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Modelling the effects of climate change and disturbance on permafrost stability in northern organic soils

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SUMMARY

Boreal and arctic regions are predicted to warm faster and more strongly than temperate latitudes. Peatlands in these regions contain large stocks of soil carbon in frozen soil and these may effect a strong positive feedback on climate change. We modelled the predicted effects of climate change and wildfire on permafrost in organic soils using a peatland-specific soil thermal model to simulate soil temperatures. We evaluated the model at a lowland black spruce site in Alaska and a sedge-dominated Canadian arctic fen. We estimated the response of soil temperatures and the active layer thickness (AcLTh) under several climate change scenarios. With surface soil temperatures increased by 4.4 °C−5.4 °C, soil temperatures at 100 cm depth increased by 3.6 °C−4.3 °C, the AcLTh increased by 12−30 cm, the zone of partially thawed soil increased, and the number of thaw days increased by 17−26 %. Wildfire caused AcLTh to increase by 26−48 % in the year following fire; AcLTh differences in 2091−2100 were significant (8 cm) at one site. By 2100, climate change effects on AcLTh were larger than wildfire effects suggesting that persistent temperature increases will have a more substantial effect on permafrost than the transient effects of disturbance.

KEY WORDS: Alaska, arctic fen; black spruce forest; Daring Lake; global warming; peatlands

INTRODUCTION

High latitudes are experiencing effects of climate change including thawing of permafrost and altered hydrology. Permafrost thaw has occurred in areas of Alaska (Osterkamp 2005) and Canada (Halsey *et al.* 1995) as a result of higher temperatures (Serreze *et al.* 2000, Chapin *et al.* 2005) and altered snow cover. Modelling results predict that small, sustained increases in air temperatures forecast by climate models will result in a 20−85 % decrease in the area of near-surface (the top 3 m) permafrost (Lawrence *et al.* 2008, Zhang *et al.* 2008) and, by 2100, a 20 % increase in thawed peat volume across Alaska and Canada (Wisser *et al.* 2011).

The effects of permafrost degradation, thaw and collapse on ecosystem processes have been an area of much recent research due to the implications for C storage in permafrost soils (Tarnocai *et al.* 2009). An estimated 50 % of below-ground soil carbon (SOC) globally (~1650 Pg) is stored in the northern circumpolar permafrost region, over 80 % of which is in areas with permafrost and > 20 % is in organic (peatland) soils (Tarnocai *et al.* 2009). Changes in climate (temperature, precipitation and seasonality), hydrology, snow cover and vegetation dynamics can result in permafrost thaw in peatlands (Camill & Clark 1998) but some effects may be buffered by the thermal properties of organic soils (Yi *et al.* 2007, Camill & Clark 1998). With thick organic soils, soil temperatures at depth remain relatively constant, despite higher air temperatures (Shur & Jorgenson 2007) and disturbances such as wildfire (Yoshikawa *et al.* 2002).

Permafrost thaw can also be initiated by the removal or disturbance of a surface soil layer, such as after wildfire (e.g. Dyrness 1982, Hayhoe & Tarnocai 1993). In recent decades, wildfire frequency has increased and large areas have burned in Alaska and Canada (Kasischke & Turetsky 2006), and these increases are predicted to continue (Flannigan *et al.* 2005). Transient effects following wildfire include higher soil temperatures that persisted for > 15 years (Liu *et al.* 2005) and a decrease in surface albedo that persisted for approximately three years (Randerson *et al.* 2006). Albedo increases follow post-fire vegetation recovery in a peatland as well (Randerson *et al.* 2006), while decreased soil temperatures that followed wildfire have been attributed to vegetation recovery and increased albedo (O'Donnell *et al.* 2009). Wildfire may affect permafrost stability and increase soil temperatures for decades (Viereck *et al.* 2008); but historically, in peatlands, vegetation and associated permafrost returned to pre-fire conditions after several centuries (Zoltai 1993).

Both climate change and wildfire alter site growing season length, seasonality and soil temperatures, and ultimately affect the carbon balance. In organic soils with permafrost, the modelled relative effects on soil temperature regimes due to climate change resulted in a small but sustained increase in air temperature, and in wildfire. The consequences of a transient temperature increase and removal of the organic soil are unknown.

In this study, we adapted an existing soil temperature model to organic soils by adding three organic soil horizons and dynamic soil moisture; and evaluated the model in two permafrost sites, a lowland black spruce forest in Alaska and a Canadian arctic fen. At these sites we compared the magnitude of change in soil temperatures, active layer thickness (we use 'AcLTh' frequently for this throughout this article), and number of thaw days, as consequences of future climate change scenarios. These scenarios are with and without increased wildfire frequency. We predict whether climate change or wildfire would have the greater effects in the twenty-first century on soil temperatures and permafrost stability in North American peatlands.

METHODS

Description of model

We used the Geophysical Institute Permafrost Lab permafrost model (GIPL-2.0) previously described by Marchenko *et al.* (2008) and Wisser *et al*. (2011). This model uses a numerical approximation to solve the heat transfer equation with phase change (solid:liquid:vapour). In this one-dimensional model, heat is transferred vertically, up or down, to cooler soils, with the daily change in soil temperature determined by the initial soil temperatures, the heat capacity of the soil (a function of the soil moisture and soil properties), and whether soil water undergoes phase change. In the simplest case, a sine wave of temperature change at the surface propagates downwards with reducing amplitude and increasing delay, the size of such effects being determined by the thermal properties of the medium, which are themselves dependent on water content. Daily soil surface temperatures, water table level, and a description of the underlying soil and bedrock were used as inputs for the GIPL model. To adapt GIPL-2.0 to peatland ecosystems, we added three peat layers and dynamic soil moisture; the model previously included mineral soil and two bedrock layers. This modified model is GIPL-2.0-Peat. The properties of the peat layers (horizon thickness, porosity and water retention) and organic content and composition of the mineral soil layer are both depth- and site-specific (Table 1). Bulk soil thermal properties were volume-weighted by means of empirical values of thermal conductivity and heat capacity (Table 1) for solid material, water or ice, and air. We did not calibrate soil thermal properties to match observed temperature values.

We determined the depth-distributed peat volumetric water content (*VWC*) as a continuous, empirically-derived function of the height (H, cm) above the water table in the active layer by fitting a logistic regression to *VWC vs. H* data obtained from TDR (time domain reflectometry) measurements at Mer Blue Bog, Ontario, Canada (N.T. Roulet, 2009, pers. comm.) and validated at Daring Lake Fen, Northwest Territories, Canada in 2008 (E. Humphreys, 2009, pers. comm.). *VWC* decreased with increasing height above the water table to a minimum value of a and was saturated ($VWC = 1$) below the water table ($H < 0$ cm):

$$VWC = \frac{1-a}{1+\exp^{b(H-H_i)}} + a \qquad [1]$$

where a (unitless), b (cm^{-1}) and H_i (cm) were specific for each peat type (fibric: $a = 0.2$, $b = 0.9$ cm^{-1}, $H_i = 5$ cm; mesic: $a = 0.4$, $b = 0.45$ cm^{-1}, $H_i = 7$ cm; humic: $a = 0.5$, $b = 0.12$ cm^{-1}, $H_i = 25$ cm). *VWC* was used to calculate the thermal properties of the peat soils within the GIPL-2.0-Peat model.

Description of sites

Black Spruce Site: BZBS, Bonanza Creek LTER

The black spruce site (148.31°W, 64.70°N) is a rather poorly-drained lowland black spruce forest located within the Bonanza Creek Experimental Forest, Fairbanks, Alaska, USA. The mean annual air temperature in Fairbanks (25 km to the east) is -2.9 °C and mean annual precipitation is 260 mm (NCDC 2002). The black spruce site has 20−25 cm of organic soil underlain by mineral soil with an AcLTh (active layer thickness) of 45−65 cm. Vegetation at the black spruce site includes moderate black spruce canopy cover and continuous cover of *Hylocomium* moss species (Figure 1). Measurements of soil temperature (2, 5, 10, 25, 50, and 100 cm depths) at the black spruce site were available from 23 May 2005−31 Dec. 2009 (Harden 2009). We gap-filled missing values (33 %) for 2 cm depths using a linear relationship with a nearby black spruce site FP5A (7.5 km away;

Hollingsworth 2005). Water table data were unavailable; volumetric soil moisture was assumed to be 43 % and 57 % in the active layer and permafrost soils, respectively, and constant over time, based on observations in black spruce sites in interior Alaska with similar organic soil composition (Harden *et al.* 2006, Waldrop *et al.* 2010).

Arctic Fen: Daring Lake Fen

Daring Lake Fen (64.865° N, 111.567° W) is an arctic wet sedge meadow with permafrost located in the Daring Lake Research Area, Northwest Territories, Canada. This site has 40−70 cm of peat underlain by silt loam (Figure 2). Daring Lake Fen is dominated by sedges (*Carex* spp. and *Eriophorum* spp.), dwarf birch, and nearly continuous *Sphagnum* cover (Lafleur & Humphreys 2007, Humphreys & Lafleur 2011). Mean annual air temperature (2006−2008) was -8.7 °C; 2007−2009 mean summer precipitation (15 May−31 August) was 114 mm. Maximum snow depths were 45 cm in 2006 and 32 cm in 2007. While no long-term climatic data are available near Daring Lake Fen, mean daily temperatures range from -34 °C−-25 °C in January and 6 °C−20 °C in July and the annual precipitation range is 200−300 mm (*Climatic Atlas of Canada* 1984).

Table 1. Parameter values for the GIPL-2.0-Peat model at the black spruce site and at the arctic fen site. The model uses six soil layers: three peat layers with different properties, a mineral soil layer, and two bedrock layers. Heat capacity in J m^{-3} K^{-1}; thermal conductivity in W m^{-1} K^{-1}.

Soil layer:	Peat 1: Fibric	Peat 2: Mesic	Peat 3: Humic	Mineral soil	Bedrock 1/ 2[a]
Arctic fen soil properties					
Thickness (m)	0.05	0.10	0.45	9.4	20 / 70
Porosity	0.95	0.92	0.9	0.62	NA
Soil composition	100 % peat	100 % peat	100 % peat	95 % mineral 5 % organic	bedrock: 100 % mineral
Volumetric water content (*VWC*):	(Equation 1)	(Equation 1)	(Equation 1)	0.43	0.96 / 0.42
Black spruce soil properties					
Thickness (m)	0.05	0.10	0.05	9.75	20 / 70
Porosity	0.98	0.95	0.91	0.60	NA
Soil composition	100 % peat	100 % peat	100 % peat	75 % mineral 25 % organic	bedrock
VWC	0.43 (active layer)		0.57 (permafrost)	0.43	0.96 / 0.42
	Peat[b, c]	Water[d]	Ice[d]	Air[d]	Mineral soil[d]
Soil thermal properties					
Heat capacity	0.58×10^6 [b]	4.18×10^6	1.9×10^6	1.25×10^3	2.0×10^6
Thermal conductivity	0.14−0.69 (frozen)[c]; 0.04−0.54 (thawed)[c]	0.57	2.2	0.025	2.0

[a] Marchenko *et al.* (2008); [b] Hillel (1980); [c] O'Donnell *et al.* (2009); [d] van Wijk & de Vries (1963).

Figure 1. The Black Spruce Site, at USGS site BZBS in the Bonanza Creek Long-Term Ecological Research Area, outside Fairbanks, Alaska, USA (photo: K. Manies).

Figure 2. The Arctic Fen Site, at Daring Lake Fen, in Daring Lake Natural Research Area, Northwest Territories, Canada (photo: M. Treberg).

Air temperature, soil temperature (0, 2, 5, 10, 20, 40 and 60 cm depths), snow depth, precipitation, and evapotranspiration were measured daily at the arctic fen from 2006−2009, and the water table level was recorded daily for the 2007−2009 summer seasons (Lafleur & Humphreys 2007). Gaps in surface soil temperature data were filled using a linear regression with a continuous record of soil temperature at 2 cm depth. Water table position during the growing season ranged from 9 cm above the peat surface to 21 cm below. Water table position during the remainder of the year (i.e. non-growing season) was held constant from freeze-up to snowmelt at the fall (autumn) freeze-up value. The 2006 water table position was estimated as the mean water table position of the 2007 and 2008 growing seasons and was held constant throughout the growing season.

Model evaluation and statistical analysis

We evaluated the model using surface soil temperature observations and volumetric water content (*VWC*) data from the black spruce forest site in interior Alaska, and from the arctic fen in Canada. We compared modelled soil temperatures from several depths within the soil profile, AcLTh, and number of thaw days (T > 0.1 °C at 0.1 m, i.e., the rooting zone) with observations visually and using the root mean square error (RMSE) of the regression between modelled and measured soil temperatures. Modelled AcLTh (active layer thickness = maximum depth of thaw during a calendar year) was compared with measurements (when available). All statistical analyses were made using R Statistical Software (R Development Core Team, 2008).

Future scenarios: climate change

Simulating permafrost response to future climate change required two inputs: surface soil temperature and soil moisture. Surface soil temperatures were taken directly from a global climate model (ECHAM5) output for the shallowest soil horizon (Roeckner *et al.* 2003). We used the ECHAM5 GCM output because it was the highest ranked model for simulating northern (60–90° N) temperatures (Walsh *et al.* 2008). We used two temperature scenarios and two moisture scenarios from the ECHAM5 model output to create four climate change scenarios for the GIPL-2.0-Peat model (Table 2). The control climate scenario developed for the IPCC (20C3M) assumes CO_2 emissions equivalent to those in 1900 and was used to recreate soil temperatures from 1900−2001 for model validation and to predict soil temperatures from 2001−2100 (Table 2, scenario #1), assuming no change in temperature or precipitation relative to 1900−2000 (Figure 3). Precipitation data from the 20C3M scenario were used for several scenarios (Table 2). The climate change scenario (A1B) had

Table 2. Eight scenarios used in the modelling experiments. Model drivers (air temperature, surface soil temperature and precipitation) were taken from IPCC AR4 scenarios 20C3M (CO_2 concentrations from 1900) and A1B (moderately-high growth in carbon emissions). See text for further details.

Scenario	Description	Temperature	Moisture	Burn year (depth)
1	Control	20C3M	20C3M	n/a
2	Warm	A1B	20C3M	n/a
3	Warm + wet	A1B	20C3M x 120 % (black spruce), A1B (the arctic fen)	n/a
4	Warm + dry	A1B	20C3M x 80 % (black spruce only)	n/a
5	Control + burn	20C3M	20C3M	2014 (0.20 m)
6	Control + fire frequency	20C3M	20C3M	2014 (0.05 m); 2075 (0.20 m)
7	Warm + burn	A1B	20C3M	2014 (0.20 m)
8	Warm + fire frequency	A1B	20C3M	2014 (0.05 m); 2075 (0.20 m)

higher 21st century temperatures because it assumed an increase in CO_2 emissions in accordance with the IPCC scenario A1B. For climate change scenarios (scenarios #2 to 4) we used A1B surface soil temperature for 2001−2100 for each site, and the control soil temperature values in 2000 to initialise the model. For the warm scenario, the air temperature increase between 2001−2010 and 2091−2100 was 5.4 °C at the arctic fen and 4.5 °C at the black spruce site, respectively, while the increase in soil surface temperature (0 m) was 5.4 °C (the arctic fen) and 4.4 °C (the black spruce site).

Under the climate change predictions using scenario A1B, runoff (defined as precipitation minus evapotranspiration, $P-E$) at the black spruce site decreased significantly between 2001 and 2100 (~20 %, $F(1,197) = 8.64$, $P = 0.004$), while runoff increased significantly at the arctic fen (12 %, $F(1,197) = 13.50$, $P < 0.001$; Figure 3). Since

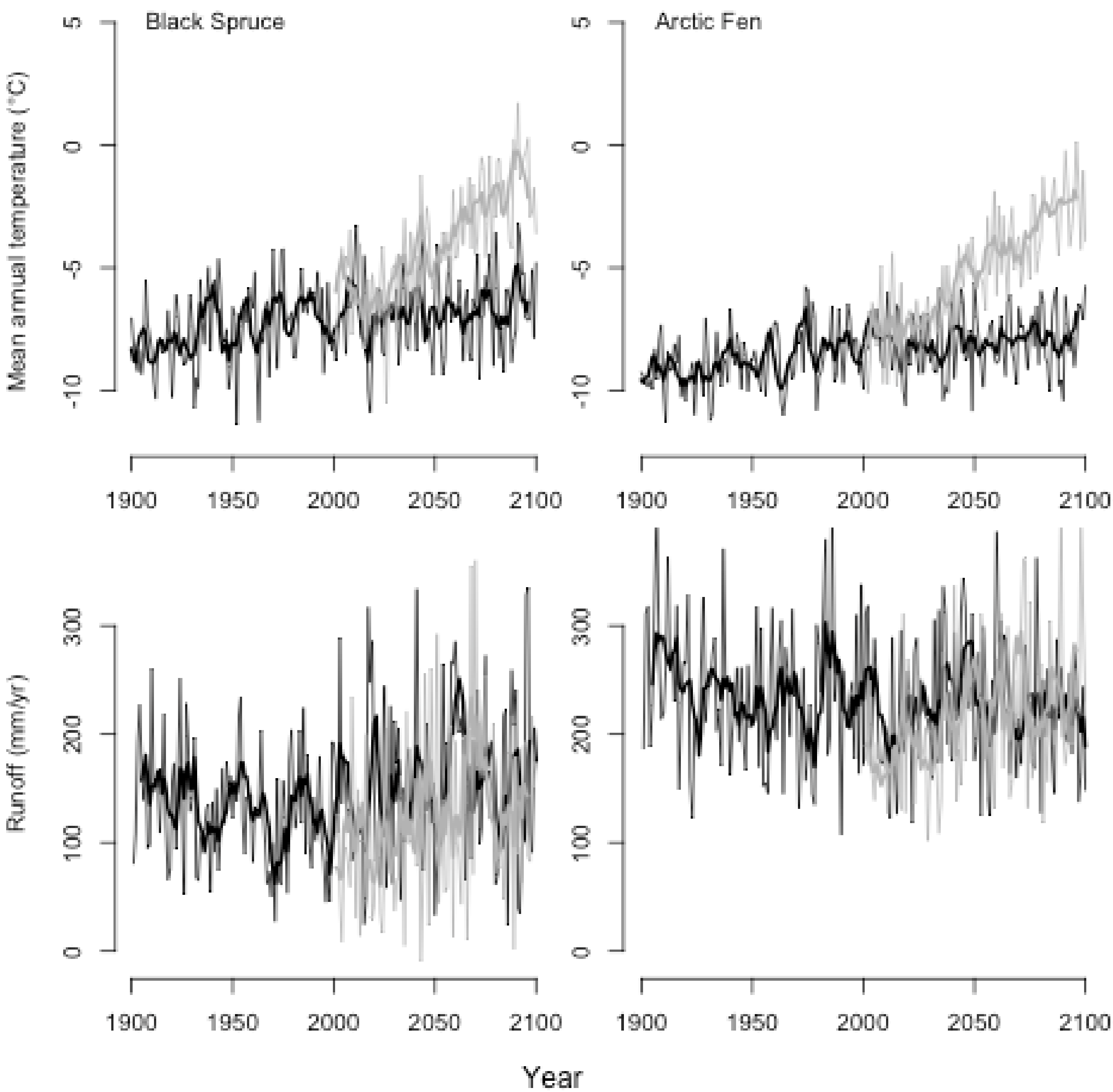

Figure 3. Top: global climate model predictions of mean annual air temperature for control (black) and warm (grey) scenarios used as model input, and 5-year moving means (bold), at the black spruce site (left) and the arctic fen (right). Bottom: modelled annual runoff ($P-E$) at the black spruce site (left) and the arctic fen (right) from 1900 to 2100 for control (black) and warm (grey) scenarios. Measured mean annual runoff for the nearest long-term gauging station to the black spruce site was 0.326 ± 0.036 m yr^{-1} (USGS # 15515500, 1963−2003) and 0.177 ± 0.042 m yr^{-1} at the arctic fen (Hydat #10PB001, 1965−2000).

ECHAM5 does not simulate organic soils (nor do other GCMs in IPCC AR4), we could not use predicted changes in soil moisture to examine the effects of higher temperatures combined with changes in soil moisture; our approach varied by site. At the black spruce site, we assumed 20 % drier, 20 % wetter, or no change in soil moisture from the control values (Table 2).

To predict changes in soil moisture at the arctic fen, we calculated future changes in water table and subsequent soil moisture from future runoff (Figure 3, lower right). Precipitation (P, mm yr^{-1}) was a standard ECHAM model output, while evapotranspiration (E, mm yr^{-1}) was predicted using an empirical relationship developed at the arctic fen using mean seasonal (May−Sep) measurements of E and the mean annual air temperature (T_{air} , °C) from 2007−2009:

$$E = aT_{\mathrm{air}} + b \qquad [2]$$

where a = 5.1 mm °C^{-1} yr^{-1} and b = 256 mm yr^{-1}. We predicted soil moisture by assuming that water table observations at the arctic fen (Lafleur & Humphreys 2007) adequately capture the water table distribution, that total summer precipitation continued to comprise 25−62.5 % of total annual precipitation at the arctic fen, and that these empirical relationships will remain constant into the future. The scaling relationship that we developed between cumulative seasonal runoff (‘$P-E$’, mm yr^{-1}) and mean seasonal water table position (WT, mm) at the arctic fen was:

$$WT = c(P - E) + d \qquad [3]$$

where c = 9.1 mm-yr, d = 6.6 mm, and negative values indicate a water table below the surface. Scaled water tables were truncated at the surface. The timing of wet and dry periods had little influence on soil temperature (Treat 2010).

There was some bias associated with using global climate model output to predict conditions at our sites that may have been due to global climate model predictions or site microclimates. Air and near-surface soil temperature (3 cm) inputs from the control scenario (20C3M, 1971−2000) compared well with observed air and surface soil temperatures for the summer months at the arctic fen (10.3 °C and 13.1 °C for control and 10.8 °C and 11.6 °C for the arctic fen air and soil temperatures, respectively), while there was a model bias towards lower air and soil temperature inputs during the winter months: -25.0 °C (air) and -25.5 °C (soil) for control and -26.8 °C (air) and -14.4 °C (soil) for the arctic fen observations. Similarly, soil temperatures at the black spruce site from the control scenario (1971−2000) were closer to the observed near-surface (2 cm) soil temperatures from 2005−2009 at the site for the summer months (11.6 °C for control compared to 10.4 °C) than for the winter months, which had a cold bias (-22.1 °C for control versus -7.6 °C for the black spruce site). The mean air temperature from the control scenario for 1971−2000 was 4 °C cooler than observations in Fairbanks for the same period; seasonally, the control air temperatures were 0.4−1 °C lower than observations at Fairbanks in Nov−Jan and 3.7 °C−7.0 °C lower during the rest of the year. Precipitation in the control scenario for 1971−2000 (mean 370 mm) was larger than the observed annual precipitation at Fairbanks for the same period (260 mm) and nearly double the mean observed precipitation at the arctic fen for 1997−2005 (Lafleur & Humpheys 2007, Treat 2010).

Future scenarios: disturbance

We considered three scenarios (‘control, ‘+burn’, ‘+fire frequency’) for both the control and climate change (A1B) model runs:

1) ‘control, #1’: no disturbance;
2) ‘+burn’: a severe wildfire on 28 June 2014 that removes 20 cm of organic soil; and
3) ‘+fire frequency’: a mild wildfire on 28 June 2014 that removes 5 cm of organic soil, followed by a severe burn that removes 20 cm of organic soil on 27 July 2075, representing increased fire frequency corresponding to a fire return interval of 60 years *vs* > 80 years in the +burn scenario (Wieder *et al.* 2009).

In all wildfire scenarios, we removed 5 cm or 20 cm of surface peat on the day following the wildfire (Kasischke & Johnstone 2005, Mack *et al.* 2011); i.e., a fire in a ‘typical’ and a major drought year. This resulted in a new peat surface layer with the soil properties (bulk density, porosity, water holding capacity, thermal properties) and soil moisture of the deeper peat layer that had been immediately below the burned peat. After the simulated burn, the water table position was closer to (or above) the new, post-fire, peat surface for the remainder of the simulation. We did not include either the accumulation of peat or the post-fire re-accumulation of peat in the model. Therefore, both wildfire and non-wildfire scenarios probably suffer from a similar temperature bias. Additional field data (Robinson & Moore 2000) and model simulations (Talbot & Frolking *in prep*) agree that, in our sites, mature peatlands accumulate ~0.4 mm of peat per year.

We developed an empirical relationship for boreal and sub-arctic regions between time since fire and the change in surface soil temperature due to decreased shading and changes in albedo. We used observed temperature changes from plot-level (Viereck & Dyrness 1979, O'Neill *et al.* 2002, Harden *et al.* 2006, Nakano *et al.* 2006) and tower studies (Chambers & Chapin 2002, Chambers *et al.* 2005, Liu *et al.* 2005) in boreal forests and peatlands. The change in surface temperature (ΔT_w, °C) is related to the time since burn (t_{burn}, years) using the following empirical relationship:

$$\Delta T_{\mathrm{w}} = ue^{-vt_{\mathrm{burn}}} - w \qquad [4]$$

where $u = 5.413$ °C, $v = -0.132$ yr^{-1}, and $w = 0.25$ °C. ΔT_w (5.2 °C initially, dropping to 0.14 °C after 20 years) was added to the surface soil temperature throughout the year until 20 years post-fire when we assumed $\Delta T_w = 0$ due to vegetation recovery (Zoltai *et al.* 1998, Wieder *et al.* 2009). We did not account for short-term temperature changes as a direct result of the fire; Yoshikawa *et al*. (2002) found that organic soil temperatures did not increase at depths > 15 cm during an experimental wildfire.

Future scenario comparison methods

We assessed how climate change (small but sustained) and wildfire (large but transient) affects permafrost at the black spruce site and the arctic fen (Table 2), considering three factors:
1) changes in soil temperature;
2) trends in AcLTh; and
3) the number of thaw days: those with thaw depth ≥ 10 cm − a measure of the period of biological activity.

To evaluate the differences between scenarios in the sensitivity and climate change modelling analyses, we used analysis of variance ($P < 0.05$) to compare differences in soil temperatures at depth, active layer thicknesses, and number of thaw days between different scenarios and between years. We used the Tukey 'Honest Significant Difference' post-hoc analysis to determine confidence intervals for sample means and determine the corrected differences between means for multiple sample groups (Miller 1981, Yandell 1997). All statistical analyses were made using R Statistical Software (R Development Core Team 2008) and the Zoo package (Zeileis & Grothendieck 2005) to calculate rolling means.

RESULTS

Model evaluation

Measured soil temperatures and modelled soil temperatures were compared for the black spruce site and the arctic fen (Figure 4). RMSE between measured and modelled temperatures at the black spruce site ranged from 0.17 °C to 1.23 °C. RMSE between measured and modelled temperatures at the arctic fen ranged from 1.29 °C to 2.05 °C.

At the black spruce site, the observed number of thaw days at 50 cm ranged from 29−91, *versus* 55−64 days for the model (2005−2009), while at 100 cm depth the model and measurements agreed (zero thaw days for all years). Modelled AcLTh at the black spruce site for 2005−2009 was 58−64 cm, which is similar to the observations of 45−65 cm (Figure 4C) and within the range (40 cm to 2.1 m) reported at a nearby BCEF CALM site by Hollingsworth (2002). At the arctic fen, the observed number of thaw days at 40 cm was 64–106 for 2006−2008, while the modelled number of thaw days was 0−66 (Figure 4G).

Climate change effects

The AcLTh (active layer thickness) at both sites did not differ significantly between the control scenario and climate change scenarios during 2001−2010 (Figure 5; P = 0.99 for both sites), but was significantly different by 2091−2100 (P = 0.0001 for both sites). At the black spruce site, mean AcLTh increased from 59 ± 3 cm in 2001−2010, and from climate change scenarios was 27−39 % deeper in 2091−2100 than in the control scenario, depending on soil moisture. For no change, drier soils, and wetter soils, respectively, AcLTh increased to 84 ± 3 cm, 88 ± 3 cm, and 80 ± 3 cm in 2091−2100. Mean AcLTh at the arctic fen increased by 26 % in the climate change scenario, from 46 ± 2 cm in 2001−2010 to 58 ± 2 cm in 2091−2100.

Soil temperatures at both sites were higher under the climate change scenarios (+warm) than the control scenario. By 2091−2100 (compared with 2001−2010), soil temperatures at 10 cm had increased by 4.2 °C ($P < 0.0001$) at the black spruce site and by 5.2 °C ($P < 0.0001$) at the arctic fen, while soil temperatures at 100 cm had increased by 3.6 °C ($P < 0.0001$) at the black spruce site and by 4.3 °C ($P < 0.0001$) at the arctic fen.

Climate change resulted in little change in the number of thaw days at 10 cm at the black spruce site (Figure 6B; P = 0.09, 17 % increase), but a

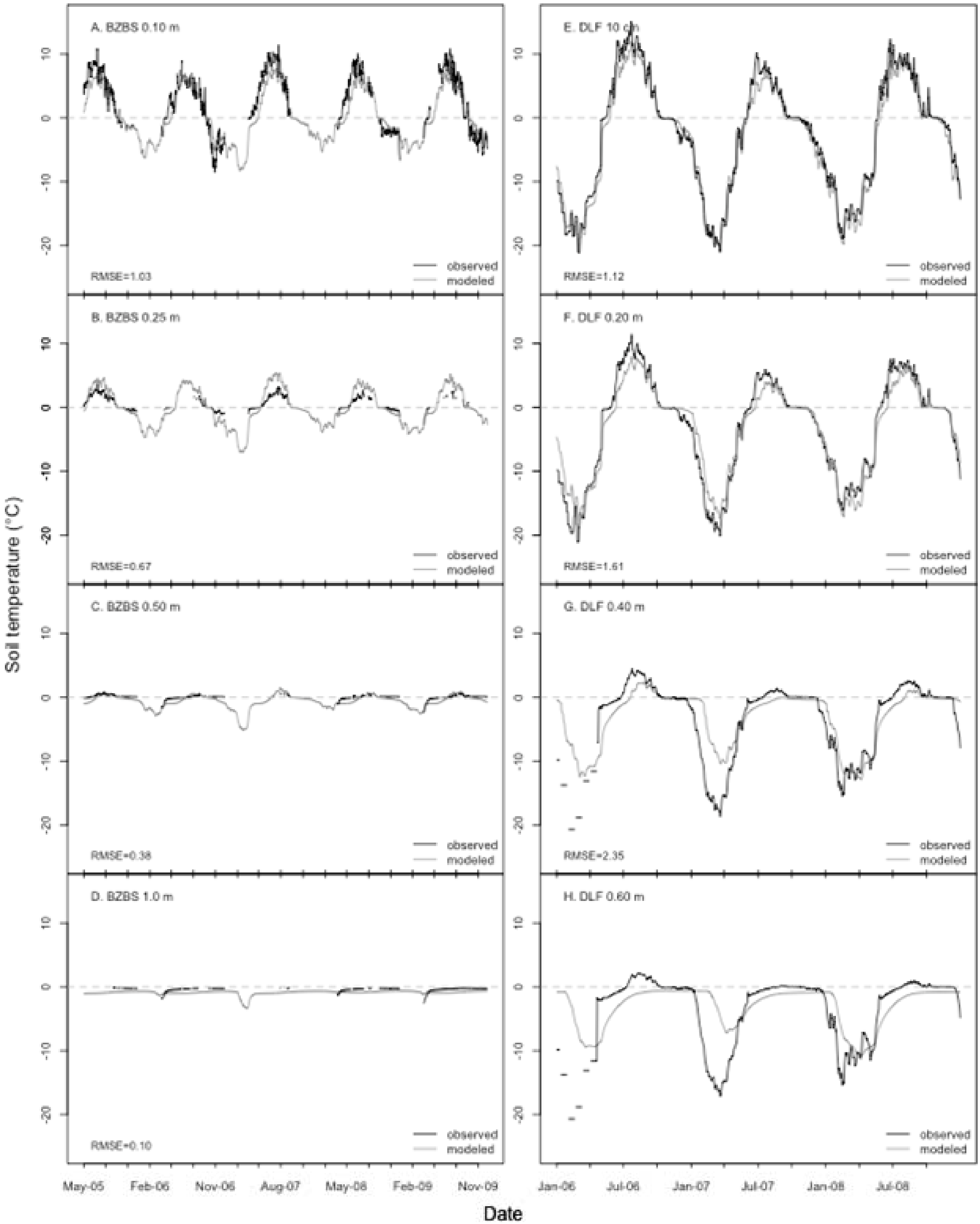

Figure 4. Measured (black) and modelled (grey) daily soil temperatures at the black spruce site (left) and the arctic fen (right) at various peat depths (10–100 cm) using the GIPL-2.0-Peat model.

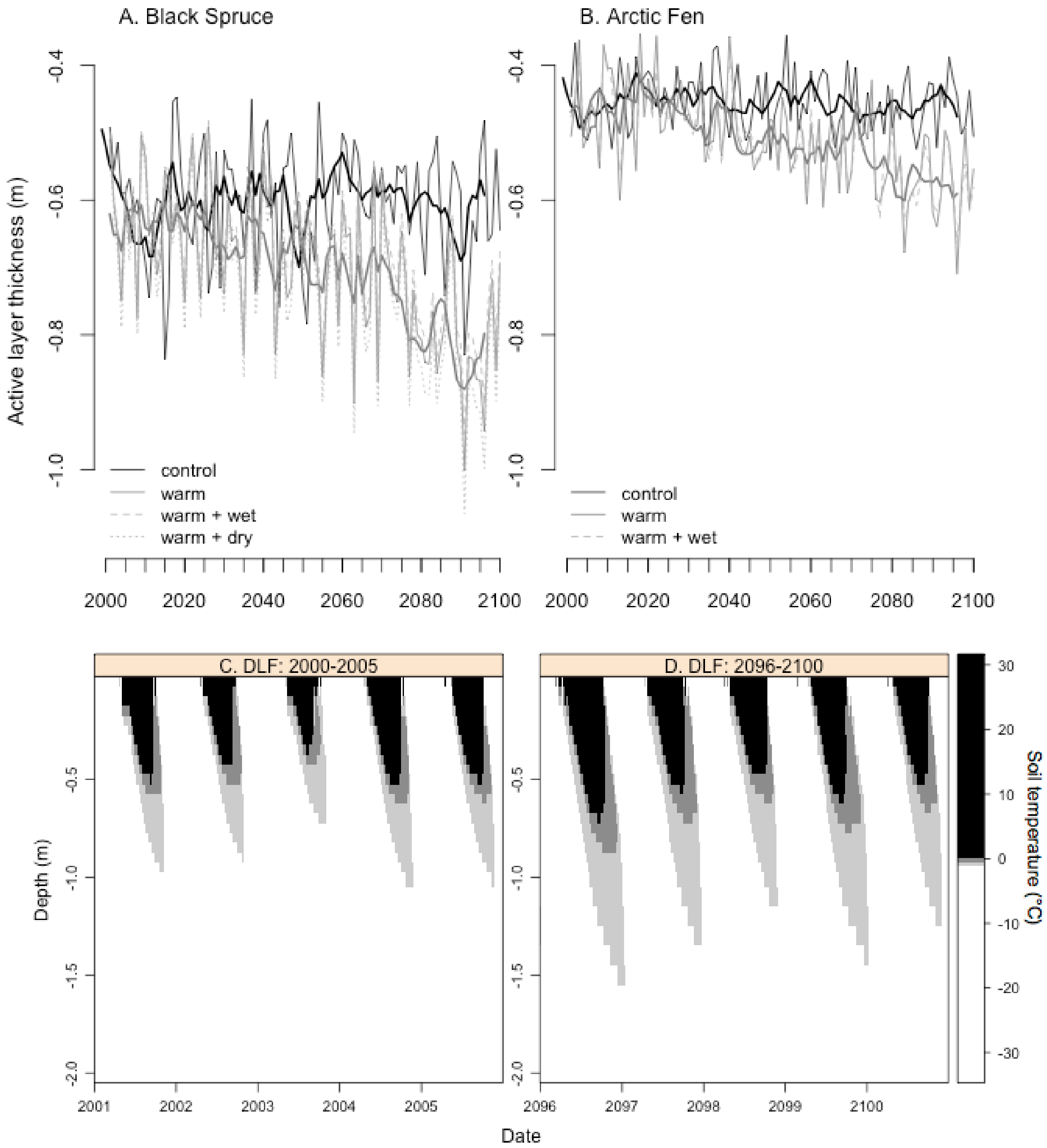

Figure 5. Top: modelled maximum annual active layer thickness (AcLTh) and five-year moving means (bold) at the black spruce site (left) and the arctic fen (right) for control model scenarios (scenario #1) and climate change model scenarios (scenarios #2 to 4: warm, warm wet, warm dry). Bottom: modelled soil temperatures (°C) for 0−2 m depths at the arctic fen for 2000−2005 (left) and 2096−2100 (right) with climate change model scenario (#2).

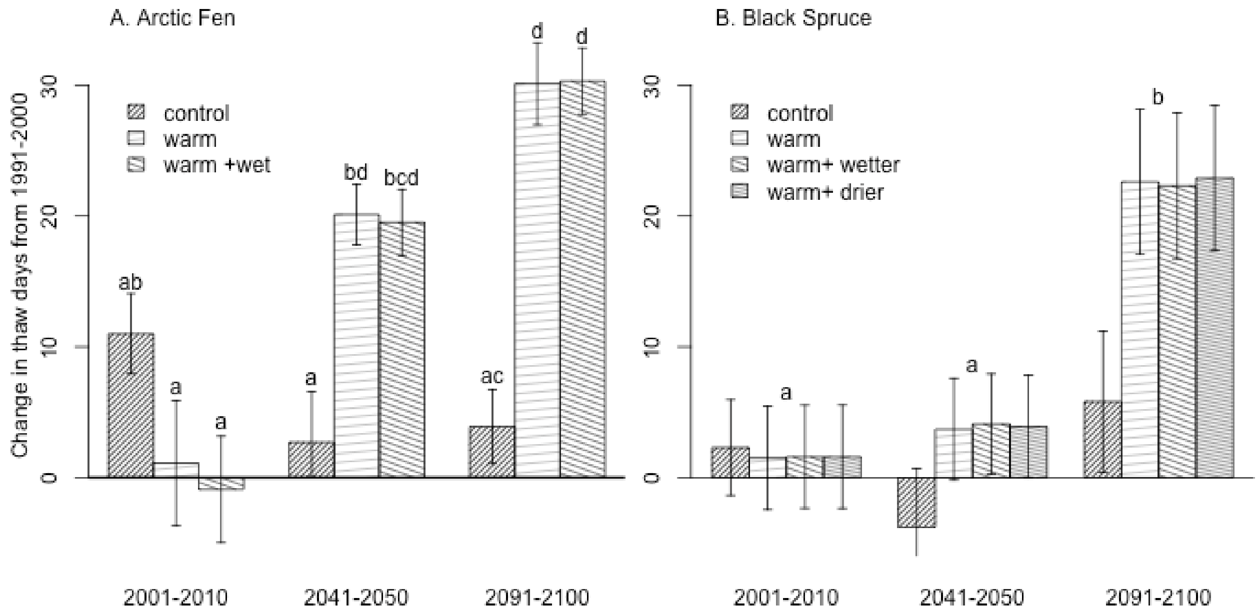

Figure 6. Modelled change in decade mean number of thaw days (T_{soil} > 0.1 °C at 10 cm) at the arctic fen (left), and the black spruce site (right), relative to mean number of thaw days annually for 1991−2000 for the climate change scenarios. Letters indicate significant differences between treatments (P < 0.05); error bars are standard error of mean thaw days (n = 10).

significant increase at the arctic fen (Figure 6A; P < 0.0001). From 1991−2000, the mean number of modelled days thawed was 138 ± 4 at the black spruce site and 116 ± 4 at the arctic fen. From 2091−2100 in the climate change scenarios, the mean number of days thawed was 159 ± 6 at the black spruce site and 146 ± 3 at the arctic fen, whereas there was no significant change in the control scenario. At the arctic fen, this represents a 26 % increase in thaw days or an increase of three thaw days per decade.

Disturbance effects

The response to wildfire was similar between control and warming climate scenarios. In the decade post-fire, the AcLThs from warm +burn scenarios were 14 ± 2 cm and 15 ± 2 cm deeper than the warm +unburned scenarios at the black spruce site and the arctic fen, respectively, but 34 cm and 35 cm deeper when compared to the original peat surface (Figure 7). Differences were significant at both sites (black spruce: $F(1,18)$ = 15.28, P = 0.001); the arctic fen: $F(1,18)$ = 24.86, P < 0.0001). By the end of the century, differences in AcLTh between burned and unburned scenarios were not significant at the black spruce site ($F(1,18)$ = 0.11, P = 0.75), but had decreased to 8 ± 1 cm and remained significant at the arctic fen ($F(1,18)$ = 6.21, P = 0.02). Similar differences were observed in the control + burn scenarios. At the arctic fen, the +burn runs showed a higher variability in the AcLTh following the simulated vegetation recovery for both the control (4 cm *vs*. 6 cm for +burn) and the warm scenario (6 cm *vs*. 7 cm for +burn). In addition, post-fire peat surfaces were 20 cm lower in the soil column; similar AcLTh between +burn and unburned scenarios resulted in the thawing of 20 cm of previously frozen soil.

Warm +fire frequency produced a maximum 27−28 cm increase in AcLTh (52−53 cm), relative to the original peat surfaces, from the unburned scenarios at both sites following the second wildfire (Figure 7), and a mean of 14 ± 2 cm at the black spruce site and 18 ± 2 cm at the arctic fen for the decade following the second fire (2076−2085). However, the differences in AcLTh decreased after the modelled post-fire vegetation recovery, resulting in no significant differences in AcLTh between the warm +frequency scenarios and the climate change scenarios in 2091−2100 at the black spruce site ($F(1,18)$ = 0.02, P = 0.89); but AcLTh remained 8 ± 1 cm deeper at the arctic fen ($F(1,18)$ = 6.89, P = 0.02). AcLThs in the control +fire frequency scenario showed similar patterns for 2091−2100.

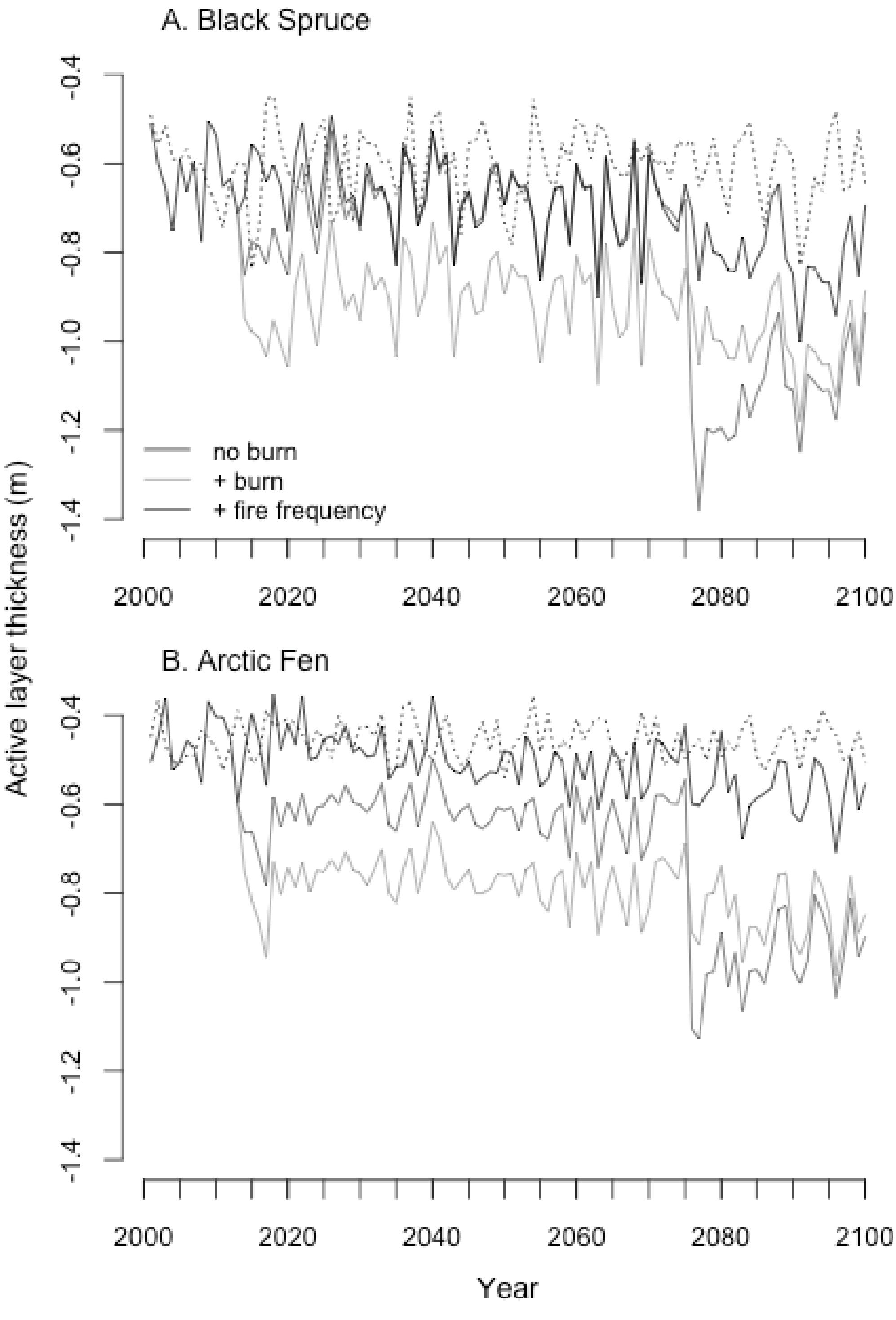

Figure 7. Modelled post-fire active layer thickness for wildfire scenarios at the black spruce site (top) and the arctic fen (bottom) for climate change scenarios. The modelled wildfire scenarios are: no burn, scenario #2 (black line); a wildfire that removes 20 cm of organic soil in 2014 (+burn, scenario #7); and a mild wildfire that removes 5 cm of organic soil in 2014 followed by a severe burn that removes 20 cm of organic soil in 2075 (+fire frequency, scenario #2) (solid grey lines). The dashed line represents the control climate scenario (scenario #1). Note that AcLTh is relative to the original peat surface, not the post-burn peat surface for the wildfire scenarios.

DISCUSSION

While AcLTh increased by 26−39 % in +warm scenarios, neither site had talik formation (a perennial thawed layer between seasonally frozen soil and the permafrost table) in 0−3 m in 2096−2100. The results from the arctic fen compare well with other predictions of climate change impacts. Zhang *et al.* (2008) also predict no talik formation or surface permafrost thaw in the area of the arctic fen by 2100. We found an increase in thaw season length of 23−30 days between 2001−2010 and 2091−2100 (Figure 6) at the arctic fen; this compares well with satellite observations and modelling results from other studies in the northern hemisphere that found an increase of 0.30−0.48 days per year from 1988 to 2000 (Euskirchen *et al.* 2006). Results from the black spruce site were mixed and are consistent with current field conditions (no permafrost degradation); but permafrost thaw currently affects > 42 % of the permafrost area within the Tanana River floodplain where the black spruce site is located (Jorgenson *et al.* 2001), and others have predicted AcLTh > 3 m by 2100 (Jiang *et al.* 2012). Differences in future predictions at the black spruce site may have been due to a contemporary bias of surface temperature data for model input (about -3.5 °C cooler than observed temperatures). Observed maximum temperatures at 100 cm depth were -0.15 °C in 2005 (Harden 2009), and surface temperatures are predicted to warm 3.5 °C by 2100.

The effects of fire on the AcLTh of permafrost soils at the black spruce site were limited to the period modelled with increased surface soil temperatures post-fire and prior to modelled vegetation recovery (Figure 7); differences in AcLTh were generally less than 5 cm after 20 years. Unlike the black spruce site, long-term differences in AcLTh of ~8 cm persisted at the arctic fen. The organic layer at the black spruce site was reduced to 5 cm, and this reduction resulted in lower soil temperatures and a shallower active layer. O'Donnell *et al.* (2009) also found lower temperatures in boreal peatland sites following wildfire. However, a long-term study of the effects of surface organic soil removal by wildfire showed a persistent increase in depth to permafrost after 36 years (Dyrness 1982, Viereck *et al.* 2008), which is more consistent with our findings at the arctic fen. The difference in site responses to wildfire is probably due to different post-fire peat thickness, which determines soil heat retention and loss.

Modelled soil temperatures in 2100 were affected more by climate change than by wildfire due to the transient nature of the simulated fires. We expected that soil temperatures under wildfire would respond differently to inter-annual variability than climate change scenarios; but inter-annual AcLTh dynamics were actually almost identical (Figure 7). Removing organic soil resulted in a small increase of AcLTh variability; changing soil moisture had similar effects. AcLTh responded most strongly to increases in temperature, while removal of organic soil (Figure 7) and differences in moisture (Figure 5) resulted in small differences. The small response of AcLTh to the removal of organic soil was surprising given other results using the GIPL-2.0-Peat model which indicated that the representation of organic soils was important to capture active layer thicknesses (Wisser *et al.* 2011). While soil moisture and water table depth varied annually, it is possible that holding the water table constant over the growing season meant that temperature and soil moisture could not be fully coupled, and this resulted in a strong temperature effect and a minimal moisture effect rather than a stronger interaction under dry conditions with a low water table. However, modelling soil temperatures at the arctic site using a constantly high water table throughout the year performed as well in a sensitivity analysis as using a measured water table (Figure 8).

Our predictions of soil warming for the future are probably conservative. The model validation, driven by observed weather data, showed an under-estimation of thaw days at depth in the peat, indicating that the model was biased towards lower soil temperatures. In addition, the surface soil temperatures from the global climate model were also lower than observations during the period of overlap. Both factors combine to lead to conservative estimates of permafrost thaw; in reality, soil temperatures in the future will probably be higher than GIPL-2.0-Peat predictions. We predict higher soil temperatures at the surface (4.2 °C and 5.2 °C) and at 2.5 m (3.5 °C and 4.3 °C) at the black spruce and arctic fen sites, respectively, which will probably increase decomposition rates at depth given favourable soil moisture conditions.

In conclusion, climate change simulations resulted in increased AcLTh at both sites by 2100 as well as longer thaw season at the arctic fen, suggesting a longer period of biological activity in the future. The effects of wildfire on AcLTh and soil temperatures were strongest during the period of post-fire recovery and persistent effects were site-dependent, while the effects of climate change on AcLTh persisted and were larger than disturbance effects by 2100. The effects of climate change and wildfire may be significantly increased by other ecosystem-level changes associated with permafrost

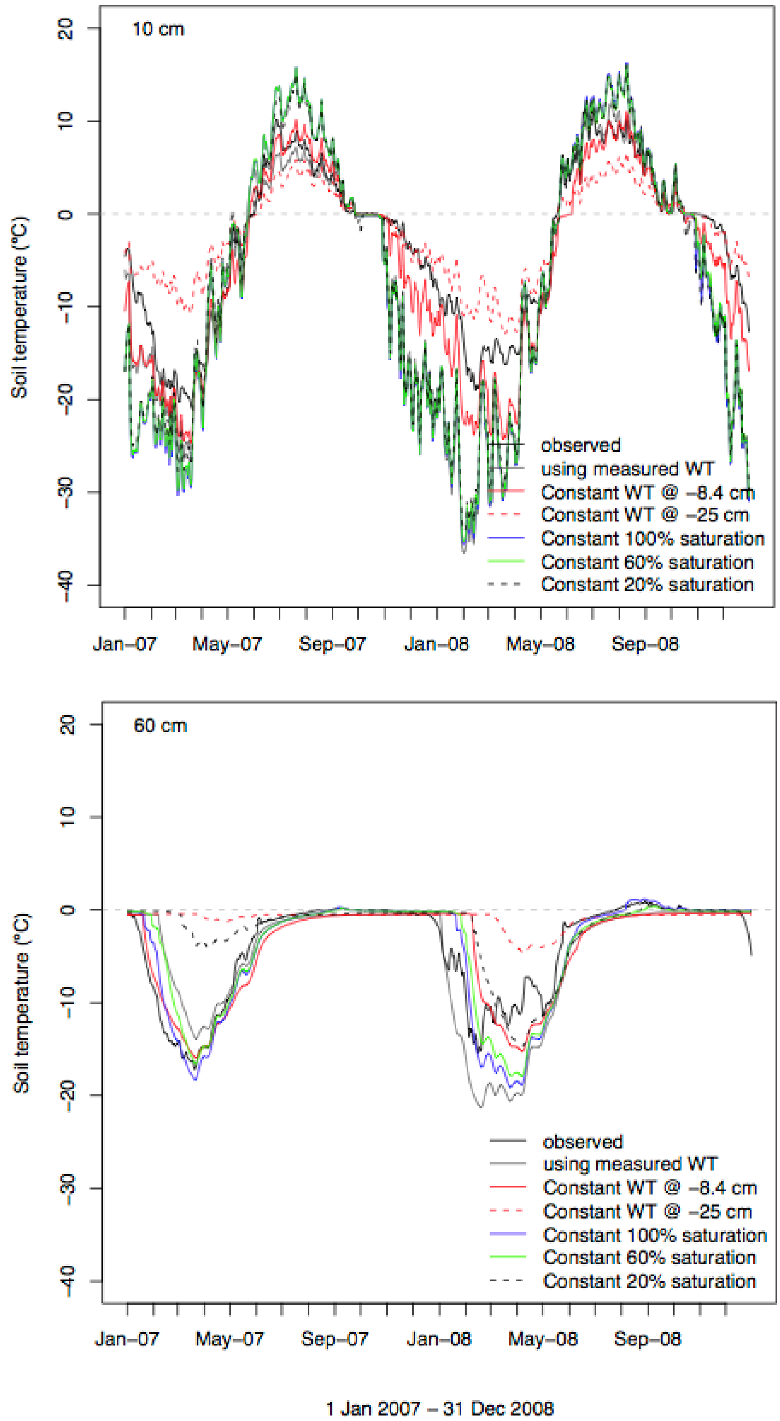

Figure 8. Modelled and measured soil temperatures at 10 cm (top) and 60 cm (bottom) at the arctic fen site. Observed soil temperatures are plotted in solid black, and soil temperatures modelled using the measured water table are plotted in grey. Modelled soil temperatures using five additional water table scenarios are shown: 1) using a constant water table throughout the year at -8.4 cm, which was the mean water table depth for the two years (solid red line); 2) constant water table throughout the year at -25 cm, the minimum water table depth during the period (dashed red line); 3) constant soil moisture throughout the year and the peat column at 100 % saturation (water table depth = 0 cm; solid blue line); 4) constant soil moisture throughout the year and the peat column at 80 % saturation (solid green line); and 5) constant soil moisture throughout the year and the peat column at 20 % saturation (dashed grey line).

thaw and disturbance, such as flooding or vegetation change, through changes in albedo that alter the site radiation budget. However, discrepancies between current observations and global climate model output suggest that there is high uncertainty associated with the future climate scenarios that led to conservative estimates of future soil temperature increases.

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