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Key Points:
- A model is validated against C fluxes under manipulated soil temperature and WT
- Impacts of changes in air temperature and soil water on C fluxes are predicted
- The fen may change from a net GHG sink into a net GHG source

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Modeling impacts of changes in temperature and water table on C gas fluxes in an Alaskan peatland

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Abstract Northern peatlands have accumulated a large amount of organic carbon (C) in their thick peat profile. Climate change and associated variations in soil environments are expected to have significant impacts on the C balance of these ecosystems, but the magnitude is still highly uncertain. Verifying and understanding the influences of changes in environmental factors on C gas fluxes in biogeochemical models are essential for forecasting feedbacks between C gas fluxes and climate change. In this study, we applied a biogeochemical model, DeNitrification-DeComposition (DNDC), to assess impacts of air temperature (T_A) and water table (WT) on C gas fluxes in an Alaskan peatland. DNDC was validated against field measurements of net ecosystem exchange of CO_2 (NEE) and CH_4 fluxes under manipulated surface soil temperature and WT conditions in a moderate rich fen. The validation demonstrates that DNDC was able to capture the observed impacts of the manipulations in soil environments on C gas fluxes. To investigate responses of C gas fluxes to changes in T_A and soil water condition, we conducted a series of simulations with varying T_A and WT. The results demonstrate that (1) uptake rates of CO_2 at the site were reduced by either too colder or warmer temperatures and generally increased with increasing soil moisture; (2) CH_4 emissions showed an increasing trend as T_A increased or WT rose toward the peat surface; and (3) the site could shift from a net greenhouse gas (GHG) sink into a net GHG source under some warm and/or dry conditions. A sensitivity analysis evaluated the relative importance of T_A and WT to C gas fluxes. The results indicate that both T_A and WT played important roles in regulating NEE and CH_4 emissions and that within the investigated ranges of the variations in T_A and WT, changes in WT showed a greater impact than changes in T_A on NEE, CH_4 fluxes, and net C gas fluxes at the study fen.

1. Introduction

Due to cold and wet conditions, northern peatlands have sequestrated a substantial amount of atmospheric carbon dioxide (CO_2) into soils since the Last Glacial Maximum [*Yu et al.*, 2010]. Although carbon (C) stocks in northern peatlands are still uncertain [e.g., *McGuire et al.*, 2009; *Tarnocai et al.*, 2009; *Yu et al.*, 2010], these C stocks are regarded to have significant impacts on the global C budget and atmospheric CO_2 change [e.g., *Schuur et al.*, 2008, 2013]. Most northern peatlands acted as sinks of CO_2 in the past and under current climate [e.g., *Lund et al.*, 2010; *McGuire et al.*, 2009]. However, peat C stocks are sensitive to climate change and may become more vulnerable to decomposition under future climate [e.g., *Frolking et al.*, 2011; *Schädel et al.*, 2014]. In addition, because of prevailing anaerobic soil conditions, northern peatlands are an important source of atmospheric methane (CH_4), releasing 31–65 Tg CH_4 yr^{-1} [*McGuire et al.*, 2009].

While climate warming has been observed over the globe during the last few decades, the greatest warming has occurred in northern high latitudes [*Arctic Climate Impact Assessment*, 2005; *Intergovernmental Panel on Climate Change* (*IPCC*), 2013]. Model projections of climate change indicate a continuation of this trend through the remainder of the 21st century [*IPCC*, 2013]. As a result of climate warming, increasing soil temperature and degradation of permafrost have been documented in northern areas [e.g., *Osterkamp*, 2007; *Payette et al.*, 2004; *Åkerman and Johansson*, 2008]. Alterations of soil water due to climate change are also becoming apparent in northern regions, although both increased wetness [e.g., *Payette et al.*, 2004] and dryness [e.g., *Hinzman et al.*, 2005] have been recorded at different locations. These impacts on soil environments can substantially change the emissions of greenhouse gases, such as CO_2 and CH_4, from northern ecosystems and therefore have a strong potential for influencing atmospheric concentration of the gases [e.g., *Dorrepaal et al.*, 2009; *Holden*, 2005; *McGuire et al.*, 2009].

Although much concern has been placed on emissions of C gases from northern peatlands, considerable uncertainty still exists [e.g., *Limpens et al*., 2008; *McGuire et al*., 2009; *Schuur et al*., 2011]. Carbon exchange between ecosystems and the atmosphere is subject to complex rate controls involving the interaction of numerous environmental factors, such as soil temperature and moisture status, quantity and quality of soil organic matter (SOM), soil nutrients, and vegetation characteristics [e.g., *Conant et al*., 2011; *Jungkunst and Fiedler*, 2007; *Olefeldt et al*., 2013]. Combinations of these factors have resulted in considerable variation in C gas fluxes in northern areas, both at local and landscape scales [e.g., *Bäckstrand et al*., 2010; *Lund et al*., 2010; *Sachs et al*., 2010]. Uncertainty also exists regarding responses of C balance to changes in soil physical environments (e.g., soil temperature and water conditions). Therefore, it is essential to understand these responses and to develop credible forecasts of feedbacks between the dynamics of ecosystem C and the climate system.

Process-based models are important tools for assessing responses of boreal ecosystems to climate change. Several large-scale models have been applied to evaluate the impacts of climate change on C gas fluxes in the northern region [e.g., *Schneider von Diemling et al*., 2012; *Wania et al*., 2009a, 2009b; *Zhuang et al*., 2006]. However, these evaluations are uncertain, due to the fact that mechanisms about the responses of boreal ecosystems to environmental changes are usually addressed differently in these models and the validations regarding the model's ability of simulating these responses are still limited [e.g., *Friedlingstein et al*., 2006]. In addition, predictions by large-scale models have generally been conducted at coarse spatial resolutions and have not effectively considered the effects of local spatial heterogeneity. By ignoring fine-scale spatial heterogeneity in key environmental factors, systematic biases may occur in the simulations of C gas fluxes [*Bohn and Lettenmaier*, 2010; *Zhang et al*., 2013].

In this study, we applied a process-based biogeochemical model to assess impacts of changes in temperature and soil water conditions on C gas fluxes in an Alaskan peatland. The model was applied to simulate net ecosystem exchange of CO_2 (NEE) and CH_4 fluxes from a rich fen with manipulations in soil surface temperature and water table (WT). Rich fens are abundant across the boreal region but have been less studied than more ombrotrophic, *Sphagnum*-dominated peatlands. Simulations were compared against field measurements to verify whether the model can capture the observed impacts of the changes in soil environments on C gas fluxes. We then used the validated model to assess the impacts of changes in air temperature (T_A) and WT on C gas fluxes and on mechanisms controlling these fluxes.

2. Methods and Data

2.1. The Study Site and Field Measurements

The study site is a moderate rich fen (64.82°N, 147.87°W) near the boundaries of the Bonanza Creek Experimental Forest (BCEF) in the interior region of Alaska, United States. This area has a continental climate, with an annual mean air temperature of −2.9°C and an average annual precipitation of 269 mm [*Hinzman et al*., 2005]. The site lacks trees and is dominated by brown moss, *Sphagnum*, and emergent vascular species (*Equisetum*, *Carex*, and *Potentilla*). The study fen contains no distinct microtopography, and the peat thickness is approximately 1 m [*Turetsky et al*., 2008].

An ecosystem-scale experiment was conducted at the study fen to investigate impacts of soil thermal and water conditions on C cycling in Alaskan peatlands [*Turetsky et al*., 2008]. The experiment established a factorial design of surface soil temperature (control versus passive soil warming using open top chambers) and water table position (control, lowered, and raised WT) manipulations and thereby included six treatments, i.e., control, control and surface soil warming, lowered WT, lowered WT and surface soil warming, raised WT, and raised WT and surface soil warming. In the first several years of the experiment, the soil warming treatment elevated the surface soil temperature during growing season by 0.7, 0.9, and 0.6°C, respectively, for the control, lowered WT, and raised WT treatments in comparison with the setting without soil warming [*Turetsky et al*., 2008]. The WT manipulation effectively maintained differences in soil water, with relatively dry, moderate, and wet conditions under the treatments of lowered, control, and raised WT, respectively. In addition, the study fen was much drier in 2006, indicating interannual differences of soil moisture conditions between 2005 and 2006 (Figure 1).

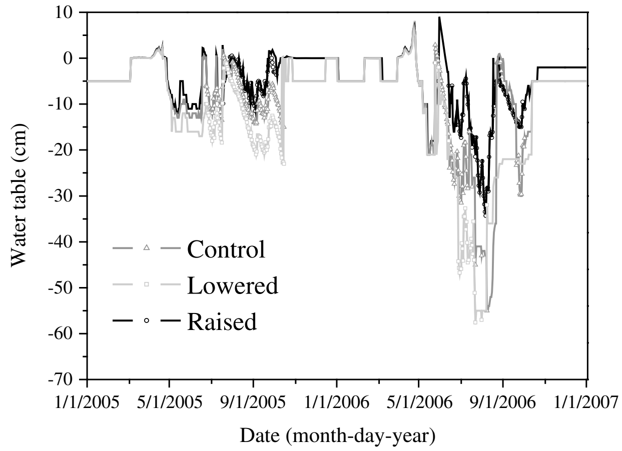

Figure 1. Simulated (lines) and observed (dots) water table dynamics for the treatments of control, lowered, and raised water table. Water table was modeled when there were no observations; otherwise, the observed water table depths were used during simulations (positive values for above ground and negative values for below ground).

The data used for verification of the DNDC model included CO_2 and CH_4 fluxes, which were measured weekly using static chambers during the growing seasons in 2005 and 2006. In addition, hourly WT depth was continuously recorded from June to mid-October each year [*Turetsky et al.*, 2008]. The data were published by *Turetsky et al.* [2008] and *Chivers et al.* [2009] and were used for model validation in this study. Daily meteorological data, including air temperature, precipitation, solar radiation, wind speed, and relative humidity, were recorded at the BCEF site (Figure 2). The technical details regarding the measurements of CO_2 and CH_4 fluxes and the relevant auxiliary data were described by *Turetsky et al.* [2008] and *Chivers et al.* [2009].

The field study indicated that (1) the WT manipulation significantly influenced the NEE at the fen, while the warming in the experimental surface soil (2 cm beneath moss) showed negligible effect on the NEE, and (2) increase in either the WT elevation (i.e., closer to the peat surface) or the surface soil temperature enhanced CH_4 emissions, with the highest emission rate observed under the treatment with both raised WT and warmed soil [*Turetsky et al.*, 2008; *Chivers et al.*, 2009]. The field data indicated that there were interactive impacts between WT and soil warming on CH_4 fluxes, stressing the necessity of considering changes in both soil temperature and moisture when predicting the effects of climate change on CH_4 fluxes from northern peatlands [*Turetsky et al.*, 2008]. The measured data were used to test DNDC for its applicability to predict impacts of the changes in soil environments on NEE and CH_4 fluxes.

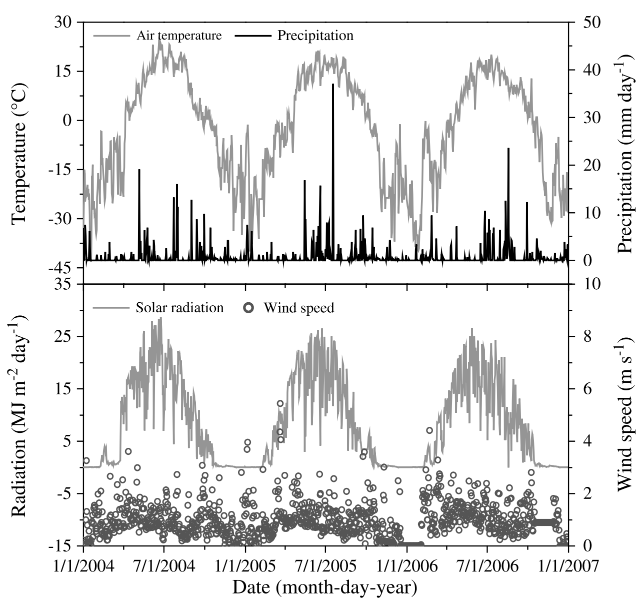

Figure 2. Daily average air temperature, wind speed, precipitation, and solar radiation during 2004 to 2006. Data were recorded at the climate station of Bonanza Creek Experimental Forest.

2.2. The DNDC Model

DNDC is a process-based model developed for quantifying C sequestration as well as carbon and nitrogen (N) gas emissions from terrestrial ecosystems [*Li et al.*, 1992, 2000; *Stange et al.*, 2000; *Zhang et al.*, 2002]. The model is composed of six interacting submodels: soil climate, plant growth, decomposition, nitrification, denitrification, and fermentation. The soil climate, plant growth, and decomposition submodels predict soil environmental factors, such as soil temperature and moisture, pH, redox potential (Eh), and substrate contents, based on the primary drivers, such as climate, topography, soil properties, vegetation, and anthropogenic activities. The nitrification, denitrification, and fermentation submodels simulate C and N biogeochemical processes that are mediated by soil microbes and controlled by soil environmental factors [*Li*, 2000; *Li et al.*, 2012].

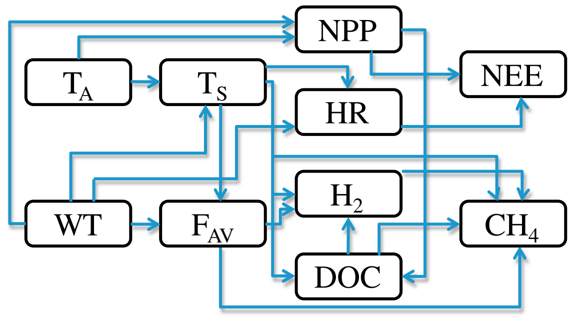

Figure 3. A scheme showing how air temperature (T_A) and water table (WT) control net ecosystem exchange of CO_2 (NEE) and CH_4 emission in DNDC. NEE is directly controlled by net primary production (NPP) and soil microbial heterotrophic respiration (HR), and CH_4 flux is directly controlled by electron donors (i.e., H_2 and DOC), soil temperature (T_S), and fraction of anaerobic volume (F_{AV}) in soil profile, in addition to transport and oxidation processes (not shown). T_A and WT can affect NEE and CH_4 emission through controlling soil temperature (T_S), F_{AV}, NPP, HR, DOC, and/or H_2.

In DNDC, NEE is predicted at a daily time step by simulating dynamics of vegetation growth and soil microbial heterotrophic respiration (HR). Vegetation growth is simulated by considering the effects of several environmental factors, including air temperature, soil moisture, radiation, and N availability. The model predicts the production of plant litter and incorporates the litter into SOM pools. HR is calculated by simulating decomposition of SOM. The model divides SOM into different pools with specific C to N (C/N) ratios and simulates decomposition of each SOM pool based on its specific rate of decomposition as well as soil thermal and moisture conditions [*Li et al.*, 2012]. Methane flux is predicted by modeling CH_4 production, oxidation, and transport processes. CH_4 production is simulated by tracking a series of reductive reactions between electron donors, i.e., H_2 and dissolved organic carbon (DOC) and acceptors, i.e., NO_3^-, Mn^{4+}, Fe^{3+}, SO_4^{2-}, and CO_2. In DNDC, CH_4 production and oxidation can occur simultaneously within a soil layer but within relatively anaerobic and aerobic microsites, whose volumetric fractions are primarily determined based on Eh [*Li*, 2007]. The concentrations of electron donors and acceptors, Eh, temperature, and pH are the major factors controlling the rates of CH_4 production and oxidation. CH_4 is transported from soil into atmosphere via plant-mediated transport, ebullition, and diffusion [*Fumoto et al.*, 2008; *Li*, 2007; *Zhang et al.*, 2002]. Figure 3 shows a simplified representation tracing the major controls from biophysical drivers (air temperature and water table depth) to NEE and CH_4 production in DNDC.

The version of DNDC adopted in this study was recently enhanced for its applicability in high latitudes. Traditionally, DNDC simulated soil thermal dynamics with a relatively simple module. The model did not explicitly simulate energy exchange within soil-snow-vegetation-atmosphere system nor did it consider the presence of permafrost [*Zhang et al.*, 2002]. However, these processes or environmental factors are important for characterizing the soil thermal and moisture status, as well as C and N dynamics in high latitudes [e.g., *Riseborough et al.*, 2008; *Waelbroeck*, 1993]. To make the model more suitable for northern ecosystems, we recently incorporated a permafrost model, NEST, into the DNDC's framework to simulate C dynamics in high-latitude ecosystems [*Zhang et al.*, 2012; *Deng et al.*, 2014]. NEST is a process-based model that simulates ground thermal dynamics, soil freeze/thaw dynamics, permafrost conditions, and soil hydrology in northern ecosystems [*Zhang et al.*, 2003]. To ensure that DNDC could synchronously simulate environmental factors and biogeochemistry in high latitudes, we embedded the NEST's functions into the framework of DNDC at the code level. The new version of DNDC is able to simulate the seasonal dynamics of soil freeze/thaw, soil water content, and their impacts on biogeochemical processes [*Zhang et al.*, 2012; *Deng et al.*, 2014].

2.3. Model Application

2.3.1. Model Validation

We performed DNDC simulations for the six treatments conducted in the field experiment. Daily meteorological data (i.e., maximum, mean, and minimum air temperature, precipitation, solar radiation, wind speed, and humidity) from 2004 to 2006 recorded at the BCEF station (Figure 2) were collected to support the simulations. The study fen has a surface soil layer of peat (1.0 m) overlying a mineral layer with loess and mixed alluvial soil [*Kane et al.*, 2010]. The peat had a mean bulk density of 0.09 g cm^{-3}, soil organic carbon (SOC) content of 0.41 kg C kg^{-1} soil dry weight, and pH (H_2O) of 5.3 [*Kane et al.*, 2013; *Turetsky et al.*, 2008]. The geothermal heat flux in the study region is 0.09 W m^{-2} [*Batir et al.*, 2013]. To simulate vegetation growth, DNDC requires several phenological and physiological parameters, including maximum biomass productivity under optimum growing conditions (MBP), shoot and root fractions, carbon to nitrogen (C/N) ratio of the plant biomass, required thermal degree days for full vegetation growth (TDD),

Table 1. Hydrological Parameters Used for Modeling Lateral Flows[a]

Manipulations	SIR	SOD (m)	SOR	GOD (m)	GOR
Control	1.3	0	0.2	−0.6	0.0001
Lowered water table	1.0	0	0.2	−0.6	0.0001
Raised water table	1.5	0	0.2	−0.6	0.0001

[a]SIR, surface inflow rate, as the fraction of rainfall (or water from snow melt) flowed into the site from its surroundings; SOD, surface outflow depth, the water table (WT) depth (positive for above ground and negative for below ground) above which surface lateral outflow occurs; SOR, surface outflow rate, as the fraction of WT above the SOD which will be lost as surface outflow per day; GOD, ground outflow depth, the deepest WT depth above which ground outflow occurs; GOR, ground outflow rate, as the fraction of WT above the GOD which will be lost as ground outflow per day. These hydrological parameters were determined by calibrating against data sets of water table depth.

plant water requirements (WR), and an index of biological N fixation (NFI). The definitions of these parameters can be found in *Deng et al.* [2014]. In this study, the values of MBP, shoot and root fractions, C/N ratio, TDD, WR, and NFI were estimated as 3500 kg C ha^{-1}, 0.8 and 0.2, 50, 2000°C, 400 g water g^{-1} dry matter, and 1.5, respectively, either by referring local studies [*Churchill*, 2011; *Fan et al.*, 2013; *McConnell et al.*, 2013] or using the model defaults.

While the simulations for the six treatments have common conditions of weather, geology, and vegetation, they differ in soil thermal and moisture regimes. In the field experiments, the soil thermal condition was altered by warming the surface soil. We therefore forced the surface soil temperature to increase into the manipulated level (0.7, 0.9, and 0.6°C for the control, lowered WT, and raised WT plots, respectively) for those simulations with soil warming. In order to predict dynamics of water table, DNDC used several parameters to estimate lateral flows. These parameters include surface inflow rate, maximum WT depths for surface and ground outflows, and surface and ground outflow rates [*Zhang et al.*, 2002]. We estimated the values of these parameters for the control, lowered WT, and raised WT treatments by comparing the modeled and observed water table depth (Table 1). To reduce the influences of the error induced by the WT prediction on biogeochemical processes, the observations of WT were used during the simulations when the measurements were available.

To initialize the soil climate conditions and composition of SOC, DNDC used a 20 year spin-up following *Fumoto et al.* [2008]. The climate data in 2004 were iteratively used for 20 years during the model initialization. Then we proceeded with the simulations for the six treatments by using the climate data in 2005 and 2006. We compared the simulated NEE and CH_4 fluxes (the sign convention is that positive values represent net CO_2 or CH_4 emission into the atmosphere and negative fluxes represent net CO_2 or CH_4 uptake) against the field measurements to evaluate whether the DNDC could reliably predict the impacts of changes in soil thermal and water conditions on C gas fluxes from the experimental peatland.

2.3.2. Investigating Impacts of Air Temperature and Water Table on C Gas Fluxes

To investigate responses of C gas fluxes to changes in air temperature and soil water conditions, we conducted a series of simulations with DNDC by varying T_A and WT. The baseline was set based on the actual conditions under the control treatment, where annual mean air temperatures were −1.7°C and −3.2°C, respectively, in 2005 and 2006. The WT depths were −8.1 cm and −20.4 cm (the negative values mean below ground), respectively, on average across the growing season in 2005 and 2006 in the baseline scenario. In order to fully represent potential combinations of T_A and WT depths, we created alternative scenarios by varying these two factors simultaneously. The ranges of variation were ±5.0°C and ±20 cm of the baseline for air temperature and water table position, respectively. The changes in T_A and WT were randomly picked from their corresponding ranges by assuming that their frequency distributions were uniform. Totally, 1000 scenarios were created by using the Latin hypercube sampling strategy [*Helton and Davis*, 2003]. To ensure same initial conditions for different scenarios, DNDC was iteratively run for 20 years by using the climate data in 2004. During the model initialization, the baseline T_A and WT were used for all the scenarios. After the initialization, DNDC was run for 2005 and 2006 with the varied T_A and WT. The simulated annual NEE, CH_4 fluxes, and net C gas fluxes (the sum of NEE and CH_4 fluxes) from different scenarios were then analyzed. We also calculated net emission of greenhouse gases (GHGs) as CO_2 equivalents by using a 100 year global warming potential of 28 kg CO_2 eq kg^{-1} CH_4 [*IPCC*, 2013].

In addition, we performed a sensitivity analysis to evaluate relative importance of T_A and WT to C gas fluxes by using a variance-based method for global sensitivity analysis [*Saltelli et al.*, 1999, 2008], the Fourier Amplitude Sensitivity Test (FAST, SimLab 2.2) [*Joint Research Centre of the European Commission*, 2011].

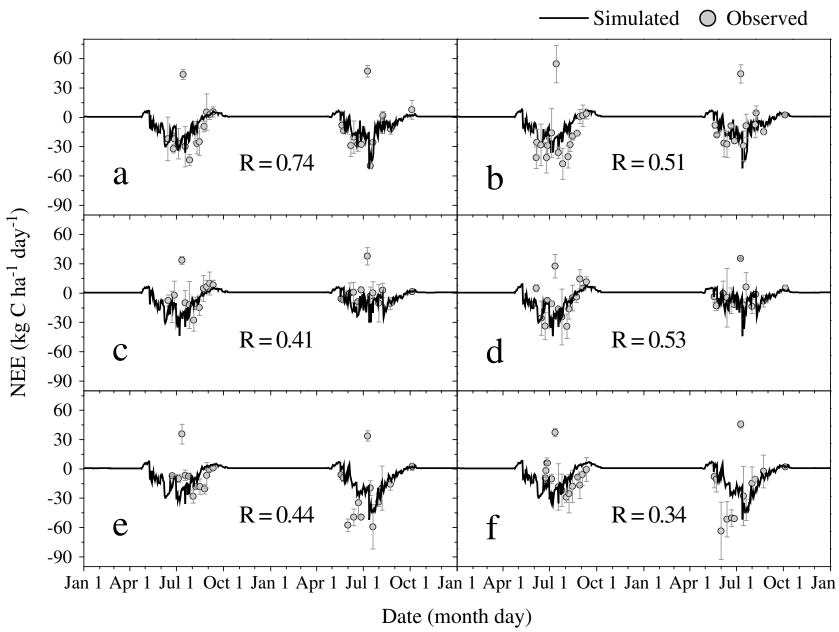

Figure 4. Simulated and observed net ecosystem exchange (NEE) of CO_2 (kg C ha^{-1}) for the treatments of (a) control, (b) control and surface soil warming, (c) lowered water table (WT), (d) lowered WT and surface soil warming, (e) raised WT, and (f) raised WT and surface soil warming in 2005 and 2006. Sign convention is NEE > 0 for net CO_2 emission to the atmosphere. The values of correlation coefficient (*R*) between the simulated and observed NEE were significant for Figures 4a–4e ($P < 0.05$) and were insignificant for Figures 4f ($P = 0.09$). The measured data are the means, and the vertical bars indicate the standard deviations of three replicate chambers. The two observations higher than +30 kg C ha^{-1} d^{-1} were measured on midnight in each treatment; these were excluded from the correlation calculation.

FAST can quantify the relative importance of model inputs (i.e., T_A and WT) to outputs (i.e., NEE, CH_4 fluxes, net C gas fluxes, and net GHG emission) by fully exploring the variance space of inputs (i.e., ±5.0°C and ±20 cm of the baseline for T_A and WT, respectively). For a specific output variable, the influence of each input and the interactions between inputs can be quantified [*Saltelli et al*., 2008]. It provides two indices, namely, first-order sensitivity index (FSI) and total sensitivity index (TSI), to evaluate both direct and total impacts of model inputs on outputs. Interactions between input parameters can be interpreted by the value of $1 - \sum$FSI, for which a value > 0 indicates that interactive effects exist [*Saltelli et al*., 1999, 2008].

3. Results and Analysis

3.1. Model Validation

3.1.1. NEE

The modeled results of daily NEE were similar between the treatments with and without soil warming if the WT position remained the same, suggesting that the slight warming of surface soil temperature (0.7, 0.9, and 0.6°C for the control, lowered WT, and raised WT plots, respectively) had minor influence on the simulations of NEE in this study (Figure 4). The modeled impacts of warming surface soil temperature on NEE were in agreement with the field observations, which showed insignificant differences in NEE between the treatments with and without soil warming [*Chivers et al*., 2009].

While the slight warming of surface soil temperature did not obviously affect the NEE at the fen, the change in WT position exerted substantial impacts. Different NEE rates occurred in both the field measurements and DNDC simulations across the treatments with control, lowered, and raised WT positions (Figures 4 and 5). During 2005 and 2006, the means of the observed NEE were −13.4, −1.8, and −16.2 kg C ha^{-1} d^{-1}, respectively, under the treatments of control, lowered, and raised WT positions without soil warming. The corresponding simulations were −12.8, −7.4, and −14.6 kg C ha^{-1} d^{-1} on average. Therefore, both the observations and simulations demonstrate an increase trend in CO_2 uptake along the increase in soil moisture. In addition, the differences between the simulations and observations were insignificant

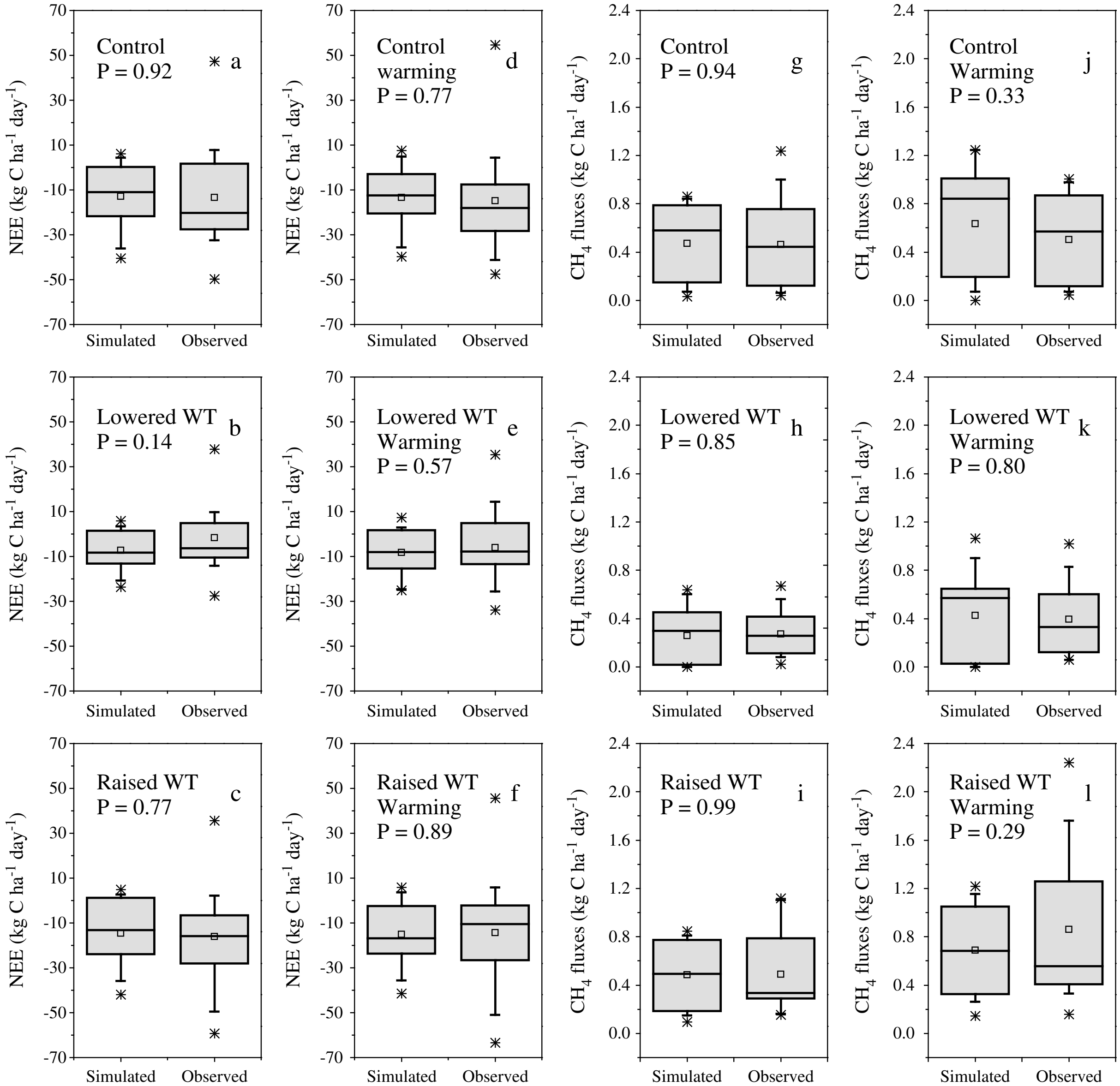

Figure 5. Box plots of simulated and observed net ecosystem exchange (NEE) of (a–f) CO_2 and (g–l) CH_4 fluxes for the control, control and surface soil warming, lowered water table (WT), lowered WT and surface soil warming, raised WT, and raised WT and surface soil warming treatments. Asterisks show min and max values, bars indicate the 10th and 90th percentiles, boxes represent the bounds of 25th, 50th (median), and 75th percentiles, and squares represent the average values. Differences between the means of the observations and corresponding simulations were insignificant for all cases.

($P > 0.05$) for all the treatments (Figures 5a–5f). These results suggest that the modeled influences of changing WT position on NEE were comparable with the observations.

DNDC generally captured the seasonal characteristics of NEE, although a few discrepancies occurred (Figure 4). The values of correlation coefficient (R) for each treatment ranged from 0.34 to 0.74. The correlations between the simulated and observed NEE were statistically significant for all treatments ($P < 0.05$, Figures 4a–4e) except for the case with raised WT and soil warming ($P = 0.09$, Figure 4f). It is worth to note that DNDC simulated daily mean fluxes, while the chamber measurements were generally measured around midday (between 11:00 A.M. and 17:00 P.M.), and may not be representative of the daily averages [e.g., *Maljanen et al.*, 2002].

3.1.2. CH_4 Fluxes

Simulated CH_4 fluxes generally increased along with the increase in soil moisture, and under the same water table conditions, DNDC simulated higher CH_4 fluxes with soil warming. The field measurements also showed

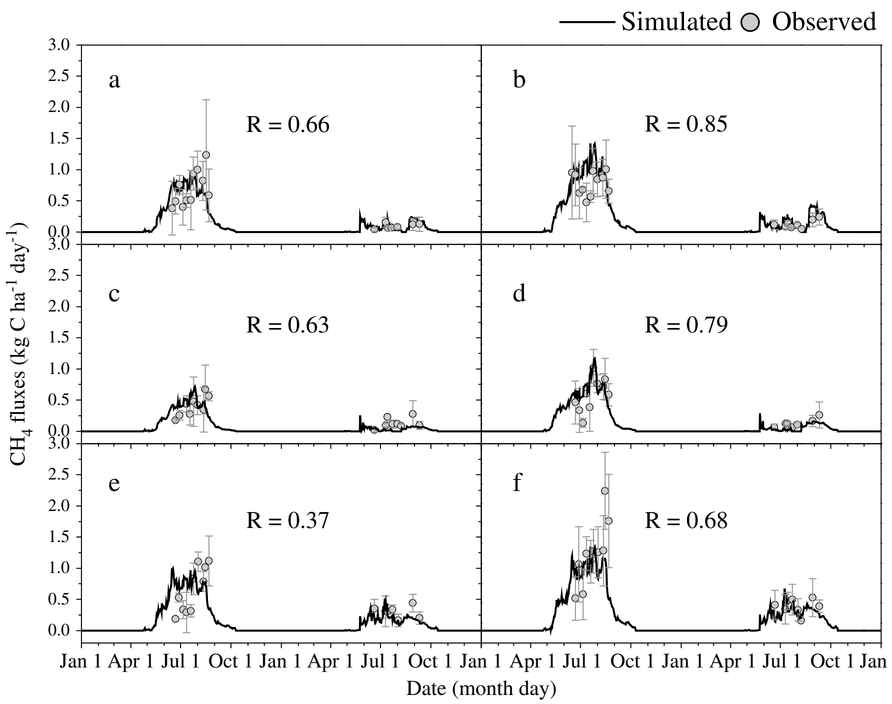

Figure 6. Simulated and observed CH_4 fluxes (kg C ha^{-1}) for the (a) control, (b) control and surface soil warming, (c) lowered water table (WT), (d) lowered WT and surface soil warming, (e) raised WT, and (f) raised WT and surface soil warming treatments in 2005 and 2006. The values of correlation coefficient (*R*) between the simulated and observed CH_4 fluxes were significant for Figures 6a–6d and 6f ($P < 0.01$) and were insignificant for Figure 6e ($P = 0.14$). The measured data are the means, and the vertical bars indicate the standard deviations of three replicate chambers.

positive impacts of soil warming or flooding on the CH_4 fluxes [*Turetsky et al.*, 2008]. The means of the observed CH_4 fluxes were 0.46 and 0.50 (without and with surface soil warming), 0.27 and 0.39, and 0.49 and 0.86 kg C ha^{-1} d^{-1}, respectively, under the treatments of control, lowered, and raised WT positions. The corresponding simulations were 0.47 and 0.63 (without and with surface soil warming), 0.26 and 0.42, and 0.49 and 0.69 kg C ha^{-1} d^{-1} on average. The magnitudes of the simulations were close to the observations, and the differences between the average observations and corresponding simulations were insignificant ($P > 0.05$) across all the treatments (Figures 5g–5l). These results indicate that the modeled influences of manipulating surface temperature and WT position on CH_4 fluxes were consistent with the observations.

The model also generally captured the seasonal patterns of CH_4 fluxes, although a few discrepancies occurred (Figure 6); *R* values between the simulated and observed CH_4 fluxes across the different treatments ranged from 0.37 to 0.85. Significant correlations between the simulated and observed CH_4 fluxes appeared in all the treatments ($P < 0.01$, Figures 6a–6d and 6f) except for the raised WT and without warming treatment ($P = 0.14$, Figure 6e). Figure 6 illustrates that significant interannual differences existed in CH_4 fluxes between 2005 and 2006. Both the DNDC simulations and field observations showed much lower CH_4 fluxes in 2006 (Figure 6) when the fen was relatively dry (Figure 1).

3.2. Responses of C Gas Fluxes to Changes in Air Temperature and Water Table

3.2.1. NEE

Figures 7a and 7b illustrate the simulated annual NEE across different T_A and WT regimes. The simulations across the regimes varied from −1367 to −181 and −1167 to +207 kg CO_2-C ha^{-1} yr^{-1}, respectively, for 2005 and 2006, indicating that considerable variations may arise due to potential changes in T_A and WT. As shown in Figures 7a and 7b, changing air temperature, while holding water table position constant, influenced the modeled results. The simulated net uptake of CO_2 was reduced by either colder or warmer temperatures, although both the field observations [*Chivers et al.*, 2009] and model results demonstrate

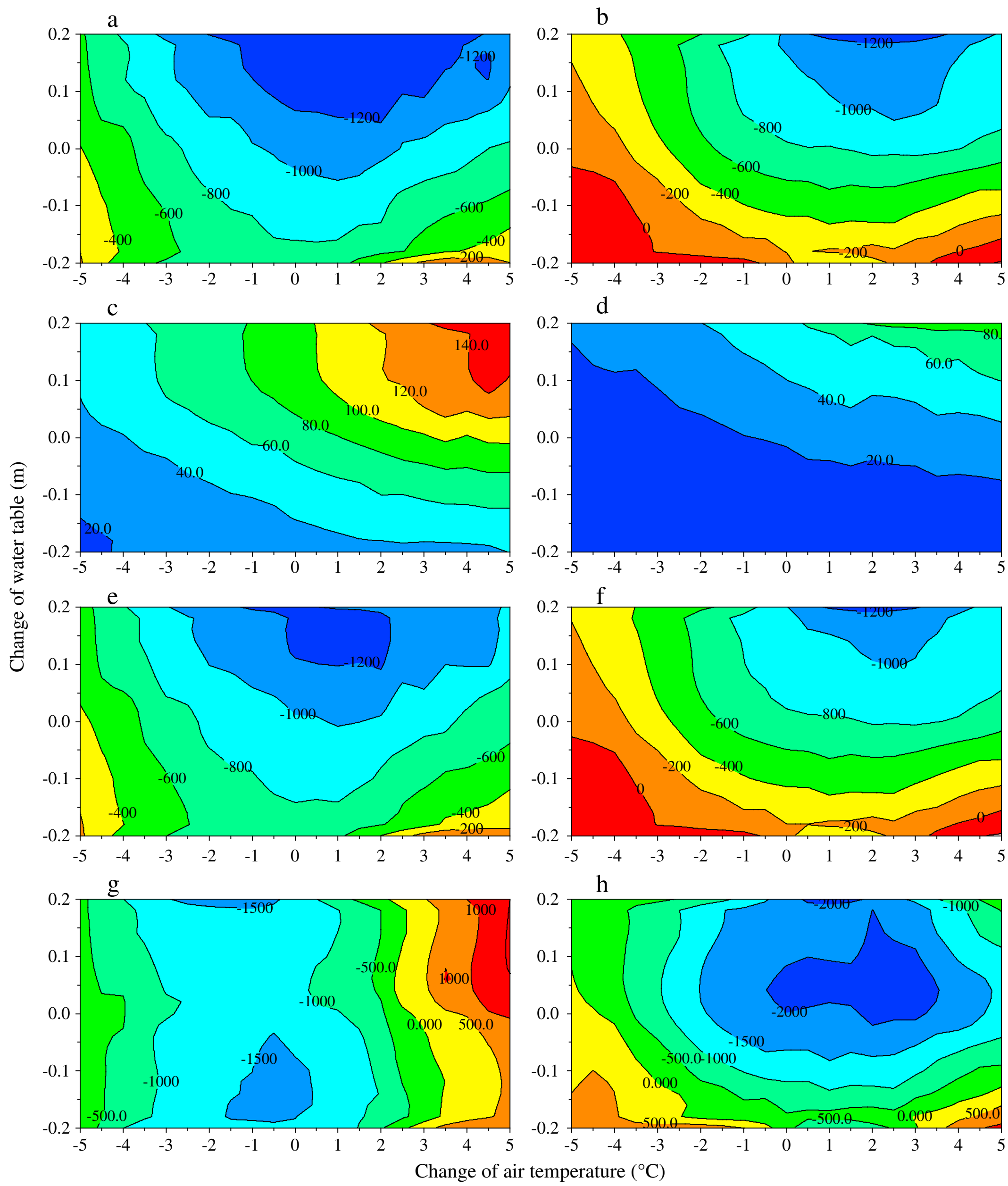

Figure 7. Simulated (a and b) NEE (kg C ha^{-1} yr^{-1}), (c and d) CH_4 fluxes (kg C ha^{-1} yr^{-1}), (e and f) net carbon fluxes (kg C ha^{-1} yr^{-1}), and (g and h) net emissions of greenhouse gases (GHG, kg CO_2 eq ha^{-1} yr^{-1}) under changes in air temperature and water table relative to the baseline condition in 2005 (Figures 7a, 7c, 7e, and 7g) and 2006 (Figures 7b, 7d, 7f, and 7h).

that slight warming of temperature (e.g., within 1.0°C increase) had minor influence on the NEE at the study fen. The model results also demonstrate that net CO_2 uptake rates were generally higher for wetter conditions, although the increasing trend stagnated under relatively wet conditions. On the contrary, a reduction of net CO_2 uptake occurred under drought conditions, which could restrict C assimilation and stimulate ecosystem respiration.

3.2.2. CH_4 Fluxes

The simulated annual CH_4 emissions across the scenarios ranged from 15.8 to 150.4 and 1.8 to 87.1 kg CH_4-C ha^{-1} yr^{-1}, respectively, in 2005 and 2006. As illustrated by Figures 7c and 7d, the modeled CH_4 emissions increased along with increasing air temperature or rising water table position (i.e., closer to

Table 2. Calculated Sensitivity Indices Quantifying the Impacts of Variations of Air Temperature and Water Table Depth on NEE, CH_4 Fluxes, Net C Fluxes, and Net Emissions of Greenhouse Gases (GHGs)

		FSI[a]				TSI[b]			
Items	Range of Variations	NEE	CH_4	Net C Fluxes	GHG	NEE	CH_4	Net C Fluxes	GHG
Air temperature	−5 to 5°C	0.39	0.37	0.40	0.81	0.43	0.44	0.44	0.84
Water table	−20 to 20 cm	0.56	0.55	0.55	0.13	0.60	0.62	0.59	0.17

[a]FSI is the first-order sensitivity index used to evaluate direct impacts of inputs on outputs, with higher values indicating greater sensitivity.
[b]TSI is the total sensitivity index used to evaluate total impacts of inputs on outputs, with higher values indicating greater sensitivity.

the peat surface). Across all the regimes, the combination of increasing T_A by 5°C and raising WT by 20 cm resulted in the highest CH_4 fluxes. In comparison with the baseline, this regime elevated the emission rate of CH_4 by approximately 1.2 (150.4 versus 69.8 kg CH_4-C ha^{-1}) and 3.0 fold (87.1 versus 22.1 kg C ha^{-1}), respectively, for 2005 and 2006. On the contrary, the scenario of lowering T_A by 5°C and WT by 20 cm generated the lowest CH_4 fluxes, decreasing the emission rate by 77% (15.8 versus 69.8 kg CH_4-C ha^{-1}) and 92% (1.8 versus 87.1 kg CH_4-C ha^{-1}), respectively, for 2005 and 2006. These results clearly demonstrate that both warming and wetting increased CH_4 fluxes at the study fen. While the field observations showed that the treatment of slight T_S warming together with raising the WT by approximately 10 cm increased the CH_4 fluxes by 75% in comparison with the control [*Turetsky et al*., 2008], the DNDC simulations suggest that the rate of CH_4 emission could be elevated more by further increasing temperature and raising WT. In comparison with the baseline, the scenario of increasing T_A by 5°C and simultaneously raising WT by 20 cm elevated the CH_4 emission by approximately 1.6 fold (237.5 versus 91.9 kg CH_4-C ha^{-1}) across 2005 and 2006.

3.2.3. Annual C Fluxes and Net Greenhouse Gas Emission

Across all the scenarios, the simulated annual net C gas fluxes ($CO_2 + CH_4$) ranged from −1256 to −164 and −1105 to 216 kg C ha^{-1}, respectively, in 2005 and 2006. Because the CH_4 component was relatively small in comparison with NEE, responses of annual net C gas fluxes to changes in T_A and WT were similar to the responses of NEE.

The simulated annual net GHG emissions across the regimes varied from −1671 to +1644 and −2429 to +1097 kg CO_2 eq ha^{-1} yr^{-1}, respectively, in 2005 and 2006. Strong sinks of net GHG (e.g., net GHG < −1500 kg CO_2 eq ha^{-1} yr^{-1}) were predicted for the scenarios with suitable air temperature (annual mean T_A was around −3.2 to −1.2°C) and WT (e.g., average WT depth between −28 and −13 cm or > 10 cm; Figure 7g) in 2005. In 2006, strong sinks of net GHG were predicted for the scenarios with suitable air temperature (annual mean T_A was around −5.0 to 1.0°C) and relatively wet soil (Figure 7h). Either cooling or warming, while holding water table constant, reduced the net GHG sink (Figures 7g and 7h). The DNDC simulations also illustrate that the net sink of CO_2 equivalents generally decreased as the water table position fell in 2006 (Figure 7h) when the soil was relatively dry in the baseline while showed less variations along the soil water gradient in 2005 (Figure 7g) when the fen was relative wet. The simulations show that the fen may change from a net GHG sink under the baseline into a net source of GHG under extreme warm and/or dry conditions (Figures 7g and 7h).

3.3. Sensitivity of C Gas Fluxes to Air Temperature and Water Table

The calculated FSI and TSI values are shown in Table 2. The results indicate that (1) both T_A and WT play important roles in regulating NEE and CH_4 emissions and thereby in regulating net C fluxes and GHG emissions; (2) changes in water table have a greater impact than changes in air temperature on NEE, CH_4 fluxes, and net C fluxes at the study fen (as demonstrated by the larger values of both FSI and TSI in WT, Table 2) for the investigated ranges of the variations in T_A and WT; however, the impact of WT on net GHG may be partially offset due to the fact that both uptake of CO_2 and CH_4 emissions simultaneously increased with increasing wetness (Figures 7a–7d); and (3) there are interactive impacts between air temperature and water table for both NEE and CH_4 fluxes ($1 - \sum FSI > 0$ for both NEE and CH_4 fluxes, Table 2), although these interactive impacts may be relatively low as compared to their direct impacts.

4. Discussions

4.1. Validation of DNDC

In this study, we applied the DNDC model to assess impacts of T_A and WT on C gas fluxes in an Alaskan peatland. DNDC was validated against the measured NEE and CH_4 fluxes under the manipulations in surface soil temperature and WT. The comparisons between the modeled and field results demonstrate that the predicted impacts of the manipulations in soil environments on NEE and CH_4 fluxes were consistent with the field observations. In addition, the modeled magnitudes and temporal dynamics of NEE and CH_4 fluxes were generally comparable with the measurements for most treatments (Figures 4–6). The model validation suggests that the DNDC is potentially capable of predicting impacts of changes in soil temperature and water table on C dynamics in northern peatlands. However, we also note some discrepancies between the modeled results and the field measurements.

As Figures 5a–5f illustrate, the simulations of daily NEE showed less variation in comparison with the observations, although the differences between the means of the predictions and observations were insignificant ($P > 0.05$) across all the treatments. Because the predictions were daily average fluxes, while the field data used for validation were instantaneous fluxes (usually measured between 11:00 A.M. and 17:00 P.M., with two observations at midnight for each treatment, Figure 4), the less variations in simulated daily NEE may be partially due to the fact that the daily predictions obscured the diurnal fluctuations of NEE included in the instantaneous measurements. In addition, we found obvious discrepancies between the modeled and observed NEE at the plots with raised WT positions. Inconsistent with field data at other plots, distinct high net uptake rates of CO_2 occurred at the raised WT plots during early June in 2006 (Figures 4e and 4f), while DNDC predicted lower uptake rates, primarily because of restriction of relative low air temperature (the mean was 11.9°C during 1–10 June) on plant productivity. Further studies are needed to clarify the differences in seasonal characteristic of NEE between the raised WT and other plots, as well as the inconsistencies between the predicted and observed NEE during this period.

Inconsistencies also appeared between the modeled and observed CH_4 emissions. For example, the correlation between the simulated and observed CH_4 fluxes was insignificant ($P = 0.14$, Figure 6e) in the setting with raised WT and unchanged soil temperature. In addition, DNDC underestimated the high peak of CH_4 fluxes for the treatment of raised WT and warmed surface soil temperature during 15–22 August 2005 (Figure 6f). These inconsistencies may also have resulted from the fact that the instantaneous CH_4 measurements could not represent the daily averages [e.g., *Long et al*., 2010]. The underestimation of the high peak of CH_4 fluxes for the treatment of raised WT and T_S (Figure 6f) may have resulted from an underprediction in the interactive impacts between WT and T_S for CH_4 fluxes as well, considering that the model generally captured the magnitudes of CH_4 fluxes under the treatment of solely rising WT (i.e., the raised WT plots) or warming surface temperature (i.e., the control and warming plots) during 15–22 August 2005. To reduce any biases that may result from the predicted interactive impacts of WT and T_S on CH_4 fluxes, further studies should focus on quantifying responses of C fluxes to simultaneous changes in soil water conditions and temperature and clarifying processes or mechanisms controlling the interactive impacts of soil water conditions and temperature. One approach to this could involve a factorial field study with warming at several levels (e.g., +2°, +4°, and +6°C) and several changes in WT (e.g., ±15 cm, ±10 cm, and ±5 cm). While admittedly labor and resource intensive, such a field study could generate temperature-moisture phase space responses (as in Figures 7 and 8) to better quantify interactive effects of warming and moisture change on C gas fluxes. In addition, there are uncertainties in model inputs. For example, increase in surface soil temperature was set as a constant for each of the treatments of soil warming (0.7, 0.9, and 0.6°C for the control, lowered WT, and raised WT plots, respectively), although the actual daily increase probably varied around these values across the growing season. Because surface soil temperature has strong influences on soil climate and biogeochemistry in DNDC, potential biases in inputs could affect model results of NEE and CH_4 fluxes. Further studies reducing uncertainties in both the measured gas fluxes and basic input information could reduce the discrepancies between simulations and observations.

4.2. Impacts of Changes in Air Temperature and Water Table on C Gas Fluxes

Both temperature and water table are critical factors regulating CO_2 fluxes in boreal ecosystems. They can affect both CO_2 assimilation through vegetation growth and soil microbial heterotrophic respiration [e.g.,

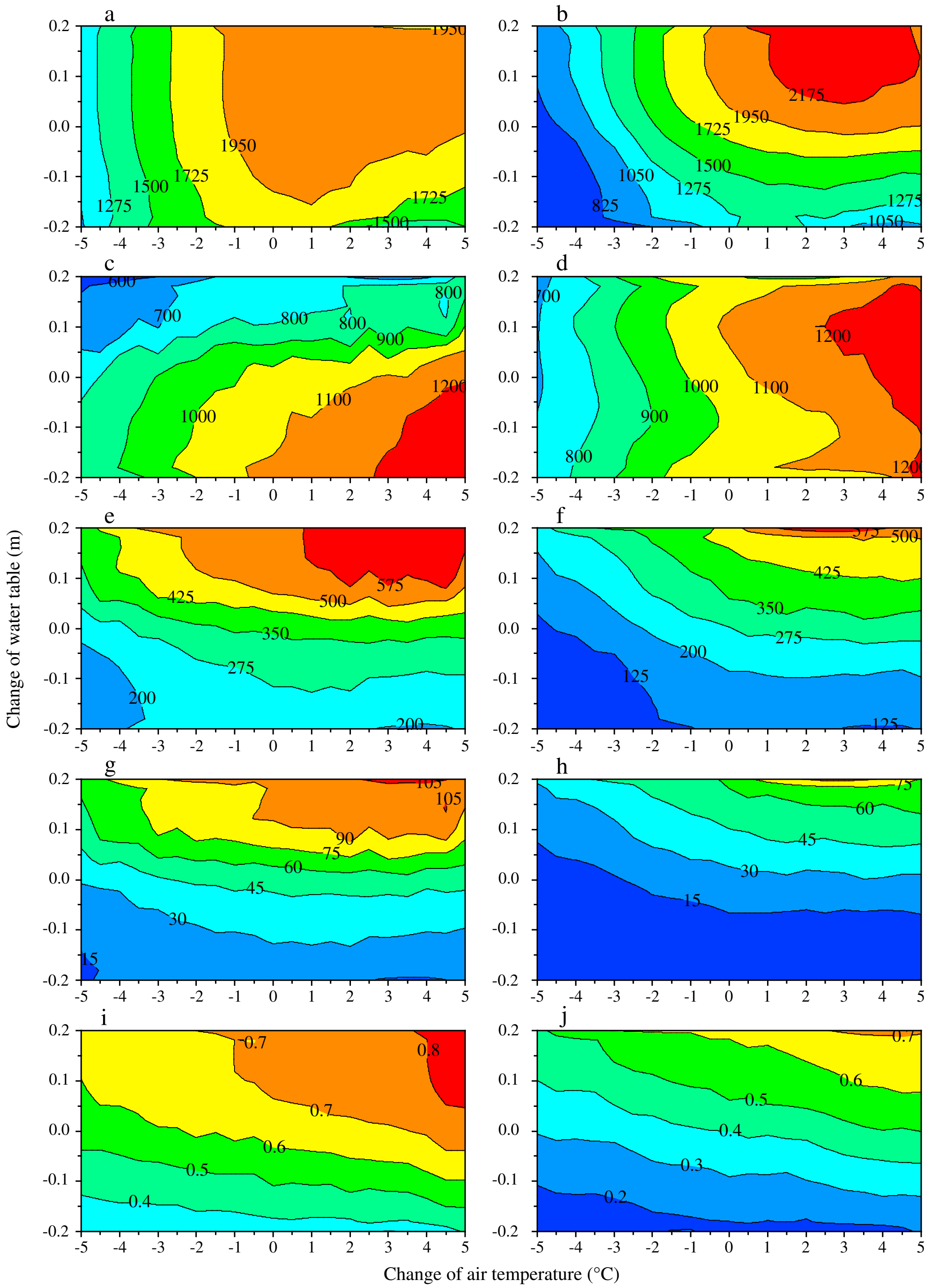

Figure 8. Simulated (a and b) (net primary production) NPP (kg C ha^{-1} $year^{-1}$), (c and d) (soil microbial heterotrophic respiration) HR (kg C ha^{-1} yr^{-1}), (e and f) DOC (dissolved organic carbon) used for CH_4 production (kg C ha^{-1} yr^{-1}), (g and h) H_2 production (kg H_2 ha^{-1} yr^{-1}), and (i and j) fraction of anaerobic volumes (F_{AV}) under changes in air temperature and water table relative to the baseline condition in 2005 (Figures 8a, 8c, 8e, 8g, and 8i) and 2006 (Figures 8b, 8d, 8f, 8h, and 8j). The F_{AV} is simulated based on soil Eh and thaw dynamics at a daily step (Figure 9), and the values shown in the Figures 8i and 8j are the means of average F_{AV} in soil profile (0–50 cm) between the days 101 and 300.

Jungkunst and Fiedler, 2007; *Conant et al.*, 2011], thereby regulating NEE in a complex manner [*Limpens et al.*, 2008]. The DNDC results also indicate that changing air temperature and/or soil water condition simultaneously affected several processes related to CO_2 exchanges, and therefore, the net effects on NEE were determined by influences of these changes on individual processes. For example, changing air temperature exerted influences on both C assimilation and HR during simulations, with warm conditions favorable for both vegetation growth (Figures 8a and 8b) and soil microbial respiration (Figures 8c and 8d). However, the increasing trend in C assimilation stagnated if air temperature was relatively high (e.g., higher than the baseline temperature; Figures 8a and 8b), which in combination with the sustained increase in soil microbial respiration (Figures 8c and 8d) resulted in the reductions or stagnations in net CO_2 uptake under relatively warm conditions (Figures 7a and 7b). While slightly increasing T_A (e.g., around 1.0°C increase as compared to the baseline) showed little influence on the NEE, further increasing T_A decreased the net uptake of CO_2 at the study fen. In comparison with the baseline, increasing T_A by 5°C reduced the NEE by 26% (−775 versus–1050 kg CO_2-C ha^{-1}) and 9% (−695 versus −768 kg CO_2-C ha^{-1}), respectively, for 2005 and 2006. The predicted responses of NEE to warming are similar to other studies of temperature manipulations in northern peatlands, which reported little or negative effect of warming on NEE, usually due to HR increasing at a similar or faster rate in comparison with C assimilation [*Oberbauer et al.*, 2007; *Updegraff et al.*, 2001; *Welker et al.*, 2004]. The model predicted lower reduction in NEE with warming in 2006 when the annual mean T_A was relatively lower (−3.2°C in 2006 versus −1.7°C in 2005), primarily due to higher increase in net primary production (NPP) in 2006 (Figures 8a and 8b), which also agrees with a general pattern of larger warming-induced increases in C assimilation at lower base temperatures [*Callaghan et al.*, 2004]. The DNDC results also show that the simulated reductions in net CO_2 uptake under colder temperatures (Figures 7a and 7b) were primarily due to reduced C assimilation (Figures 8a and 8b).

The CH_4 simulations across the scenarios demonstrate that changes in either air temperature or water table can substantially affect CH_4 fluxes at the study fen, with positive impacts exerted by warming or wetting. In comparison with the baseline, increasing T_A by 5°C elevated the emission rate of CH_4 by approximately 50% in both 2005 (105.1 versus 69.8 kg CH_4-C ha^{-1}) and 2006 (33.5 versus 22.1 kg CH_4-C ha^{-1}). Raising the WT above the ground surface (i.e., the scenario of raising the WT in 2005 by 20 cm) increased the simulated CH_4 emission by 34% above the control (93.4 versus 69.8 kg CH_4-C ha^{-1}) and 2.0 fold (93.4 versus 31.1 kg CH_4-C ha^{-1}) above the dry simulation (i.e., the scenario of lowering the WT in 2005 by 20 cm). The modeled responses of CH_4 emission to environmental changes are of similar magnitude to previous studies, which generally showed 0 to 50% increase in CH_4 emission due to soil warming of 1.5 to 5°C [*Granberg et al.*, 2001; *Olefeldt et al.*, 2013; *Updegraff et al.*, 2001] and 35% to 5.0 fold increase in CH_4 emission due to inundation or flooding [*Bubier et al.*, 2005; *Updegraff et al.*, 2001; *Turetsky et al.*, 2008], although the reported responses varied considerably depending on specific conditions of the ecosystem (e.g., a combination of temperature and water table conditions, soil properties, and vegetation communities). The DNDC results further provide more information about the mechanisms functioned for the positive impacts of warming or wetting. DNDC simulated higher CH_4 emissions under warmer conditions primarily because (1) warmer weather stimulated plant growth (Figures 8a and 8b) and hence had more DOC produced through plant exudation (Figures 8e and 8f) which supported CH_4 production and (2) higher soil temperature stimulated the methanogen activity. DNDC predicted higher CH_4 emissions under wetter conditions primarily because (1) higher plant growth rates and consequently more substrates used for CH_4 production (Figures 8e and 8f) and (2) increased anaerobic zone (Figures 8i and 8j) that supported production of both H_2 (an electron donor used for CH_4 production; Figures 8g and 8h) and CH_4 while restricting CH_4 oxidation. The model results also illustrate that interannual differences appeared between 2005 and 2006 regarding the responses of CH_4 emission to environmental changes (Figures 7c and 7d), implying that the baseline condition should be taken into considerations when evaluating the responses of CH_4 emission to climate change.

The simulated responses of annual net C gas fluxes to changes in T_A and WT were similar with the responses of NEE (Figures 7e and 7f). However, the responses of net GHG emissions were noticeably different from the responses of net C gas fluxes at the study fen (Figures 7g and 7h) due to the more powerful radiative forcing potential of CH_4. The modeled results provide some indications on how C gas fluxes would change with future environmental alternations at the study fen. As illustrated by Figures 7e and 7f, with no perturbation to the water table, net C uptake rates decreased or stagnated along with increasing T_A when air temperature was higher than the baseline condition. GHG uptake rate also reduced along with increasing the baseline T_A, and the study fen may even change into a source of net GHG emissions under some warm conditions (e.g., Figure 7g). These results suggest that the study fen will sequester less carbon from the atmosphere, and its net climate cooling function will decrease or even be reversed into a net warming with climate warming. This conclusion is consistent with a number of studies [e.g., *Fan et al*., 2013; *Koven et al*., 2011; *Tarnocai*, 2006], which also reported positive feedbacks of northern peatlands to climate warming. Specifically, *Fan et al*. [2013] estimated the response of SOC of the study fen to climate change by using the peatland version of the dynamic organic soil-Terrestrial Ecosystem Model (peatland DOS-TEM). While the magnitude of net C gas fluxes is not consistent between the DNDC and peatland DOS-TEM simulations, perhaps associated with the differences in both model formulations and scenario setting, the two sets of model simulations arrive at similar conclusions—both models predicted a reduction in the rate of net C sequestration after an initial increase, due to the fact that the increase in respiration induced by the projected warming is eventually greater than the increase in carbon inputs via production. The C sequestration and GHG uptake rates may also be reduced by a falling water table, which in combination with warming could change the study fen into a source of both net C gas and GHG emissions under some extreme warm and dry conditions (e.g., Figures 7f and 7h). However, it should be noted that the predicted behavior of the study fen is a short-term response of 2 years because we set the same initial conditions for different scenarios, and so the results are indicative of interannual variability and not necessarily of a response to persistent climate change. We also note that the net GHG uptake rate of the fen could be reduced due to a rising WT (e.g., Figure 7h), indicating that the changes of WT could result in a trade-off of GHG caused by simultaneously increasing CO_2 uptake and CH_4 emission across the gradient of soil moisture (Figures 7a–7d). The trade-off of GHG results in responses of C gas fluxes that are not a simple function of changes in soil water. The uncertainty of future soil water changes [*Seneviratne et al*., 2010] and their impacts on C gas fluxes, together with substantial influences of WT on C gas fluxes (Table 2), stress that great concern should be placed on soil water changes when predicting responses of C gas fluxes to climate change in northern peatlands.

4.3. Modeling Responses of C Gas Fluxes to Changes in Air Temperature and Soil Water

Modeling impacts of changes in air temperature and soil water on C gas fluxes is essential for forecasting feedbacks of ecosystem C pools to climate change. This requires a process-based model framework that effectively represents the interacting dynamics of a number of processes that affect net C fluxes. The differences in CH_4 simulations between 2005 and 2006 show how simulated CH_4 fluxes are related to changes in soil temperature, fraction of anaerobic zone, NPP, DOC, and H_2 (Figures 9a and 9b). As shown in Figure 3, DNDC includes a relatively complete suite of processes or mechanisms, which explicitly simulate key variables (e.g., soil temperature, fraction of anaerobic zone, NPP, HR, DOC, and H_2) that directly influence NEE and CH_4 emission. These processes provide the model with the capability to predict the complex impacts of changing air temperature and soil water condition on C gas fluxes in northern peatlands. It should be noted that interactive impacts may exist between T_A and soil water on C gas fluxes. For example, changing T_A can affect soil temperature and thaw dynamics, which not only directly control all biogeochemical processes involved (Figure 3) but also impact fraction of soil volume that is anaerobic (Figures 3, 8i, and 8j) and thereby indirectly influence CH_4 production. Changing soil water content can affect NPP (Figures 8a and 8b), HR (Figures 8c and 8d), production of DOC and H_2 (Figures 8e–8h), fraction of soil anaerobic zone (Figures 8i and 8j), and soil temperature (Figure 3) through influencing soil thermal properties (e.g., soil heat conductivity and capacity) and therefore can also impact NEE and CH_4 fluxes both directly and indirectly. These interactions should be considered when predicting the impacts of climate change on C gas fluxes.

We also have identified some missing mechanisms or processes in the current model framework through this study. As shown in Figure 3, both NEE and CH_4 fluxes could be affected by vegetation growth (or NPP), which is partially determined by the model parameters describing vegetation characteristics during simulations. The importance of these inputs stresses that changes in vegetation characteristics should be considered when

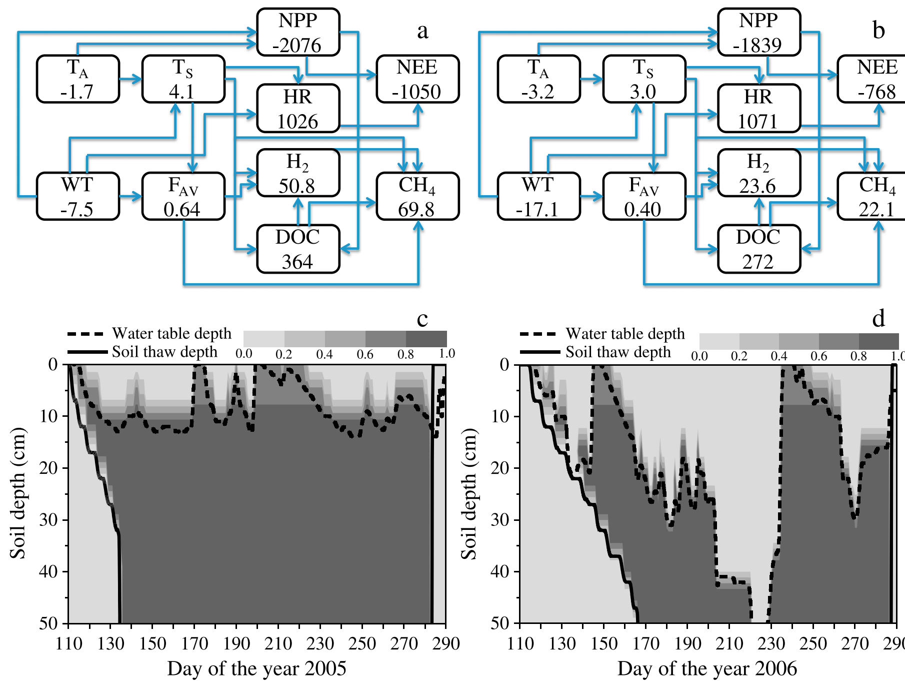

Figure 9. Mean annual values for key biophysical and biogeochemical variables (refer to Figure 3) controlling NEE and CH_4 flux for the baseline simulation in (a) 2005 and (b) 2006 and daily water table depth, soil thaw depth, and fraction of anaerobic volume in soil profile (0–50 cm) between the days 110 and 290 for the baseline simulation in (c) 2005 and (d) 2006. The values of water table and F_{AV} shown in Figures 9a and 9b are the means of water table depth and average F_{AV} in soil profile (0–50 cm) between the days 101 and 300, respectively. In DNDC, fraction of anaerobic volume is determined by both soil thaw dynamics and redox potential (Eh), which is subsequently controlled by water table depth and biogeochemical activity.

predicting long-term responses of C turnover to climate change. Although changes in vegetation have been observed along with climate warming and/or changing soil water condition in northern areas [e.g., *Goetz et al.*, 2011; *Tape et al.*, 2006], vegetation transitions were not considered in this study when warmer/colder and/or wetter/drier conditions were considered. To reduce any biases that may result from neglecting vegetation transitions, it will be necessary to incorporate vegetation changes dynamically into the model's framework.

5. Conclusions

A biogeochemical model, DNDC, was recently enhanced for predicting biogeochemistry in high latitudes. In this study, we applied the model to assess impacts of variations in T_A and WT on C gas fluxes in an Alaskan peatland. DNDC was validated against field measurements of NEE and CH_4 fluxes from a moderate rich fen with manipulations in surface soil temperature and WT. The validation demonstrates that DNDC was able to represent the observed impacts of the manipulations in soil environments on NEE and CH_4 fluxes. To investigate responses of C gas fluxes to changes in T_A and soil water condition, we conducted a series of simulations by varying T_A and WT. The results demonstrate that (1) net CO_2 uptake rates were reduced by either much colder or warmer temperatures than observed at the study fen and generally increased with increasing soil moisture; (2) CH_4 emissions showed an increasing trend as the T_A or WT increased; and (3) variations of net C gas fluxes and emissions of GHG were jointly controlled by the changes in NEE and CH_4 emissions, such that the site may change from a net GHG sink into a net GHG source under some warm and/or dry conditions. However, it should be noted that the predicted behavior of the study fen is a short-term response of 2 years, and the long-term responses of C gas fluxes to persistent environmental changes may differ from the predicted short-term response. A sensitivity analysis evaluated the relative importance of T_A and WT to C gas fluxes and indicated that both T_A and WT play important roles in regulating NEE and CH_4 emissions, and changes in WT may have a greater impact than changes in T_A on NEE, CH_4 fluxes, and net C gas fluxes at the site for the investigated ranges of the variations in T_A and WT.

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