibrium with climate (i.e., existing in regions between 0 °C to +1.5 °C mean annual air temperatures, Halsey et al., 1995). However, based on soil heat conduction modeling, Smith and Riseborough (2002) argued that relict permafrost in peatlands along the southern margin of the sporadic discontinuous permafrost zone is currently in equilibrium with mean annual air temperature as high as +1.5 °C because the large thermal offset caused by dry peat and other vegetation maintains mean annual ground temperature at 0 °C near the surface. The modeled mean annual air temperature threshold of +1.5 °C therefore incorporates several of the local factors that could contribute to lagged dynamics, offering a simple method for assessing the maximum length of time that permafrost can exist in peatland regions during climate warming (e.g., dotted lines in Figure 5).

Several recent studies indicate that permafrost thaw will change ecosystem properties and surface energy budgets dramatically in boreal and arctic uplands and peatlands. In boreal peatlands, carbon sequestration increases between 60–100% when Picea-dominated permafrost plateaus thaw and form *Sphagnum* and *Carex*-dominated collapse scars (Camill, 1999a; Robinson and Moore, 2000; Turetsky et al., 2000; Camill et al., 2001). Models of tundra systems suggest that permafrost thaw can initiate a long-lasting increase in carbon accumulation (Waelbroeck et al., 1997), following initial transient increases in soil CO_2 efflux that agree with experimental evidence of a short-term carbon release (Billings, 1987) as a result of tundra drying (Chapin et al., 2000b). These studies contrast with those from boreal uplands, however, which suggest that thaw may hasten decomposition from large pools of soil C (Goulden et al., 1998, Tarnocai, 1999). Several studies of net energy partitioning over boreal and arctic ecosystems suggest that surface energy changes resulting from thaw pond formation (increased winter albedo and decreased summer sensible heat flux) may be large enough to affect regional climate (Lynch et al., 1999; Chapin et al., 2000a; Eugster et al., 2000). These results may be especially pronounced in boreal permafrost peatlands, where the loss of the *P. mariana* canopy and shifts to treeless bogs following thaw could have substantial effects on surface energy budgets. To the extent that these land surface–atmosphere interactions are tightly coupled in the Northern Hemisphere (Eugster et al., 2000), accelerating permafrost thaw will likely initiate complex feedbacks on high latitude and global temperatures.

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References

Anisimov, O. A. and Nelson, F. E.: 1996, 'Permafrost distribution in the Northern Hemisphere under scenarios of climatic change', *Global Planetary Change* **14**(1–2), 59–72.

Baldocchi, D., Kelliher, F. M., Black, T. A., and Jarvis, P.: 2000, 'Climate and vegetation controls on boreal zone energy exchange', *Global Change Biol.* **6**(Suppl 1), 69–83.

Beilman, D. W., Vitt, D. H., and Halsey, L. A.: 2001, 'Localized permafrost peatlands in western Canada: definition, distributions, and degradation', *Arctic Antarctic Alpine Res.* **33**(1), 70–77.

Beltrami, H. and Mareschal, J. C.: 1991, 'Recent warming in eastern Canada inferred from geothermal measurements', *Geophys. Res. Lett.* **18**(4), 605–608.

Billings, W. D.: 1987, 'Carbon balance of Alaskan tundra and taiga ecosystems: past, present, and future', *Quaternary Sci. Rev.* **6**, 165–177.

Brown, R. J. E. and Péwé, T. L.: 1973, 'Distribution of permafrost in North America and its relationship to the environment: A review 1963–1973', in *Proceedings of the 2nd International Conference on Permafrost*, *Yakutsk, USSR*, North American contribution. Washington, DC, National Academy of Science, pp. 71–100.

Brown, J., Ferrians, Jr., O. J., Heginbottom, J. A., and Melnikov, E. S.: 1998, 'Digital circum-Arctic map of permafrost and ground-ice conditions', in *International Permafrost Association, Data and Information Working Group, Comp. Cimcumpolar Active-Layer Permafrost System (CAPS)* Version 1.0.

Camill, P.: 1999a, 'Peat accumulation and succession following permafrost thaw in the boreal peatlands of Manitoba, Canada', *Ecoscience* **6**(4), 592–602.

Camill, P.: 1999b: 'Patterns of boreal permafrost peatland vegetation across environmental gradients sensitive to climate warming', *Can. J. Bot.* **77**(5), 721–733.

Camill, P. and Clark, J. S.: 1998, 'Climate change disequilibrium of boreal permafrost peatlands caused by local processes', *Am. Nat.* **151**(3), 207–222.

Camill, P., Lynch, J. A., Clark, J. S., Adams, J. B., and Jordan, B.: 2001, 'Changes in biomass, aboveground NPP, and peat accumulation following permafrost thaw in the boreal peatlands of Manitoba, Canada', *Ecosystems* **4**, 461–478.

Chapin, III, F. S., Eugster, W., McFadden, J. P., Lynch, A. H., and Walker, D. A.: 2000a, 'Summer differences among Arctic ecosystems in regional climate forcing', *J. Climate* **13**(12), 2002–2010.

Chapin, III, F. S., McGuire, A. D., Randerson, J., Pielke, R., Baldocchi, D., Hobbie, S. E., Roulet, N., Eugster, W., Kasischke, E., Rastetter, E. B., Zimov, S. A., and Running, S. W.: 2000b, 'Arctic and boreal ecosystems of western North America as components of the climate system', *Global Change Biol.* **6** (Suppl 1), 211–223. Chapman, W. L. and Walsh, J. E.: 1993, 'Recent variations of sea ice and air temperature in high latitudes', *Bull. Am. Meteorol. Soc.* **74**, 2–16.

Efron, B. and Tibshirani, R.: 1993, *An Introduction to the Bootstrap,* Chapman and Hall, New York.

Englefield, P. G. C.: 1994, *Rate of Permafrost Degradation in Peatlands*. M.S. Thesis. University of Alberta, Edmonton.

Environment Canada: 2002, '*Canadian Daily Climate Data: Temperature and Precipitation, Western Canada 2000',* Climate Products and Publications Division Atmospheric, Climate, and Water Systems Branch, Atmospheric Environment Service, Downsview, ON.

Eugster, W., Rouse, W. R., Pielke, R. A., McFadden, J. P., Baldocchi, D. D., Kittel, T. G. F., Chapin, F. S., Liston, G. E., Vidale, P. L., Vaganov, E., and Chambers, S.: 2000, 'Land-atmosphere energy exchange in Arctic tundra and boreal forest: Available data and feedbacks to climate', *Global Change Biology* **6**(Suppl 1), 84–115.

Gold, L. W.: 1963, 'Influence of snow cover on the average annual ground temperature at Ottawa, Canada', *Int. Assoc. Sci. Hydrol.* **61**, 82–91.

Goodrich, L. E.: 1982, 'The influence of snow cover on the ground thermal regime', *Can. Geotechnical J.* **19**(4), 421–432.

Goulden, M. L., Wofsy, S. C., Harden, J. W., Trumbore, S. E., Crill, P. M., Gower, S. T., Fries, T., Daube, B. C., Fan, S. M., Sutton, D. J., Bazzaz, A., and Munger, J. W.: 1998, 'Sensitivity of boreal forest carbon balance to soil thaw', *Science* **279**, 214–217.

Gullet, D.W. and Skinner, W.R.: 1992: 'The state of Canada's Climate: Temperature change in Canada 1895–1991', Environment Canada, SOE Report No. 92–2, pp. 35.

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**(1), 57–73.

Harris, S. A.: 2002, 'Causes and consequences of rapid thermokarst development in permafrost or glacial terrain', *Permafrost Periglacial Process.* **13**(3), 237–242.

Harris, C., Vonder Muhll, D., Isaksen, K., Haeberli, W., Sollid, J. L., King, L., Holmlund, P., Dramis, F., Guglielmin, M., and Palacios, D.: 2003, 'Warming permafrost in European mountains', *Global Planetary Change* **39** (3, 4), 215–225.

Hinkel, K. M., Paetzold, F., Nelson, F. E., and Bockheim, J. G.: 2001, 'Patterns of soil temperature and moisture in the active layer and upper permafrost at Barrow, Alaska: 1993–1999', *Global Planetary Change* **29**(3, 4), 293–309.

Intergovernmental Panel on Climate Change (IPCC): 2001, '*Climate Change 2001: The Scientific Basis*', Cambridge University Press, Cambridge.

Jorgensen, M. T. and Kreig, R. A.: 1988, 'A model for mapping permafrost distribution based on landscape component maps and climatic variables', in *Proceedings of the Permafrost: Fifth International Conference, Trondheim, Norway,* Vol. 1. Tapir Publishers, Trondheim, Norway, pp. 176–182.

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**(4), 551–579.

Laberge, M. J. and Payette, S.: 1995, 'Long-term monitoring of permafrost change in a palsa peatland in northern Quebec, Canada: 1983–1993', *Arctic Alpine Res.* **27**(2), 167–171.

Lachenbruch, A. H. and Marshall, B. V.: 1986, 'Changing climate: Geothermal evidence from permafrost in the Alaskan Arctic', *Science* **234**, 689–696.

Ling, F. and Zhang, T. J.: 2003, 'Impact of the timing and duration of seasonal snow cover on the active layer and permafrost in the Alaskan Arctic', *Permafrost Periglacial Process* **14**(2), 141–150.

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 Periglacial Process* **14**(2), 93–101.

Lunardini, V. J.: 1978, 'Theory of n-factors', in *Proceedings of the Third International Conference on Permafrost,* Vol. 1. Edmonton, Canada, National Research Council of Canada: Ottawa, pp. 40–46.

Lunardini, V. J.: 1996, 'Climatic warming and the degradation of warm permafrost', *Permafrost Periglacial Process* **7**(4), 311–320.

Lynch, A. H., Bonan, G. B., Chapin, F. S., and Wu, W.: 1999, 'Impact of tundra ecosystems on the surface energy budget and climate of Alaska', *J. Geophys. Res. Atmos.* **104**(D6), 6647–6660.

Mackay, J. R.: 1995, 'Active layer changes (1968–1993) following the forest-tundra fire near Inuvik, N.W.T., Canada', *Arctic Alpine Res.* **27**(4), 323–336.

Majorowicz, J. A.: 1996, 'Accelerating ground warming in the Canadian prairie provinces: Is it a result of global warming?', *Pure Appl. Geophys.* **147**(1), 1–24.

Majorowicz, J. A. and Skinner, W. R.: 2001, 'Reconstruction of the surface warming history of western interior Canada from borehole temperature profiles and other climate information', *Climate Res.* **16**(3), 157–167.

Melillo, J. M., Steudler, P. A., Aber, J. D., Newkirk, K., Lux, H., Bowles, F. P., Catricala, C., Magill, A., Ahrens, T., and Morrisseau, S.: 2002, 'Soil warming and carbon-cycle feedbacks to the climate system', *Science* **298**, 2173.

Nelson, F. E., Anisimov, O. A., and Shiklomanov, N. I.: 2002, 'Climate change and hazard zonation in the circum-Arctic permafrost regions', *Natural Hazards* **26**(3), 203–225.

Oechel, W. C., Hastings, S. J., Vourlitis, G., Jenkins, M., Riechers, G., and Grulke, N.: 1993, 'Recent change of Arctic tundra ecosystems from a net carbon dioxide sink to a source', *Nature* **361**, 520–523.

Oechel, W. C., Vourlitis, G. L., Hastings, S. J., Zulueta, R. C., Hinzman, L., and Kane, D.: 2000, 'Acclimation of ecosystem CO_2 exchange in the Alaskan Arctic in response to decadal climate warming', *Nature* **406**, 978.

Oelke, C., Zhang, T. J., Serreze, M. C., and Armstrong, R. L.: 2003, 'Regional-scale modeling of soil freeze/thaw over the Arctic drainage basin', *J. Geophys. Res. Atmos.* **108** (D10), Art. No. 4314.

Osterkamp, T. E. and Romanovsky, V. E.: 1999, 'Evidence for warming and thawing of discontinuous permafrost in Alaska', *Permafrost Periglacial Process* **10**(1), 17–37.

Osterkamp, T. E., Viereck, L., Shur, Y., Jorgenson, M. T., Racine, C., Doyle, A., and Boone, R. D.: 2000, 'Observations of thermokarst and its impact on boreal forests in Alaska, USA', *Arctic Antarctic Alpine Res.* **32**(3), 303–315.

Pollack, H. N., Huang, S. P. and Shen, P. Y.: 1998, 'Climate change record in subsurface temperatures: A global perspective', *Science* **282**, 279–281.

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 Alpine Res.* **32**, 155–166.

Romanovsky, V. E. and Osterkamp, T. E.: 1995, 'Inter-annual variations of the thermal regime of the active layer and near-surface permafrost in northern Alaska', *Permafrost Periglacial Process.* **6**(4), 313–335.

Rouse, W. R.: 2000, 'The energy and water balance of high-latitude wetlands: Controls and extrapolation', *Global Change Biol.* **6**(Suppl 1), 59–68.

Serreze, M. C., Walsh, J. E., Chapin, F. S., Osterkamp, T., Dyurgerov, M., Romanovsky, V., Oechel, W. C., Morison, J., Zhang, T., and Barry, R. G.: 2000, 'Observational evidence of recent change in the northern high-latitude environment', *Climatic Change* **46**(1, 2), 159–207.

Smith, M. W.: 1975, 'Microclimatic influences on ground temperatures and permafrost distribution, Mackenzie Delta, Northwest Territories', *Can. J. Earth Sci.* **12**(8), 1421–1438.

Smith, M. W. and Riseborough, D. W.: 1996, 'Permafrost monitoring and detection of climate change', *Permafrost Periglacial Process* **7**, 301–309.

Smith, M. W. and Riseborough, D. W.: 2002, 'Climate and the limits of permafrost: A zonal analysis', *Permafrost Periglacial Process.* **13**, 1–15.

Stendel, M. and Christensen, J. H.: 2002, 'Impact of global warming on permafrost conditions in a coupled GCM', *Geophys. Res. Lett.* **29**(13), Art. No. 1632.

Stieglitz, M., Dery, S. J., Romanovsky, V. E., and Osterkamp, T. E.: 2003, 'The role of snow cover in the warming of arctic permafrost', *Geophys. Res. Lett.* **30**(13), Art. No. 1721.

Stieglitz, M., Giblin, A., Hobbie, J., Williams, M., and Kling, G.: 2000, 'Simulating the effects of climate change and climate variability on carbon dynamics in Arctic tundra', *Global Biogeochemical Cycles* **14** (4), 1123–1136.

Tarnocai, C.: 1999, 'The effect of climate warming on the carbon balance of cryosols in Canada', *Permafrost Periglacial Process* **10**(3), 251–263.

Thie, J.: 1974, 'Distribution and thawing of permafrost in the southern part of the discontinuous permafrost zone in Manitoba', *Arctic* **27**, 189–200.

Trumbore, S. E. and Harden, J. W.: 1997, 'Accumulation and turnover of carbon in organic and mineral soils of the BOREAS northern study area', *J. Geophys. Res.* **102** (D24), 28, 817–828, 830.

Turetsky, M. R., Wieder, R. K., Williams, C. J., and Vitt, D. H.: 2000, 'Organic matter accumulation, peat chemistry, and permafrost melting in peatlands of Boreal Alberta', *Ecoscience* **7**(3), 379–392.

Waelbroeck, C., Monfray, P., Oechel, W. C., Hastings, S., and Vourlotis, G.: 1997, 'The impact of permafrost thawing on the carbon dynamics of tundra', *Geophys. Res. Lett.* **24**(3), 229–232.

Zhang, T., Barry, R. G., Gilichinsky, D., Bykhovets, S. S., Sorokovikov, V. A, and Ye, J. P.: 2001, 'An amplified signal of climatic change in soil temperatures during the last century at irkutsk, Russia', *Climatic Change* **49**(1, 2), 41–76.

Zhang, T., Roger, G., Barry, K., Knowles, J. A., Heginbottom, and Brown, J.: 1999, 'Statistics and characteristics of permafrost and ground ice distribution in the Northern Hemisphere', *Polar Geogr.* **23**(2), 147–169.

Zhang, T. and Stamnes, K.: 1998, 'Impact of climatic factors on the active layer and permafrost at Barrow, Alaska', *Permafrost Periglacial Process* **9**(3), 229–246.

Zhuang, Q., McGuire, A. D., Melillo, J. M., Clein, J. S., Dargaville, R. J., Kicklighter, D. W., Myneni, R. B., Dong, J., Romanovsky, V. E., Harden, J., and Hobbie, J. E.: 2003, 'Carbon cycling in extratropical terrestrial ecosystems of the Northern Hemisphere during the 20th century: A modeling analysis of the influences of soil thermal dynamics', *Tellus Series B-Chemical and Physical Meteorology* **55**(3), 751–776.

Zoltai, S. C.: 1972, 'Palsas and peat plateaus in central Manitoba and Saskatchewan', *Can. J. Forest Res.* **2**, 291–302.

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