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Simulating peatland methane dynamics coupled to a mechanistic model of biogeochemistry, hydrology, and energy: Implications to climate change

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Abstract

Northern peat lands have a strong potential to modify climate through changes in soil organic carbon (SOC) and methane (CH_4). A dynamic interaction among climate, soil physical properties (e.g., temperature and moisture), and biogeochemistry (e.g., quantity and quality of SOC) determines the peat land system. Due to this interaction, CH_4 production, oxidation, and transport dynamics changes dramatically under climate change. To appropriately study the future CH_4 in a predictive manner, a simulation model must be able to reproduce the inherent dynamic interaction in the peat land system.

Here, these complex interactions were simulated simultaneously in a biogeochemical peat land model coupled with mechanistic soil hydrology and thermal dynamics (ED2.0-peat). The model successfully reproduced soil physical profiles and the resultant SOC and CH_4 observed in a poor fen of northern Manitoba. With an experimental simulation of 4°C warming, a significant long-term decline in CH_4 emission was found, caused by a loss in substrate and prevalence of aerobic conditions. However, there was a transient increase in CH_4 emission shortly after warming because of time lag between the temperature dependence of microbial activity (a fast response to climate change) and the loss in peat depth (a slow response).

1. Introduction

High latitudinal regions are predicted to undergo particularly intensive warming (Holland and Bitz, 2003), with SOC in northern peat lands likely to be strongly affected (Ise et al., 2008). Peat decomposition has a potential to induce a strong biogeochemical feedback to the global climate system by adding excess CO_2 to the atmosphere (Friedlingstein et al., 2006). In addition, northern peat lands are a large source of CH_4, (~10%; Schlesinger, 1997; Frolking et al., 2006), another major greenhouse gas. Developing a process-based understanding of peat land dynamics therefore is critical to predicting peat land responses to climate and feedbacks onto global climate.

Soil thermal and moisture conditions strongly controls wetland CH_4 dynamics, in addition to SOC accumulation and decomposition (Pelletier et al., 2007). The position of water table is the essential determinant of peat land CH_4 dynamics because CH_4 production by methanogens is a strictly anaerobic process, and CH_4 oxidation by methanotrophs consumes CH_4 in aerobic layers (Fig. 1). In addition, those biological processes are dependent on temperature of each layer. To accurately simulate CH_4 dynamics of a peat land, appropriate reproduction of short-term (sub-daily), depth-structured soil physics (i.e., hydrology and energy) is needed.

Moreover, in long-term, changes in peat quantity and quality that alter substrate conditions should be appropriately represented. Biogeochemical and physical dynamics in organic soils are markedly different from those in mineral soils. In particular, the amount of SOC stored in peat affects its physical properties, with peat surfaces rising and falling as SOC changes. During periods of SOC accumulation, the area becomes moister as humified peat generally has a higher water holding capacity and a lower hydraulic conductivity than mineral soils (Clymo, 1984). This causes the water table to rise, and the resultant anaerobic condition slows SOC decomposition, leading to further accumulation (positive feedback). The rate of water table rise does not keep up with the peat growth rate indefinitely, however, and thus this eventually acts as a negative feedback on further SOC accumulation (the proportion of SOC below water table becomes smaller through time, and the resultant higher decomposition rate restricts peat growth; Ise et al., 2008). Water table depth, which is a critical factor regulating decomposition rates, should be simulated from hydrological changes in the physical characteristics of peat, thereby capturing those feedbacks on SOC accumulation and decomposition. To our knowledge, only ED2.0-peat (Ise et al., 2008) has examined those processes simultaneously and mechanistically. Thus the mechanistic calculation of soil energy and moisture by ED2.0-peat is advantageous to study the future trend of CH_4 in a predictive manner, under various environmental conditions.

In this paper, we introduce CH_4 production, oxidation, and transportation sub models into ED2.0-peat—a peat carbon model with dynamic hydrological and thermal processes—to simulate peat land CH_4 dynamics in a predictive manner, together with dynamically-changing soil conditions. The peat biogeochemical model is coupled with a soil physics model, allowing peat depth to change with SOC, and simulate the resultant changes in soil properties. As a continuation from Ise et al. (2008), we parameterize the model with field observations from a poor fen in Manitoba, Canada and evaluate the model with the observed SOC, CH_4 emission rate, soil temperature, and water table depth. Using an experimental warming, responses of peat SOC to a warming climate are then studied. It should be noted that the explicit reproduction of the dynamic peat land system (i.e., vertical

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profiles of temperature, moisture, and SOC) is the prerequisite for the predictive study of CH_4 dynamics, and we describe the model structure and outputs of ED2.0-peat accordingly.

2. Methods

ED2.0-peat was applied to the Northern Study Area (NSA) Fen site of the Boreal Ecosystem and Atmosphere Study (BOREAS; Sellers et al., 1995; Trumbore and Harden, 1997) in northern Manitoba, Canada. This study area is close to the northern limit of boreal forest, and in the discontinuous permafrost zone (Veldhuis et al., 2002). The area is periodically covered by standing water especially in spring.

The site-specific parameters were obtained and summarized from the BOREAS dataset. The average bulk density of fibrous peat is 0.092 gSoil/cm³. The average bulk density of humic peat (0.38 gSoil/cm³) is taken from the modal estimate for Oh horizons in BOREAS Northern Study Area, among the range of 0.13 gSoil/cm³. The carbon fraction of fibrous peat is 0.4 gC/gSoil, and that of humic peat is 0.3 gC/gSoil (Apps and Halliwell, 1999). Litter input rate to fibrous layer was estimated from the net primary productivity (NPP) reported by Bond-Lamberty et al. (2004; 0.26 kgC m⁻² y⁻¹) and partitioned into labile (0.17 kgC m⁻² y⁻¹) and recalcitrant (0.09 kgC m⁻² y⁻¹) fractions according to a relationship between nitrogen density and lignin fraction of plant biomass described by Parton et al. (1987), using a generalized lignin fraction of boreal forest species including bryophytes calculated by Ise and Moorcroft (2006). Meteorological data (1994-2005) from the eddy covariance tower at the Old Black Spruce site (OBS; 7 km southwest of the Fen site; Dunn et al., 2007) were used to drive the simulation with a 30-minute time step. Missing meteorological data (<10%) were filled with data from the closest weather station at Thompson Airport, Manitoba (39 km east of the site).

ED2.0-peat model structure and data acquisition are described in detail by Ise et al. (2008). To evaluate the model performance, ED2.0-peat was first driven by the meteorological data of 1994, the year of the BOREAS field campaign for soil thermal and hydrological observation at the Fen site. Mean water table depth, soil temperature, and CH_4 emission data of 4 observation subsides at Fen site for year 1994 were calculated to evaluate the model. 12 years of meteorological data (1994-2005) from the OBS flux tower were then used repeatedly to drive long-term simulations (see Supplementary Information in Ise et al. (2008) for the 12-year variability in simulation). To obtain insights about possible effects of future climate change, transient responses of the peat land system under the climate change and SOC sensitivities under a new climate regime were studied. We simulated CH_4 production, oxidation, transport, and emission to the atmosphere at NSA Fen site based on Walter and Heimann (2000) and parameterization was identical to their application to a poor fen in Michigan unless otherwise noted below.

The dynamic peat depth is characteristic to ED2.0-peat, and the CH_4 dynamics simulation is applied to each peat layer separately (Fig. 1). The position of water table determines the ratio between CH_4 production and oxidation. CH_4 production rates are different among substrates (fibrous and humid peat). The CH_4 production rate of the fibrous layer $R_{prod\,f}$ [µmol m⁻² h⁻¹] is:

$$R_{prod \cdot f} = R_0 \cdot f_{labile \cdot f} \cdot f_{in} \cdot TD_f \cdot 1000 \cdot z_f \cdot f_{anox \cdot f} \tag{1}$$

where TD_f is the temperature dependence factor of the fibrous layer calculated as equation 5 in Walter and Heimann (2000), with mean soil temperature of that layer simulated by ED2.0-peat. $f_{labile\ f}$ is the relative liability of fibrous layer (1.0) based on Ise and Moorcroft (2006). R_0 is the CH₄ production rate [μM h⁻¹] at the reference temperature, as described in Walter and Heimann (2000). The depth of the fibrous layer z_f and the anoxic fraction of that layer $f_{anox\cdot f}$ are obtained from ED2.0-peat (Ise et al., 2008). Similarly, CH₄ production from humid layer is:

$$R_{prod\cdot h} = R_0 \cdot f_{labile\cdot h} \cdot f_{in} \cdot TD_h \cdot 1000 \cdot z_h \cdot f_{anox\cdot h} \qquad (2)$$

TD_h, z_h, and $f_{anox\cdot h}$ are based on ED2.0-peat variables. $f_{labile\ f}$ is the relative liability of humid layer (0.044) based on Ise and Moorcroft (2006). Then, CH₄ oxidation rates of the fibrous layer $R_{oxid\ f}$ [μmol m⁻² h⁻¹] and the humid layer $R_{oxid\ h}$ [μmol m⁻² h⁻¹] is Michaelis-Menten type functions of CH₄ concentration of each layer $[CH_4]_f$ and $[CH_4]_h$, respectively:

$$R_{oxid\cdot f} = V_{max} \cdot \frac{[CH_4]_f}{k_m + [CH_4]_f} \cdot TD_f \cdot 1000 \cdot z_f \cdot \left(1 - f_{anox\cdot f}\right) \qquad (3)$$

$$R_{oxid\cdot h} = V_{max} \cdot \frac{[CH_4]_h}{k_m + [CH_4]_h} \cdot TD_h \cdot 1000 \cdot z_h \cdot \left(1 - f_{anox\cdot h}\right) \qquad (4)$$

where V_{max} and K_m are oxidation parameters described by Walter and Heimann (2000). Three modes of CH₄ transport (diffusion, bubbling, and vascular transport) were explicitly modeled. We assume that the plant rooting depth is at the boundary between fibrous and humid peat and root distribution is uniform. Thus, when the water table is above this boundary, the fast CH₄ transportation through ebullition (bubbling) occurs as described in Walter and Heimann (2000).
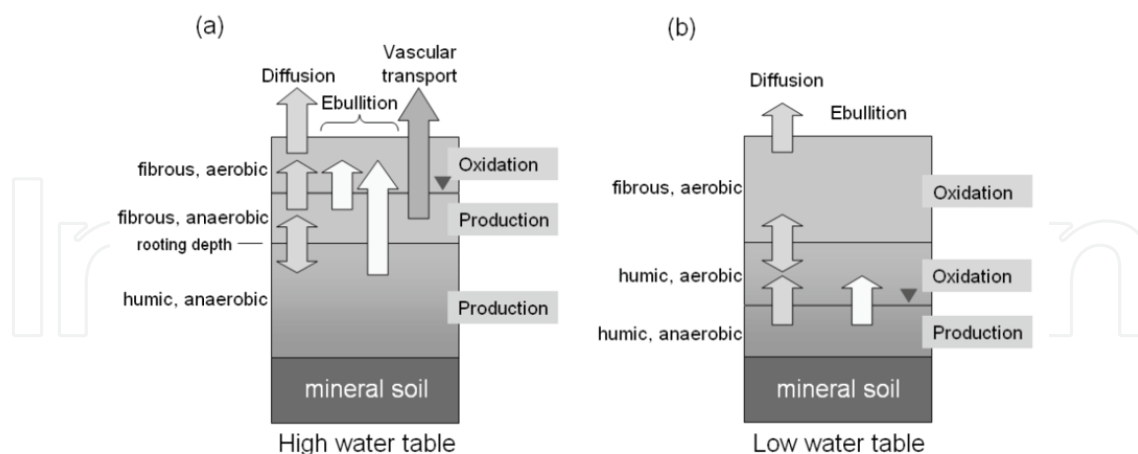

Fig. 1. Schematic diagram of ED2.0-peat, when water table is in fibrous layer (a) or in humic layer (b). Position of water table determines proportions of aerobic vs. anaerobic peat depth in each layer. CH₄ production occurs in anaerobic layers, and CH₄ oxidation occurs in aerobic layers. Three modes of CH₄ transportation are also shown. Diffusion is a slow, continuous process driven by CH₄ concentration gradient. Ebullition occurs when CH₄ concentration of an anaerobic layer exceeds a threshold (see section 2). When water table is above rooting depth, CH₄ is also transported through plant vascular system (see section 2).

To evaluate the model performance, we compared the simulation results by ED2.0-peat against field-observed data of water table depth, soil temperature at 10 cm below peat surface, and CH_4 emission rate from BOREAS NSA Fen site for 1994. Observed variables are gap-filled composites from 4 observation subsides and 32 measurement collars located in hummock, hollow, lawn, and moat. Gaps in the data were filled by linear interpolation. Each measurement time series are weighted equally to estimate mean and variance. Residuals were assumed to be normally distributed to generate 95-percent confidence intervals.

3. Results

The model reasonably reproduced water table and soil temperature dynamics observed at the site for 1994 (Fig. 2). ED2.0-peat generally captured seasonal patterns of soil thermal and moisture conditions, and the simulated trends were generally within the range of intra-site variations. There were some notable, systematic underestimate in the simulation of soil temperature in early summer because ED2.0-peat lacked treatment of lateral water flow that can bring a large amount of warm surface water into the site, which is typical for fens especially after soil melt. CH_4 emission rates were influenced by soil temperature and water table position and showed a similar seasonal pattern with these soil physical properties. The simulated CH_4 dynamics was generally consistent with the field observation. The SOC accumulation under the current climate was 116 kgC/m^2, (Ise et al., 2008), within the estimate range of 79-120 kgC/m^2 based on field studies (Trumbore and Harden, 1997).

Fen SOC was very sensitive to climate change. An experimental warming of 4°C caused an 86% loss of SOC (Fig. 3), because of the higher sensitivity caused by a positive feedback process between water loss and decomposition; an acceleration in SOC decomposition caused by the warming lowered the water table, resulting in further decomposition due to enhanced aerobic conditions (Fig. 3a and b). A reduction in summer-time soil insulation also accelerated decomposition (see Ise et al., 2008). Because of the radical changes in soil depth and hydrological and thermal environments, CH_4 emission responded to the climate change sensitively and showed a complex trajectory (Fig. 4). Due to the drier conditions caused by the climate change and loss in substrate, the equilibrium CH_4 emission rate under the warmer climate regime was significantly smaller than that under the current climate. However, the warming caused a transient increase in CH_4 emission due to the temperature dependency of methanogenic microorganisms (fast response: dominating in simulation years 2000-2100). Then, however, the SOC exposed to warmer and drier climate started to decompose and the reduction in soil depth and water holding capacity eventually decreased CH_4 emission (slow response). During the transition period after the climate change (simulation years 2200-2700), the water table was periodically in humid layer (Fig. 3b), and this caused dramatic reduction of CH_4 emission. After simulation year 2700, the new equilibrium of peat system was established and the mean position of water table is again in the fibrous layer, and thus the CH_4 emission rates were partially recovered.
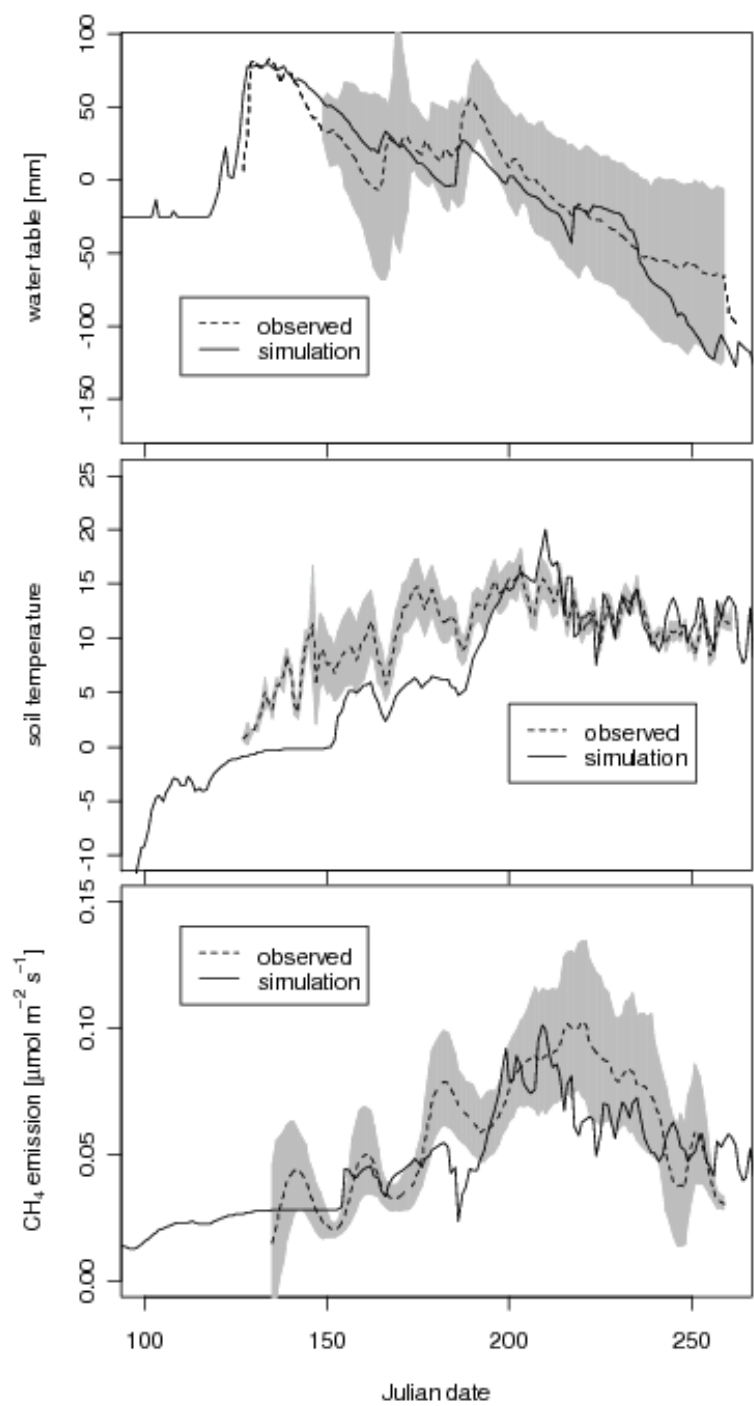
Fig. 2. (a) Water table depth, (b) soil temperature [°C] at 10 cm below peat surface, and (c) CH_4 emission dynamics for BOREAS Fen site in 1994. Observed variables are gap-filled composite datasets from 4 observation subsides and 32 measurement collars located in hummock, hollow, lawn, and moat. Each measurement time series are weighted equally to estimate mean and variance. Residuals were assumed to be normally distributed to generate 95-percent confidence intervals (grey shades).
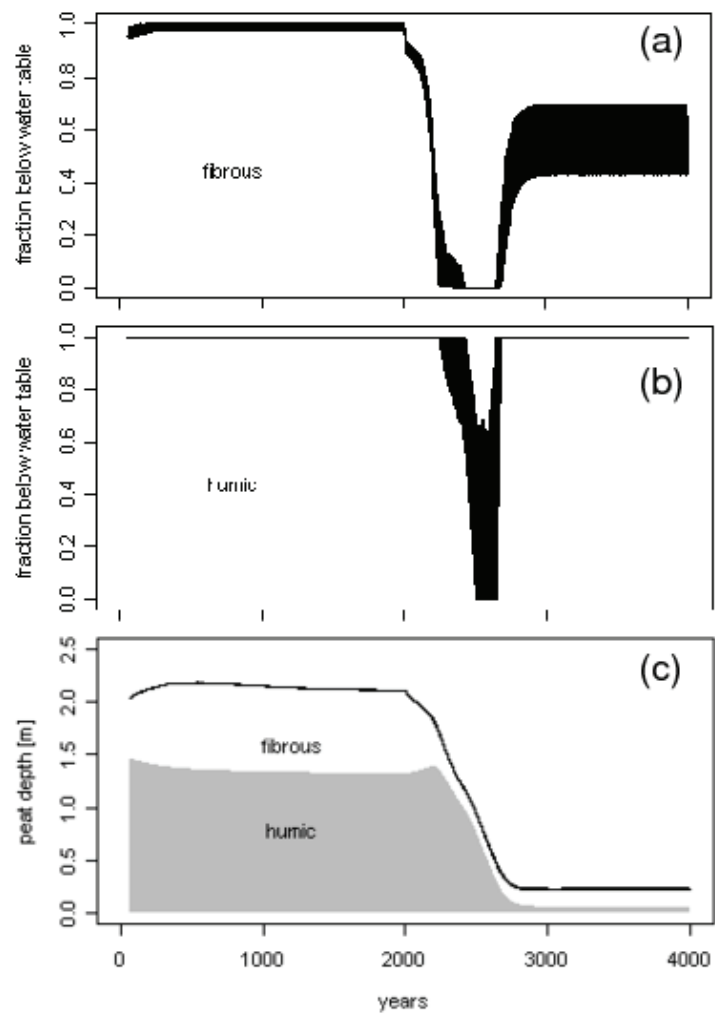
Fig. 3. 4000-year simulation of 12-year means of fraction below water table, (a) fibrous and (b) humid layers and (c) changes in peat depth. This simulation is applied to BOREAS Northern Study Area Fen site. 1994-2005 meteorological data is used repeatedly for this 4000-year simulation. A uniform rise of temperature by 4°C is applied after simulation year 2000.
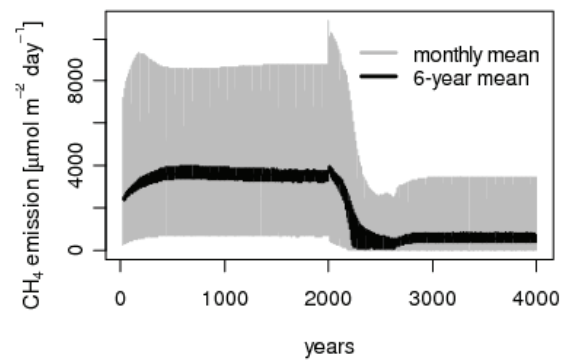
Fig. 4. 4000-year simulation of CH_4 emission from BOREAS Northern Study Area Fen site. 1994-2005 meteorological data is used repeatedly for this 4000-year simulation. A uniform rise of temperature by 4°C is applied after simulation year 2000.

4. Discussion

To our knowledge, this study is the first attempt to simulate CH_4 dynamics with a physics-based, fast-timescale model of soil temperature and moisture coupled to a long-term, biogeochemical model. ED2.0-peat captured the essential physical dynamics of BOREAS NSA Fen site. The short-term CH_4 dynamics with environmental dependency was reasonably reproduced. In contrast to the preexisting CH_4 models (e.g., Walter and Heimann, 2000), ED2.0-peat does not need soil moisture and temperature data as forcing variables. Thus, this model can be used in a predictive manner, under the future environmental changes. Moreover, ED2.0-peat explicitly considers long-term changes in soil properties such as peat depth. Thus, the CH_4 dynamics under a novel environment is estimated from an integrated system of soil temperature, moisture, and biogeochemistry. In addition, due to the characteristics of a mechanistic physics model, the model can reproduce a transient behavior in CH_4 dynamics under climate change. Together with a study for the shallow peat site (Ise et al., 2008) ED2.0-peat correctly reproduced soil biophysics of various peat lands in Northern Manitoba.

To appropriately study the future CH_4 in a predictive manner, ED2.0-peat explicitly simulated the dynamic interaction of soil temperature, moisture, and SOC in the peat land system. Our modeling scheme with mechanistically simulated soil hydrological and thermal processes has implications to future climate-soil interactions. An increase in temperature due to anthropogenic climate change will affect SOC decomposition rates because of their sensitivity to temperature. The Fen site lost 86% of SOC when subjected to a warming of 4°C, a rather conservative estimate of projected long-term climate change in boreal regions (IPCC, 2007). This significant collapse of peat land SOC is plausible when the global distribution of SOC is considered (Fig. 5). The transition from boreal to temperate biomes is currently characterized by a significant loss in stored SOC. If a temperature rise of 4°C at this site allows it to cross this threshold, a considerable shift in equilibrium SOC may occur. However, it should be noted that the Fen site also showed transient resistance against the collapse (Fig. 3c, simulation years 2000-2200); during the first few hundred years after the climate change, the decrease in SOC is rather slow, due to recalcitrance of slowly decomposing SOC.
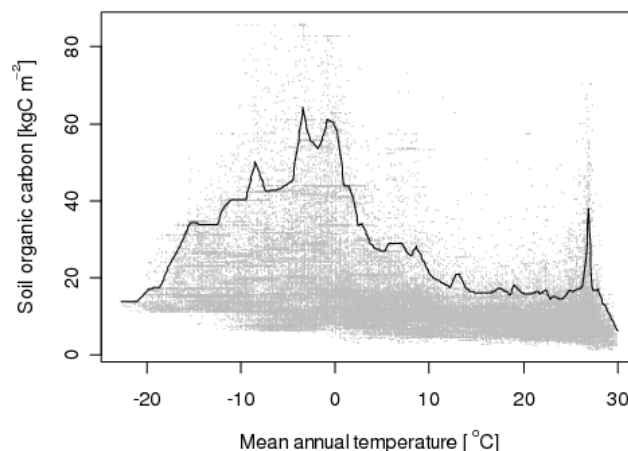

Fig. 5. Global pattern of terrestrial SOC and mean annual temperature. Data from 1° x 1° mean annual temperature of 1961-1990 and SOC up to 1 m (Global Soil Data Task 2000). The curve is a piecewise 90-percentile quintile regression.

For this study, as noted in Ise et al. (2008), we intentionally turned off the dynamic vegetation processes of ED2.0 (Medvigy et al., 2009) to construct the current version of ED2.0-peat. Responses of vegetation processes against climate change such as litter production may have a strong effect on CH_4 dynamics through substrate quantity and quality. However, as shown here, this study is the first attempt to explicitly simulate a long-term physical interplay between soil properties and biogeochemistry, and the resultant transient dynamics was complex and nonlinear. Our aim here was to show the inherent behavior in soil. Considering dynamic vegetation will increase the complexity of the system further, and a systematic analysis will be very difficult. Thus, we kept the model as simple as possible for this study, and an explicit treatment of dynamic vegetation will be our next project. In summary, this study has shown how the mechanistic linkages that exist between the physical and biogeochemical dynamics of peat lands have strong implications for the response of northern peat lands to climate change.

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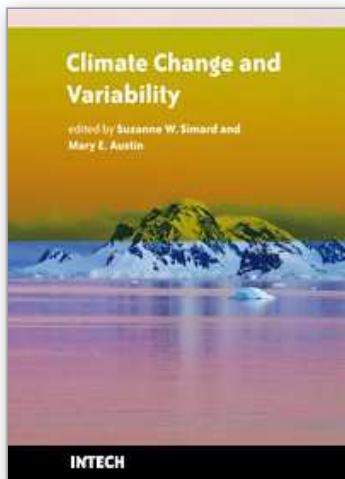
Climate Change and Variability

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Climate change is emerging as one of the most important issues of our time, with the potential to cause profound cascading effects on ecosystems and society. However, these effects are poorly understood and our projections for climate change trends and effects have thus far proven to be inaccurate. In this collection of 24 chapters, we present a cross-section of some of the most challenging issues related to oceans, lakes, forests, and agricultural systems under a changing climate. The authors present evidence for changes and variability in climatic and atmospheric conditions, investigate some the impacts that climate change is having on the Earth's ecological and social systems, and provide novel ideas, advances and applications for mitigation and adaptation of our socio-ecological systems to climate change. Difficult questions are asked. What have been some of the impacts of climate change on our natural and managed ecosystems? How do we manage for resilient socio-ecological systems? How do we predict the future? What are relevant climatic change and management scenarios? How can we shape management regimes to increase our adaptive capacity to climate change? These themes are visited across broad spatial and temporal scales, touch on important and relevant ecological patterns and processes, and represent broad geographic regions, from the tropics, to temperate and boreal regions, to the Arctic.

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