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Modelling holocene carbon accumulation and methane emissions of boreal wetlands – an earth system model approach

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Abstract

Since the Last Glacial Maximum, boreal wetlands have accumulated substantial amounts of peat, estimated at 180–621 Pg of carbon. Wetlands have significantly affected the atmospheric greenhouse gas composition in the past and will play a significant role in future changes of atmospheric CO_2 and CH_4 concentrations. In order to investigate those changes with an Earth System Model, biogeochemical processes in boreal wetlands need to be accounted for. Thus, a model of peat accumulation and decay was developed and included in the land surface model JSBACH of the Max Planck Institute Earth System Model (MPI-ESM). Here, we present the evaluation of model results from 6000 yr BP to the preindustrial period. Over this period of time, in the model 240 Pg of peat carbon accumulated in the areas north of 40° N. Simulated peat accumulation rates agree well with those reported for boreal wetlands. The model simulates CH_4 emissions of 49.3 Tg yr^{-1} for 6000 yr BP and 51.5 Tg yr^{-1} for preindustrial times. This is within the range of estimates in the literature, which range from 32 to 112 Tg yr^{-1} for boreal wetlands. The modeled methane emission for West Siberian Lowlands and Hudson Bay Lowlands agree well with observations. The rising trend of methane emissions over the last 6000 yr is in agreement with measurements of Antarctic and Greenland ice cores.

1 Introduction

Wetlands, and particularly peatlands of the boreal latitudes, store considerable amounts of carbon (C) in the form of peat and constitute a significant natural source of methane (CH_4), even though they cover only 3 % of the global land surface. Previous studies suggest that the size of the boreal peat carbon stock is as large as 180 to 621 Petagramm C (PgC) (Gorham, 1991; Turunen et al., 2002; Smith et al., 2004; Yu et al., 2010) and CH_4 emissions are in the range of 32 to 112 Teragramm ($TgCH_4$) per year (Zhuang et al., 2004; Bergamaschi et al., 2007; McGuire et al., 2010). By storing carbon

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and taking up carbon dioxide (CO_2) from the atmosphere, boreal peatlands have had a cooling effect on climate during the last millennium (Frolking and Roulet, 2007). This positive carbon balance also applies to the greenhouse gas (GHG) emissions, in particular CH_4 emissions of boreal wetlands. Undisturbed boreal peatlands are likely to continue functioning as a net carbon sink (Smith et al., 2004; Tolonen and Turunen, 1996). On the other hand these carbon pools might be destabilized in the future since they are sensitive to climate change (Christensen, 1995; Dise, 2009; Kayranli et al., 2010). Given that the processes of peat accumulation and decay are strongly dependent on hydrology and temperature, this balance may change significantly in the future. Considering the projected future warming, boreal peatlands could potentially have a large impact on carbon cycle-climate feedback mechanisms and therefore play an important role in global carbon cycle dynamics (McGuire et al., 2009). However, global biogeochemistry models used for simulations of carbon cycle dynamics in past and future climates usually neglect peatland processes (Frolking et al., 2009).

1.1 Modelling carbon cycling in boreal wetlands

The boreal wetlands existing today were established after the Last Glacial Maximum and have continued to grow during the Holocene (Jones and Yu, 2010; Yu et al., 2010). They are linked to the terrestrial carbon cycle in many respects. On the one hand there is the large carbon stock in the soil which was built up despite the comparatively low net primary production (NPP) with an average of 100 to 400 $gC\,m^2\,yr$ (Blodau, 2002). On the other hand these boreal wetlands produce carbon emissions, which, as a result of several competing processes, may exceed the carbon uptake and turn the peatland from a carbon sink into a carbon source. These emissions occur either in the form of CO_2 due to oxic decomposition or in the form of CH_4 due to anoxic decomposition of organic material. As CH_4 has the second-largest radiative forcing of the long living GHGs after CO_2, it is of particular importance to identify the composition of carbon emissions from boreal wetlands.

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In the soil column of peatlands there is a sharp transition between the upper and the lower soil layers (Charman, 2002), with different biogeochemical properties. The reason for this is the high water table (wt), which divides the soil column into an oxic part above and an anoxic part below the wt. Ingram (1977) named the upper layer acrotelm, and the lower one catotelm. Usually, the boundary between the acrotelm and the catotelm is defined as the deepest point to which the water table descends in an annual cycle (Charman, 2002).

Wetlands form peat when conditions are suitable for the growth of plants and hydrology inhibits the aerobic decomposition of dead organic matter. Therefore, organic matter accumulation in wetlands is a function of the balance between net primary productivity and abiotic and biotic decomposition processes (Reddy and DeLaune, 2008). The biogeochemistry of wetland soils is primarily controlled by hydrology, which in turn is first and foremost represented by the water table. Carbon that is fixed in the vegetation becomes litter when plants die, either from disturbances or at the end of the vegetation period. Later, in the acrotelm, the main plant structure collapses and becomes part of the catotelm, where it finally accumulates. These structural layers of litter, acrotelm, and catotelm, in principle, are fixed and continuously move upward with the growth of the peat surface (Charman, 2002). The boundary of the functional zones between acrotelm and catotelm, however, does move, particularly when the position of the water table changes through the seasons. A key factor in determining chemical transformations in peatlands is the degree of aeration (Charman, 2002). The decomposition of the acrotelm happens relatively fast. The catotelm is anaerobic during the entire year, therefore only anaerobic microbes decompose the organic matter very slowly.

Carbon emissions from boreal wetlands consist either of CO_2 or of CH_4. Two main mechanisms govern the amount and ratio of CO_2 to CH_4 that is emitted to the atmosphere: again the degree of aeration, and the microbial CH_4 production and its oxidation (Sundh et al., 1994; Kamal and Varma, 2008). The production depends on the composition of the microbial community and several abiotic factors such as the availability

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of suitable organic material, soil temperature, and soil moisture. The quantity of CH_4 being oxidized in the soil depends strongly on the pathway of the freshly produced CH_4 to the surface (Wille et al., 2008; Dinsmore et al., 2009). Three pathways are common in boreal wetlands: diffusion, plant mediated transport, and ebullition. Diffusion through the soil column could lead to a strong oxidation of CH_4 whereas plant mediated transport through the stems of the plants reduces the probability of the oxidation of CH_4. Ebullition, or bubble formation, leads to little oxidation, since the bubbles rise quickly to the surface.

Apart from the functional segmentation in the vertical plane, peatlands are characterized by environmental gradients in the horizontal plane: patterns of vegetation variation can be found everywhere in peatlands. The change from floating mats of Sphagnum or sedges at the edge of a water body, through taller vascular plants away from the water, perhaps to a shrub community and a forested margin at the edge of a peatland, is obvious. Many of these patterns are brought about by gradual spatial variations in environmental conditions (Charman, 2002). The largest boreal wetland areas are located between 50° N and 70° N and are classified as bogs and fens (Reddy and DeLaune, 2008).

1.2 Models of peat dynamics

1.2.1 Local peat models

The first site-specific models of peat bog growth were developed in the late 70s and early 80s by Wildi (1978) and Clymo (1984). These site-specific models describe the growth of peat as a dynamic imbalance between input of plant material and its decay in the soil column. Clymo (1984) used two distinct carbon pools to represent the peat dynamics which constitute the functional layers of the acrotelm as the “active” zone and the catotelm for storing the carbon as defined by Ingram (1977). During the following years a number of peat models were developed with improved representation of peat accumulation processes. The geophysical model by Ingram (1982) takes into account

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the interaction of peat with the surrounding waters and illustrates how peat deposits are formed. Hilbert et al. (2000) analysed the positive feedback between water table and peat accumulation in bogs in depth. They found two possible equilibrium states, one with deep water tables in drier sites, where peat depth increases with increasing water input, and another one for wet conditions, where the water table is near the surface. Annual litter cohorts were used as an input in the model by Bauer (2004) to investigate the effect of different litter quality on the peat accumulation. She found that a different vegetation community above a peatland could alter the peatland response to climate change. Based on an approach of modelling annual peat cohorts, the Millennia model by Heinemeyer et al. (2010) comprises climate-driven water table dynamics with a parameterization constrained by pollen-based vegetation reconstructions. The latest advance of local peat models is represented by the approach of Frolking et al. (2010), who described the accumulation and decay of peat with a definition of annual peat layers.

1.2.2 Global peat models

Recently, Kleinen et al. (2012) presented a study where both boreal peat growth and wetland extent are modelled in combination within the Dynamic Global Vegetation Model (DGVM) LPJ. They showed an accumulation of 330 PgC during the last 8000 yr for areas above 40° North and a modelled wetland area that scores well in comparison with data. This approach allows for modelling peatlands in different climate states, such as previous interglacials, since all required inputs are determined internally. Wetland fraction and water table from this approach were used in our model setup.

1.2.3 Methane emission models

The importance of peatlands with respect to GHG emissions was taken into account by the development of a process-based model by Cao et al. (1996), who drove their wetland methane emission model with data sets for climate, vegetation, soil, and wetland

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distribution. It could be shown that the amplitude of CH_4 emissions depends on a combination of available soil carbon, its decomposition rate, soil moisture and bacterial activity.

The first process-based CH_4 emission model that was calibrated for specific sites was developed by Walter et al. (1996). It was first published as a one-dimensional model, but has been developed further for global applications (Walter and Heimann, 2000; Walter et al., 2001a, b). It describes the production and oxidation of CH_4 in the soil column and accounts for three pathways of CH_4 to the surface, diffusion, plant-mediated transport, and ebullition. This mechanistic approach has been a starting point for other CH_4 models. Van Huissteden et al. (2006) implemented this approach into a site-specific model to assess the effect of water-table management on CO_2 and CH_4 fluxes from peat soils.

Wania (2007, 2009a,b) implemented Walter's model in the DGVM LPJ. Furthermore, they included processes such as permafrost and wetland specific Plant Functional Types to investigate the CH_4 cycle in boreal regions. The key benefit of this approach is that – except for climate data, a soil map, and prescribed wetland extent – all input data are determined by the DGVM itself.

1.2.4 Methane emission in earth system models

Gedney et al. (2004) developed a simple CH_4 emission scheme that runs within the UK Met Office climate model HadCM3. They parameterized the flux from wetlands by including the basic controls of temperature, water table position and soil carbon. Eliseev et al. (2008) implemented a module of CH_4 emissions from wetland ecosystems and a module for soil thermal physics into their climate model of intermediate complexity. The extent of wetlands was prescribed. They showed that CH_4 emissions increased from 130–140 $TgCH_4\,yr^{-1}$ (preindustrial) to 170–200 $TgCH_4\,yr^{-1}$ at the end of the 21st century. Meng et al. (2011) and Riley et al. (2011) developed a biogeochemical model and integrated it into the Community Land Model (CLM4Me) with the purpose of understanding the uncertainty and its sources that emerged during the development and

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application of the models described above. Because of their advanced model of CH_4 production and emission, they found large sensitivities in CH_4 fluxes to changes in model parameters and express low confidence in the predictions of future terrestrial CH_4 feedback strength. For an overview of peat and CH_4 emission models, see Table 1.

1.3 Outline

This study aims at the evaluation of the effect of boreal wetlands on climate through fluxes of CO_2 and CH_4 on millennial timescales, based on plausible peat accumulation patterns (Sect. 1). We developed a generic model of peatland carbon dynamics embedded in an Earth System Model. Given that our intention is to run this model globally over long timescales such as the Holocene, we pursue the strategy of using a simple model that captures the main processes i.e. plants produce litter which successively enters the acrotelm and finally, if not respired, becomes a part of the catotelm. This is important for the land carbon balance throughout the Holocene. The main factors governing the strength of the CH_4 emissions are the different pathways of CH_4 emissions including its oxidation. The implemented CH_4 emission model represents these processes. Both the peat carbon accumulation and the CH_4 emission model are applied for the past 6000 yr (Sect. 2).

We compare the results of this model with observations and results from an inversion model for the present-day situation (Sect. 3). This allows us to address the question of changes of CH_4 emissions from boreal regions and their contribution to the atmospheric concentration reconstructed from the ice cores at millennial timescales (Sect. 4). We end with a conclusion in Sect. 5.

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2 Methods

2.1 Model description

JSBACH is the modular land surface scheme of the MPI-ESM (Roeckner et al., 2003; Raddatz et al., 2007). Within JSBACH the CBALANCE model describes the changes in carbon storage from the growth and death of plants and the remineralization of carbon in soils. Since we focus on the biogeochemical cycles of boreal wetlands, we modified the CBALANCE submodel by integrating wetland specific parameterizations. The modified CBALANCE submodel is henceforth called peatBALANCE.

Carbon accumulation due to the slow decomposition of plant material under anoxic conditions is not represented in the CBALANCE model. To investigate the carbon cycle dynamics of boreal wetlands, we extended the CBALANCE model to the typical wetland processes which have an effect on the carbon cycle: (i) the division of the soil column into the two functional layers of acrotelm (oxic and anoxic conditions during the course of the year) and catotelm (permanently anoxic conditions), (ii) a moving water table which defines these functional layers, and (iii), as an outcome of the interaction of the components listed above, the accumulation of carbon in the catotelm. Carbon emissions in the form of CH_4 are considered in this model setup by integrating the Walter model (Fig. 1).

2.1.1 The standard CBALANCE submodel in JSBACH

The CBALANCE model uses three different pools (green, litter, soil) to describe the storage of organic carbon in living, dead, and decaying plants, which are the state variables of the model. Generally, the land biosphere grows by filling the vegetation carbon pool with the carbon gained from photosynthesis (NPP_G, Eq. 1). This "green pool" (C_G, Eq. 1) contains carbon of the green or living parts of plants (leaves, fine roots, sapwood). Through seasonal leaf shedding, carbon is transferred from the C_G to the "litter pool" (C_L, Eq. 2), which is described by the flux F_{litter} (Eq. 5). Here the

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litter flux is determined by assuming that the "green pool" is loosely coupled to the LAI (Eq. 4). The C_L pool loses carbon due to heterotrophic respiration (R_L, Eq. 6), calculated through a Q_{10} model, where T is the temperature of the uppermost soil layer in ° C (Eq. 6). This fraction of slowly decomposing parts of the plant ($\beta_L R_L$, Eq. 3) is transferred to the "soil pool" (C_S, Eq. 3). Finally dependent on the turnover time of the "soil pool", part of the carbon is respired to the atmosphere (R_S, Eq. 7), using the Q_{10} model as well.

$$\frac{dC_G}{dt} = NPP_G - F_{litter} \quad (1)$$

$$\frac{dC_L}{dt} = F_{litter} - R_L C_L \quad (2)$$

$$\frac{dC_S}{dt} = \beta_L R_L - R_S C_S \quad (3)$$

$$C_G^{max}(t) = \frac{\gamma G}{sla} LAI(t) \quad (4)$$

$$F_{litter} = \begin{cases} 0 & \text{if} \quad C_G > C_G^{max} \text{ or } \frac{dLAI}{dt} > 0 \\ \frac{\gamma G}{sla}\frac{dLAI}{dt} & \text{otherwise} \end{cases} \quad (5)$$

$$R_L = \alpha \frac{Q_{10}^{T/T_{ref}}}{\tau_L} \quad (6)$$

$$R_S = \alpha \frac{Q_{10}^{T/T_{ref}}}{\tau_S}. \quad (7)$$

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2.1.2 The peatBALANCE submodel in JSBACH

The peatBALANCE model uses the same carbon pools for vegetation, plant litter, and the associated carbon fluxes as described above (Eqs. 1 to 2 and 4 to 6). Newly introduced are an "acrotelm carbon pool" (C_A, Eq. 8) with temporarily oxic and anoxic conditions that replaces the "soil pool" and a "catotelm carbon pool" (C_C, Eq. 9) with permanently anoxic conditions.

The key factor controlling the decomposition rates of the total peat column is the position of the water table. Decomposition under anoxic conditions is slower by more than an order of magnitude. The fraction of the "acrotelm pool" decaying under oxic or anoxic conditions (f_{ae}, Eq. 11) is determined by the position of the dynamic water table in relation to the height of the acrotelm, applying acrotelm density ρ and fraction of carbon C_f in the acrotelm (Eq. 10). The acrotelm with oxic conditions decays with a faster turnover time ($\tau_{A_{ae}} = 14.92$ yr) than the anoxic part of the acrotelm ($\tau_{A_{an}} = 42.64$ yr). An overview of all parameters used is listed in Table 2. The acrotelm loses carbon due to heterotrophic respiration (k_A, Eq. 12), the remaining slowly decomposing carbon passes into the catotelm ($\beta_A C_A$, Eq. 9).

The "catotelm carbon pool" is the place where the carbon accumulates as soon as the peat accumulation flux $\beta_A C_A$ is larger than the respiration flux (k_A, Eq. 12). The turnover time is $\tau_C = 30\,000$ yr for the catotelm. The anaerobic respiration k_C is modelled through a Q_{10} model (Eq. 13).

$$\frac{dC_A}{dt} = \beta_L R_L - k_A C_A \tag{8}$$

$$\frac{dC_C}{dt} = \beta_A C_A - k_C C_C \tag{9}$$

$$h_A = C_A/(\rho_A C_f) \tag{10}$$

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$$f_{ae} = 1 - \frac{wt}{h_A} \tag{11}$$

$$k_A = \frac{f_{ae} Q_{10}^{T/T_{ref}}}{\tau_{A_{ae}}} + \frac{(1 - f_{ae}) Q_{10}^{T/T_{ref}}}{\tau_{A_{an}}} \tag{12}$$

$$k_C = \alpha \frac{Q_{10}^{T/T_{ref}}}{\tau_C} \tag{13}$$

$$P_{CH_4} = (k_A C_A + k_C C_C) f_m \tag{14}$$

All carbon respired by the oxic parts of the soil column enters the atmosphere as CO_2. The carbon respired by the anoxic parts, however, is a potential CH_4 flux. Carbon respired under anoxic conditions can either exist in the form of CO_2 or CH_4. Potential CH_4 emissions are scaled by the ratio of CO_2 to CH_4 emissions ($f_m = 0.4$) observed empirically (Scanlon and Moore, 2000) and this potential flux (P_{CH_4}, Eq. 14) is transferred to the methane emission model. The peatBALANCE model has a daily time step.

2.1.3 Methane transport model

In order to simulate methane emissions we employ the widely used (e.g. van Huissteden et al., 2006; Bohn et al., 2007; Wania et al., 2009a, b; Ringeval et al., 2010) Walter model (Walter and Heimann, 2000; Walter et al., 1996, 2001a). It is a process-based model, which explicitly simulates the three most dominant pathways of CH_4 to the surface:

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i. Diffusion. The molecular diffusion of CH_4 through the water logged soil column is slow and occurs everywhere. The calculation of this diffusion flux is based on Fick's first law.

ii. Ebullition. If a certain concentration of dissolved CH_4 is exceeded, CH_4 bubbles form. These are trapped in the peat and when a certain pressure threshold is reached, ebullition occurs. This release of CH_4 to the atmosphere happens so rapidly that only small amounts of CH_4 are oxidized.

iii. Plant-mediated transport. The transport of CH_4 through aerenchymous plant tissue from the place of origin directly to the atmosphere is defined as plant-mediated transport. Bypassing the aerobic zone in the peat column is a very effective transport mechanism leading to little oxidation of CH_4. The plant-mediated transport to the surface depends on the distribution of roots in the acrotelm and catotelm and on plant phenology.

The production of CH_4 is calculated within the peatBALANCE model and distributed to the root zone of the methane model, which has a vertical resolution of 1 cm per layer. Oxidation of CH_4 is only possible in the aerobic part of the soil column above the water table.

We coupled this model asynchronously to the peatBALANCE model described above and performed time-slice model experiments with both models combined. The CH_4 emission model is called once per model day. Since the purpose of the CH_4 emission model is solely to estimate the relation between CO_2 and CH_4 emissions, there is no feedback to the peatBALANCE model.

The model output from the peatBALANCE model consists of carbon accumulation rates, peat height, fraction of carbon above respectively below water table, respiration of the oxic and anoxic parts of the soil and the amount of carbon stored in the acrotelm and the catotelm respectively. The coupled methane emission model gives the ratio and amount of CH_4 to CO_2 emissions.

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2.2 Experiments

The peatBALANCE model is driven by soil temperature of the uppermost soil layer (topSoilTemp) (Fig. 2, left), net primary production (NPP) (Fig. 2, middle), leaf area index (LAI) and soil moisture (α). These driving data were extracted from a transient simulation with the MPI-ESM covering the last 6000 yr with orbital forcing on a yearly basis following Bretagnon and Francou (1988) and greenhouse gas concentrations set to pre-industrial values (Fischer and Jungclaus, 2011).

In a previous publication (Kleinen et al., 2012) we described a scheme to dynamically determine the peatland extent and water table, based on the TOPMODEL approach (Beven and Kirkby, 1979), implemented in the CLIMBER2-LPJ model. We determined the water table distribution within a grid cell from the grid cell mean water table and topographic information. The summer mean grid cell fraction with a water table at or above the surface is considered an area wet enough for peat to accumulate. For the present experiments, the grid cell peatland fractions (Fig. 3) as well as the position of the water table within the peatland fraction are prescribed (Fig. 4), as determined by the CLIMBER2-LPJ model in a preindustrial control run. Kleinen et al. (2012) showed that changes in the peatland area are rather small over the time period 8000 yr BP to preindustrial, so that we neglect changes in peatland area in the present study.

Using these boundary conditions we conducted Holocene simulations (6000 yr PB to preindustrial) of the peatBALANCE model accompanied by time-slice simulations with the coupled Walter model (runs of 30 yr every 1000 yr). The peatBALANCE model runs at truncation T31, corresponding to a horizontal resolution of a $3.75° \times 3.75°$ longitude-latitude grid (approx. 400×400 km).

In order to get reliable starting conditions of the soil carbon pools (excluding catotelm peat, which never reaches equilibrium in our time frame of interest) we allowed the peatBALANCE model 1000 yr to spin up prior to the 6000 yr Holocene simulation.

We focused our analysis of peat accumulation and CH_4 emissions on the boreal zone above 40° North, subdivided into: Europe (EU), Asia (AS), and North America (NA).

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For comparison with data we defined smaller wetland areas as defined in Winderlich et al. (2011) for the West Siberian Lowlands (WSL) and Pickett-Heaps (2011) for the Hudson Bay Lowlands (HBL), see Table 3 for coordinates.

3 Results

3.1 Results for peat accumulation

Results from the transient 6000 yr Holocene experiment show an accumulation of 240 PgC in the permanently anoxic catotelm pool (Fig. 5, left). The investigated boreal wetlands cover a region almost circumpolar at latitudes from 40° N up to 80° N. The peatBALANCE model simulates the largest increase in peat carbon storage in the areas around the HBL, in Europe, and in the WSL (Fig. 5, right). These are the major peatland areas observed today.

We compare modelled catotelm peat accumulation rates against observations of catotelm peat accumulation rates compiled from Gorham et al. (2003), Kremenetzki et al. (2003), Beilman et al. (2009), and Yu et al. (2010), as described in Kleinen et al. (2012) (Fig. 6). Measured carbon accumulation rates are slightly larger, but the general patterns of peat accumulation are represented well by our model. This discrepancy could possibly be explained by a measurement bias, since often the deepest (oldest) part of the peatland is sampled (Korhola et al., 2010) and the model represents a substantially larger area than a local peat site.

3.2 Results for CH_4 emission

3.2.1 Preindustrial times

Several hotspots of CH_4 emissions can be detected at 6000 yr BP, 3000 yr BP and preindustrial (Fig. 7): the Hudson Bay Lowlands and Newfoundland, Eastern Europe

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and Finland, the West Siberian Lowlands and the Far East (Manchuria). We use the last of our 30-yr time slice model run to calculate the global preindustrial CH_4 emissions.

To evaluate model performance, we compare the CH_4 emissions against data sets from two specific regions: the West Siberian Lowlands and the Hudson Bay Lowlands. These two data sets integrate CH_4 emissions over a larger area, which allows direct comparison with our global model output. Site scale CH_4 flux measurements are likely biased since they are measured where emissions occur, whereas our model averages over a comparatively large area. To upscale methane emission rates from individual study sites to large study regions, extensive field knowledge of individual land cover classes in an investigation area is indispensable (Schneider et al., 2009), but not available for the whole boreal zone.

Our model results show CH_4 emissions for the West Siberian Lowlands of 6 Tg yr^{-1} (Fig. 8, blue). Based on the atmospheric concentration data from four tower stations in this region (ZOTTO, Winderlich et al., 2010; Sasakawa et al., 2012), an atmospheric transport inversion results in emissions of 6.89 Tg for the year 2009 (Winderlich, 2011). The seasonal cycle of our model compares well to the results of the data-driven inversion (Fig. 9). However, the modelled summer emissions are smaller (13.2 instead of 17.5 Tg in July) than the atmospheric data implies. The strongly simplified freeze-thaw processes in our model could explain the enhanced winter emissions.

For the Hudson Bay Lowlands area as defined by Pickett-Heaps et al. (2011) our model gives CH_4 emissions of 1.6 Tg yr^{-1} for preindustrial times (Fig. 8, red). Pickett-Heaps et al. (2011) published observational data from two stations, quantified by using the GEOS-Chem chemical transport model. Their best estimate for this area is 2.3 Tg yr^{-1} in the year 2008.

3.2.2 Holocene time slices

Apart from the preindustrial simulation, we also analyzed the CH_4 emissions for another six time slices, going back in time until 6000 yr BP. Our model results indicate that the spatial patterns of CH_4 emissions (Fig. 2, right and Fig. 7) change in preindustrial times

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compared to 6000 yr BP. We find a decrease in CH_4 emissions in Newfoundland and the high Eurasian Arctic, and an increase in the Hudson Bay Lowlands area.

Adding up the emissions for circumpolar boreal regions (above 40° N) results in 49.3 (±2.3) Tg yr^{-1} at 6000 yr BP, which increases to 51.5 (±2.75) Tg yr^{-1} in preindustrial times. In general, the boreal emissions show an increase over the last 6000 yr, with some variability (Fig. 10, right).

We analyzed the development of CH_4 emissions in three sub-boreal regions to get a detailed picture of where the carbon emissions originate: (i) North America, (ii) Europe, and (iii) Asia, (Fig. 10, left; Table 3). (i) In the North American domain we find a small increase of the emissions around 3000 yr BP, which decline to the initial values in preindustrial times. (ii) In the Asian domain we find an increase of CH_4 emissions from 6000 yr BP (10 Tg yr^{-1}) to preindustrial times (11 Tg yr^{-1}). (iii) In Europe we see an increase between 6000 and 4000 yr BP, followed by a stable phase until preindustrial times.

4 Discussion

4.1 Peat accumulation

Comparing the areas where data of soil organic carbon content suggest present-day peatlands (e.g. Tarnocai et al., 2009) to the wetland area determined by the model, we see that the modelled wetland distribution contains most areas where Tarnocai et al. show high carbon concentrations (Fig. 11). Since climate varies with latitude as a first approximation, we assume that the good fit to the latitudinal distribution also leads to a reasonable representation of peat accumulation, though the exact distribution and area of peatlands may not be represented by the model (Kleinen et al., 2012). The modelled peatland distribution however has the advantage of providing a consistent wetland distribution at the global scale whereas global datasets based on measurements come along with different rates of accuracy and uncertainty.

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Many investigations address the size of the boreal wetland peat carbon stocks. One common approach is to determine the basal peat age and to measure the height of the peat to derive carbon accumulation rates (Beilman et al., 2009; Yu et al., 2010). Estimates for peat accumulation rates for the Holocene, which are derived from radiocarbon analysis of peat cores have been published by Yu et al. (2009). The time-weighted average rate in their study is 18.6 g C m^{-2} yr^{-1} during the Holocene based on 33 peat cores from northern peatlands.

Our model shows a slightly lower number for the average peat accumulation rate, which is 16.6 g C m^{-2} yr^{-1}. Overall, the changes of peat accumulation rates throughout the Holocene are rather small. This is in line with other Holocene peat accumulation studies such as Yu et al. (2009). Borren (2004) found the peat accumulation rate to be as large as 30 to 50 g C m^{-2} yr^{-1} during the last 6000 yr (even with a peak of up to a 100 g C m^{-2} yr^{-1} shortly before the year 4000 PB). Since their study concerns the southern taiga of western Siberia, higher values than those found in a global approach including the higher latitudes can be expected.

When comparing measured to modelled peat accumulation rates, it should be kept in mind that our model calculates the average for the whole wetland fraction of the grid cell, whereas the site studies mostly are mostly located in the centre of the wetland, which could possibly lead to higher values.

The peatBALANCE model accumulates 240 PgC within 6000 yr of simulation. Considering the initialisation and expansion of peatlands in the early Holocene between 11 000 and 8000 yr BP (MacDonald et al., 2006; Jones and Yu, 2010; Korhola et al., 2010; Yu et al., 2010) and an estimated size of the accumulated carbon from the last glacial until preindustrial times of 180 to 621 Pg C (Gorham, 1991; Turunen et al., 2002; Smith et al., 2004; Yu et al., 2010), the accumulation of 240 Pg C over 6000 yr in our simulation fits well into this pattern of peat accumulation. The estimated carbon stock, however, does not include permafrost carbon stocks in the northern cryosphere region, which store an amount of 1400 to 1850 Pg C (Tarnocai et al., 2009; McGuire et al., 2010).

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Our results demonstrate that the temporal behaviour of carbon accumulation is fundamentally different for the acrotelm (the periodically aerobic upper part of the peat profile) and the permanently anoxic catotelm (below the acrotelm). The acrotelm carbon pool reaches an equilibrium state with a size of 16 PgC after a comparatively short period of 150 to 250 yr. This roughly corresponds to a peat layer depth of 0.4 m, which is in line with estimates in the literature (e.g. Charman, 2002).

Under Holocene climatic conditions, the amount of the carbon in the catotelm, in contrast to the acrotelm, grows almost linearly over the 6000 yr of transient simulation without a significant indication of saturation. In this time frame, peatlands are therefore a non-equilibrium system with regard to the carbon cycle.

If productivity at the surface and the relative decomposition rates in the acrotelm and catotelm remain constant over a long period of time, the total amount of respired (mineralized) carbon increases with time. Ultimately, the total peat decay reaches a level equivalent to the production at the surface and there will be no further net accumulation of peat mass. This is the principle upon which Clymo's (Clymo, 1984) idea of a limit to peat growth is based (Charman, 2002). The net peat accumulation becomes more variable if changes in water table conditions are incorporated (Hilbert et al., 2000). In the Hilbert model peatlands are capable of switching from net sinks to sources of carbon quite rapidly (Charman, 2002). In our model and for our time frame of interest, the Holocene, the terrestrial carbon cycle in peatlands is a non-equilibrium system. Presumably, it will take much longer than 60 000 yr for these peatlands to come to an equilibrium at which catotelm decay of old carbon balances additions of carbon from the intermittently aerobic acrotelm above, as in the Clymo model (Clymo, 1984; Gorham et al., 2003).

The evolution of peat carbon stocks under future warming scenarios is a potential area of application for this modelling approach. Generally, an increase in soil temperature will increase the rate of organic matter decomposition; conversely, when soil is saturated with water, anaerobic conditions slow down decomposition rates.

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4.2 Methane emissions

The intensity of CH_4 emissions from natural wetlands are very uncertain because these emissions vary considerably in time and space (Frankenberg et al., 2005). The time slice simulations conducted with the peatBALANCE model are aimed at the quantification of CH_4 emissions from boreal wetlands, both in time and space. Bottom-up analyses indicate CH_4 emissions for boreal regions from 32 to 112 Tg yr^{-1} (McGuire et al., 2009) whereas atmospheric analyses (top-down analyses) indicate emissions that are smaller and in the range of 15–50 Tg yr^{-1} (Mikaloff Fletcher et al., 2004; McGuire et al., 2010) for preindustrial times.

Our results show emissions in the range of 49.3 to 51.5 Tg yr^{-1} for boreal wetlands north of 40° over the course of our Holocene experiment from 6000 yr BP to preindustrial. We identified the increasing carbon stock as the main driver of rising CH_4 emissions. Lower soil temperatures as existing in the forcing would lead to a natural decrease in emissions, which we do not see in our results.

Measurements along the Dome C Antarctic ice core and the GRIP ice core in central Greenland show a minimum in CH_4 concentration around the year 5000 BP followed by an increase until the present day (Blunier et al., 1995; Flückiger et al., 2002). Results from our model experiment indicate that CH_4 emissions from natural boreal wetlands contribute to this trend of rising atmospheric CH_4 concentrations as an increase of 1 ppb CH_4 yr^{-1} would correspond to a CH_4 increase in the global atmosphere of 2.13 TgC yr^{-1}. However, the slowly rising natural emissions cannot explain the rapid CH_4 increase towards the end of the Holocene as indicated by ice core measurements.

Not all three examined subdomains show this increase. In the North American domain the emissions decline towards preindustrial and in Europe there is no clear trend visible in the mean values. Only the Asian domain shows a clear rising trend (from 10 to 11 Tg yr^{-1}) and the maximum values of the European domain rise from 17 to 19 Tg yr^{-1}.

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For two selected regions, the Hudson Bay Lowlands and the West Siberian Lowlands – two major areas of wetlands today – the modelled preindustrial CH_4 emissions agree well with observations. Both model and data show the highest emissions in summer (JJA) and the lowest emissions in winter (DJF). The modelled CH_4 summer emissions reproduce well the data from Winderlich et al. (2011) but its seasonal shoulders are too broad. The modelled winter emissions are higher than observed, because the freezing of the soil and the associated discontinuity of the methane transport are not represented by our model.

Modelling carbon cycling in the HBL area involves additional uncertainties. The HBL were basically shaped by the Laurentide Ice Sheet, which disintegrated about 7800–8000 yr ago, and have been rising isostatically since then Glaser et al., 2004). These low-lying wetlands started to accumulate peat shortly after the emergence from the sea. Yu et al. (2010) indicate basal dates in the HBL area younger than 8000 yr BP. Our fixed wetland distribution does not account for this evolution of wetlands. Regarding our time frame of interest, starting 6000 yr BP, this evolution, however, is negligible.

Typically, the HBL are assumed to contribute 10 % to boreal wetland emissions (Pickett-Heaps et al., 2011). Since our model results show CH_4 emissions of $\sim 50\,\mathrm{Tg\,yr^{-1}}$ for the boreal zone, we would expect emissions of about $5\,\mathrm{Tg\,yr^{-1}}$ for the HBL accordingly. If we choose the HBL exactly as defined by Picket Heaps et al. (2011) we get emissions of $1.6\,\mathrm{Tg\,yr^{-1}}$. Since our coarse model does not resolve the HBL in detail we would like to point out that our model produces methane south of the defined HBL area as well, which should be included in the HBL budget (Fig. 7).

Spaceborne CH_4 concentration measurements with the SCIAMACHY instrument on board the ENVISAT satellite show high CH_4 concentrations in the area of Manchuria, China, in 2003 (Frankenberg et al., 2005), although not every year. Our model shows CH_4 emissions in Manchuria as well, but they were not investigated in more detail, because no measurements exist.

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4.3 Limitations of the model approach

There are some limitations of this modelling approach. First, the model has a coarse resolution. Second, the model is simplified. It is exactly these two restrictions, however, that allow modelling over long time frames and the integration in global models.

Some processes, which are observed in reality, are missing in the current version of our peatBALANCE model: sulphur deposition, permafrost, and Sphagnum-associated methane oxidation. Boreal wetlands have always been strong CH_4 sources, accounting for 3 % to 9 % of the net land source of 552 $Tg\,yr^{-1}$ estimated by AR4 (Denman et al., 2007). With increases in CO_2 and temperature, and the associated increases in wetland productivity, CH_4 fluxes would be expected to increase. However, SO_4^{2-} deposition (from industrial combustion) has the potential to divert substrate flow away from methanogens and thereby inhibit CH_4 flux to the atmosphere (Schimel, 2004). Permafrost processes in the northern boreal zone inhibit soil decomposition leading to a huge build up of frozen organic carbon and hinders methane production. And last but not least, Sphagnum-associated methane oxidation occurs ubiquitously across the globe (van Winden et al., 2010; Parmentier et al., 2011) and could reduce the amount of CH_4 significantly.

Modelling carbon cycling of boreal wetlands in the context of global Earth System models remains challenging. Wetlands are highly heterogeneous ecosystems both in spatial extent and at the process level. The main focus of future research could be a better representation of this diversity in the model, even if it is supposed to run at the global scale. The identification of the major processes and finding the simplicity in complexity are prerequisites for modelling the carbon cycle of boreal wetlands within a global climate model. For further progress in this direction, it is important to include a dynamic wetland model in JSBACH such as developed by Stacke and Hagemann (2012).

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5 Conclusions

We developed the peatBALANCE model with peat accumulation and decay and implemented it in the land surface model JSBACH of the MPI-ESM. In a transient Holocene experiment, the model was driven by soil temperature, LAI, soil moisture, and NPP from MPI-ESM simulations by Fischer and Jungclaus (2011) and preindustrial wetland fraction and water table levels from CLIMBER-LPJ simulations by Kleinen et al. (2012). The peatBALANCE simulation yields an accumulation of 240 PgC in the boreal wetlands over the last 6000 yr. This carbon accumulation is an important long-term component of the carbon cycle and it is essential that it be accounted for in the simulations of the carbon balance on a millennial timescale.

We furthermore coupled the Walter methane emission model to our peatBALANCE model. Simulated preindustrial CH_4 emissions are 51.5 Tg yr^{-1} for boreal wetlands above 40° North, which is in the range of estimates of 15–112 Tg yr^{-1} for boreal wetlands. The model run suggests that CH_4 emissions were slightly lower at 6000 yr BP than at preindustrial. Emissions rise until preindustrial times with some variability. These dynamics in boreal CH_4 emissions resemble the minimum in the atmospheric CH_4 concentration around 5000–4000 yr BP with the following increase. The rising trend in CH_4 concentration over the last several thousand years, therefore, may be explained not only by anthropogenic factors (CH_4 emissions from landuse, Ruddiman, 2003) but also by natural processes.

Our approach does not only add processes in boreal wetlands that were important for carbon balance in the past, but also provides a framework for accounting for wetland response to future climate change. This is important, as on long timescales boreal wetlands are a significant component of the carbon and methane cycles that could either amplify or dampen human-induced global warming.

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Table 1. Survey of models of peat accumulation and methane emission

Model	Rationale	Forcing	Peat acc.	CH_4 emiss.	Coupled to ESM	Coupled to DGVM	Global appr.	Single-site
Wildi (1978)	Interaction between plants, water, and peat	Functions derived from field meas		□	□	□	□	
Clymo (1984)	Peat growths model with proportional decay function	Productivity and decay rates		□	□	□	□	
Hilbert (2000)	Peatland dyn. Interactions between water table and peat growths	Precip, wet and dry conditions		□	□	□	□	
Yu (2001)	Generic model framework	Water budget data		□	□	□	□	
Frolking (2001)	Long-term peat accumulation model	Vegetation, NPP, decomp. rates		□	□	□	□	
Bauer (2004)	Litter-quality dependent peat dynamics over millennia	NPP, water table position		□	□	□	□	
Ise (2008)	Physical-biogeochemical soil model with peat depths	Temp., radiation, wind, hydrology		□	□	□	□	
Frolking (2010)	Peat acc. Incl. feedbacks of hydrology, plants and peat	Precip, litter, stable temp.		□	□	□	□	
Wang (2010)	EMIC study of NP carbon cycle dynamics in the Holocene	Prescribed peatland growth and extent	(□)	□		□		□
Kleinen (2012)	Dyn. wetland ext. and peat dyn.	–		□				(□)
Walter (2001)	CH_4 emissons from nat. wetlands	Precip, soil temp.	□		□	□	(□)	
Eliseev (2008)	Response of CH_4 (wetland) to climate change	Wetland extent, CH_4 emissions	□		□	□		□
Wania (2009)	Including wetlands and its CH_4 emissions into LPJ	Temp., precip, soil type	□		□			□
Our study	CO_2 and CH_4 emissions on millennial time scales	Wetlands extent, water table position				□		(□)

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Table 2. Abbreviations and parameters.

Parameter	Value	Name/Units	Description
C_X	–	mol(C) m^2(canopy)	Size of carbon pool X
F_X	–	mol(C) m^2(canopy) s	Carbon flux to the carbon pool X
NPPx	–	mol(C) m^2(canopy) s	Part of NPP allocated to carbon pool X
R_X	–	mol(C) m^2(canopy) s	Respiration flux from carbon pool X
k_X	–	mol(C) m^2(canopy) s	Decomposition flux from carbon pool X
f_{ae}	–	–	Fraction indicates the oxic fraction of the acrotelm carbon pool
Q_{10}	1.8	–	Base for temp. dependence of respiration
T_{ref}	273.15	K	Q_{10} reference temperature
α	–	Alpha	Mean water stress factor
β_X	–	Beta	Fraction of the respiration flux that goes into the carbon pool X
τ_L	660	$days^{-1}$	Turn over time of litter carbon pool
τ_S	150	$years^{-1}$	Turn over time of soil carbon pool
$\tau_{A_{ea}}$	14.92	$years^{-1}$	Turn over time of oxic acrotelm pool
$\tau_{A_{an}}$	42.64	$years^{-1}$	Turn over time of anoxic acrotelm pool
τ_C	30 000	$years^{-1}$	Turn over time of catotelm pool
ρ_A	4579.14	mol(C) m^3	Density of acrotelm pool
ρ_C	6277.73	mol(C) m^3	Density of catotelm pool
C_f	0.52	–	Carbon fraction of biomass pools
sla	0.451	m^2 leaf mol(C)$^{-1}$	Specific leaf area
Y_X	1.7	–	Factor relating leaf carbon to the carbon content of the whole pool
LAI	–	–	Leaf Area Index
f_m	0.4	–	Factor to determine the methane production flux
P_{CH_4}	–	–	CH_4 production
h_A	–	–	Height of acrotelm carbon pool

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Table 3. List of areas and sites.

Areas and Sites	Abbr.	Coordinates
Europe	EU	10° W–60° E, 40° N–80° N
Asia	AS	60° E–120° E, 40° N–80° N
North America	NA	55° W–165° W, 40° N–80° N
West Siberian Lowlands	WSL	59° E–90° E, 56° N–66° N
Hudson Bay Lowlands	HBL	75° W–96° W, 50° N–60° N

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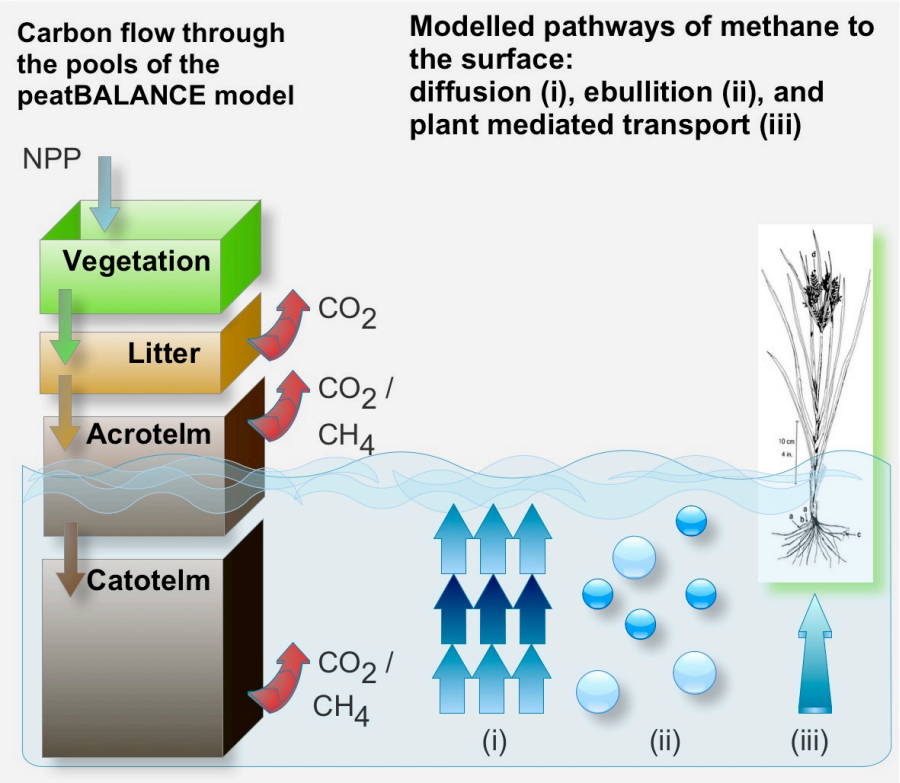

Fig. 1. Diagrammatic sketch of the carbon fluxes in the peatBALANCE model. The transport pathways of CH_4 fluxes are shown at the right.

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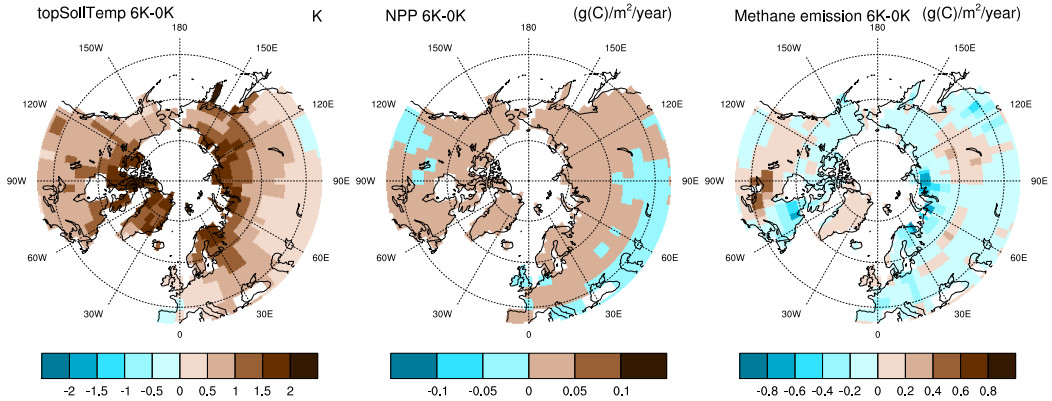

Fig. 2. Left and middle panel: changes of variables simulated by the MPI-ESM and used here for driving the peatBALANCE model. Shown are 10-yr averages for preindustrial (0 yr BP) minus 6000 yr BP. Annual temperatures of the uppermost soil layer (Kelvin, left). NPP ($gC\,m^{-2}\,yr^{-1}$, middle). Right panel: Modelled CH_4 emissions ($gCH_4\,m^{-2}\,yr^{-1}$) for preindustrial (0 yr BP) minus 6000 yr BP.

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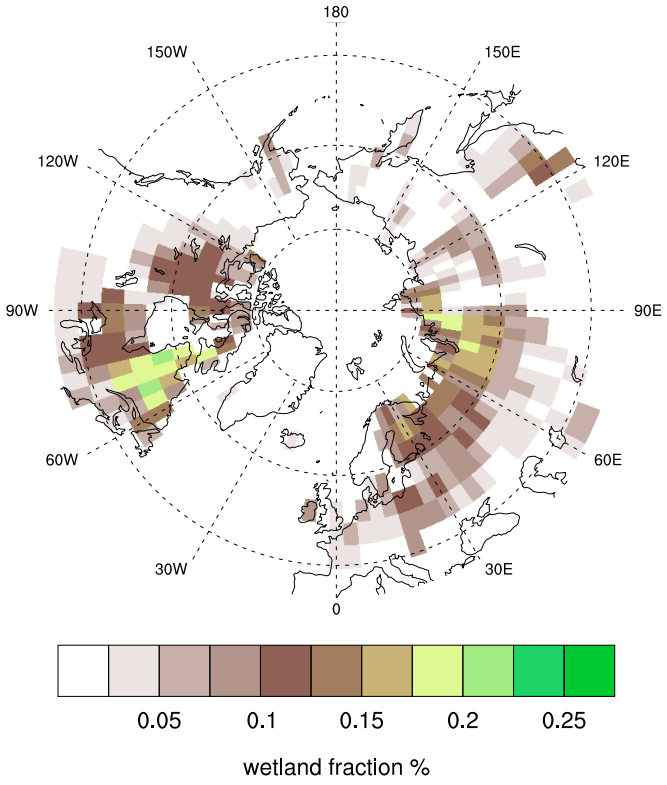

Fig. 3. Wetland fraction displayed in the model resolution used in the transient simulations (as published by Kleinen et al., 2012).

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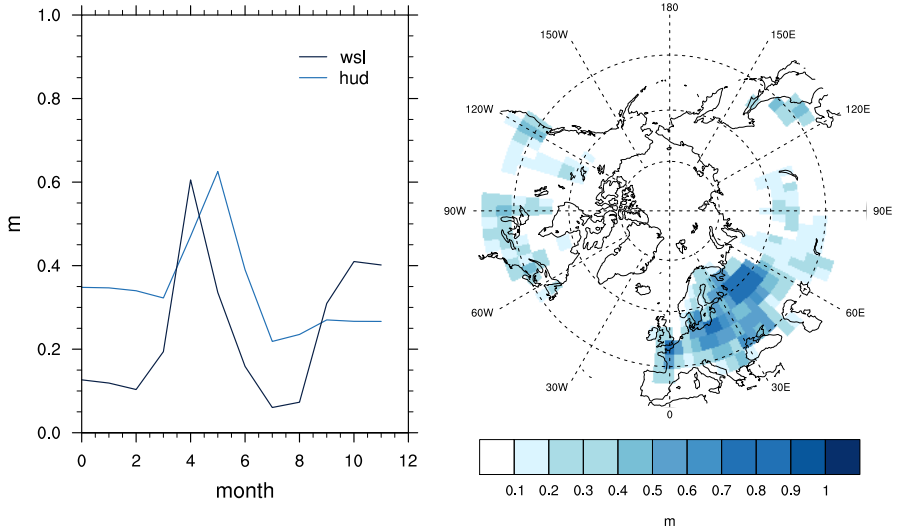

Fig. 4. Left panel: seasonal dynamics of water table (m) for 2 different sites (Table 2). Right panel: amplitude of changes in water table between spring season (MAM) and autumn (SON). All plots are for pre-industrial conditions, data as published by Kleinen et al. (2012).

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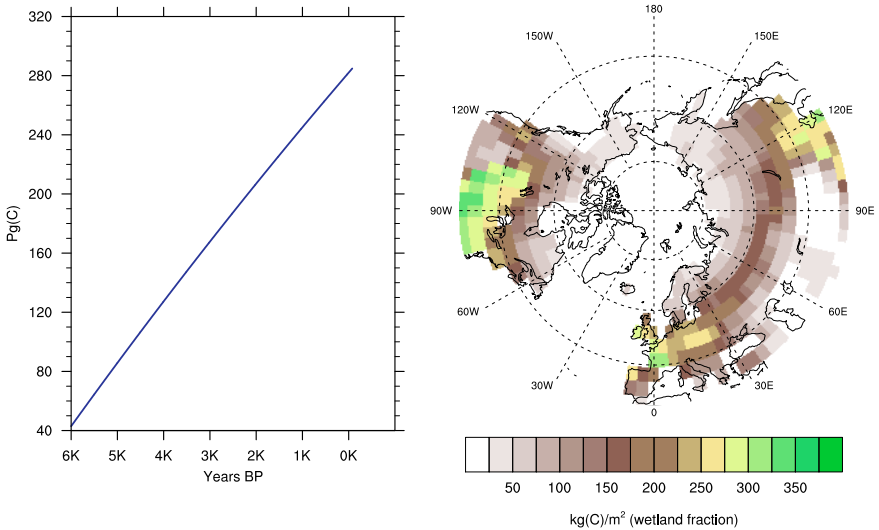

Fig. 5. Peat carbon (PgC) accumulated during a 6000 yr peatBALANCE model run. Left panel: peatlands above 40° N. Right panel: peat carbon (kgC m^{-2}) in the wetland fraction of the model grid cells.

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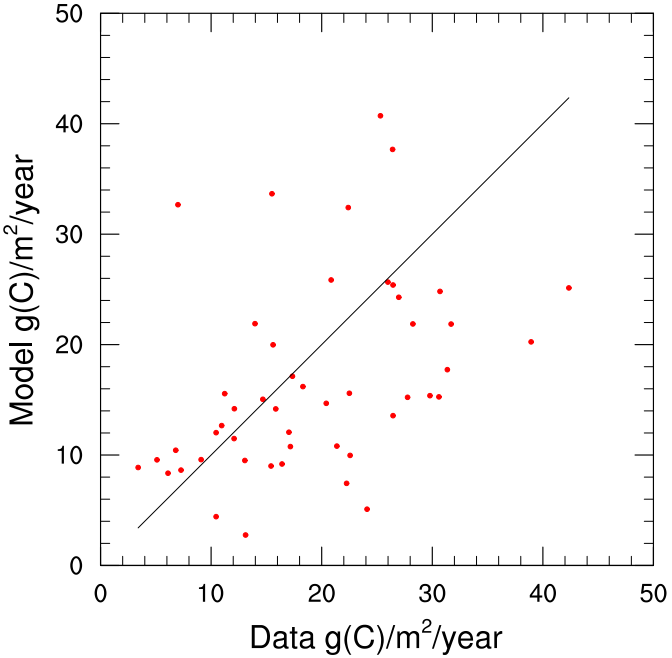

Fig. 6. Modelled peat accumulation rates for pre-industrial times and at different sites compared to a dataset of site scale peat accumulation rate measurements compiled by Kleinen et al. (2012) with data from Gorham et al. (2003), Kremenetzki (2003), Beilman et al. (2009), and Yu et al. (2010).

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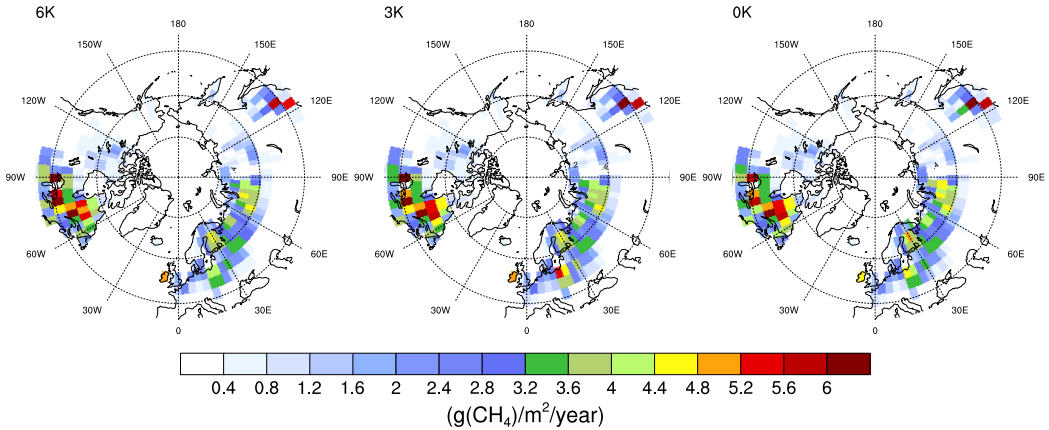

Fig. 7. Methane emissions ($gCH_4\ m^{-2}\ yr^{-1}$) from the time slice simulations for 6000 yr BP (left), 3000 yr BP (middle) and pre-industrial (right), averaged over 10 yr of model siulation. Carbon fluxes are represented with respect to grid box area.

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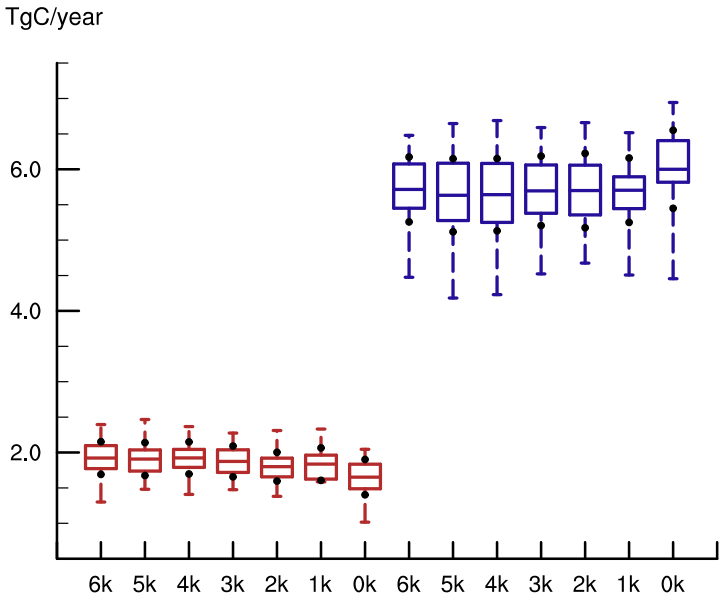

Fig. 8. Box-and-whisker plots for CH_4 emissions ($TgCH_4\,yr^{-1}$) averaged over the regions of Hudson Bay (left, red) and West Siberian Planes (left, blue) as defined by Picket-Heaps (2011) and Winderlich (2011) for 6000 yr BP to preindustrial. The tailored box plots show the mean, minimum value, maximum value, and the 25th and 75th percentiles of a 30-yr time series.

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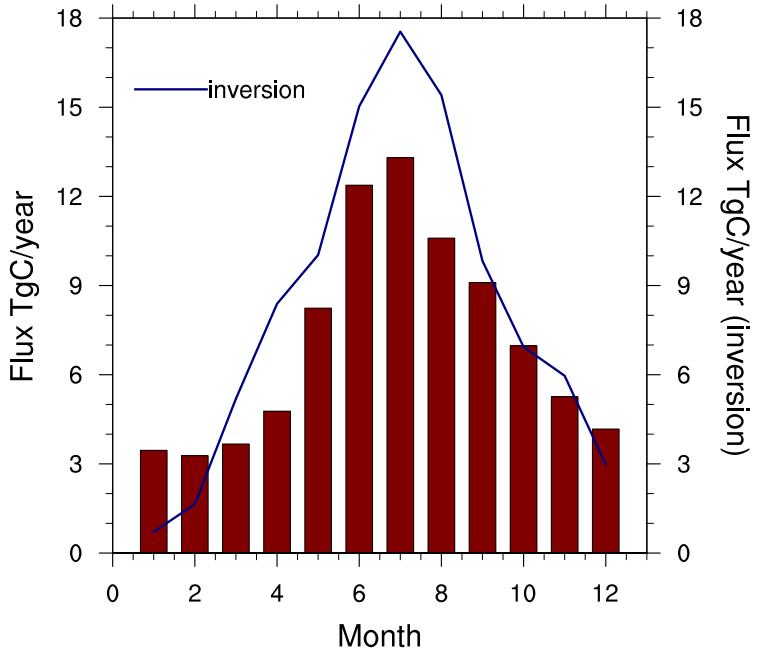

Fig. 9. Sum of monthly CH_4 emissions in the West Siberian Lowlands: bar chart represents 30 yr mean at present day, solid line shows results from an data-driven inversion study for the year 2009 (Winderlich, 2011).

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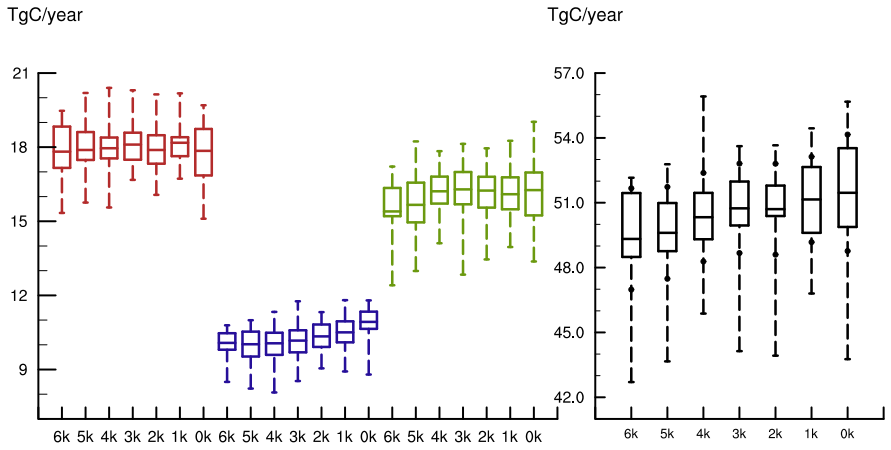

Fig. 10. Left panel: box-and-whisker plots for CH_4 emissions ($TgCH_4\,yr^{-1}$) averaged over the domains of North America (left, red), Asia (left, blue), and Europe (left, green), for the years 6000 BP until preindustrial. The tailored box plots show the mean, minimum value, maximum value, and the 25th and 75th percentiles of a 30-yr time series. Right panel: box-and-whisker plots for total CH_4 emissions ($TgCH_4\,yr^{-1}$) of boreal wetlands above 40° N, also from 6000 yr BP until preindustrial.

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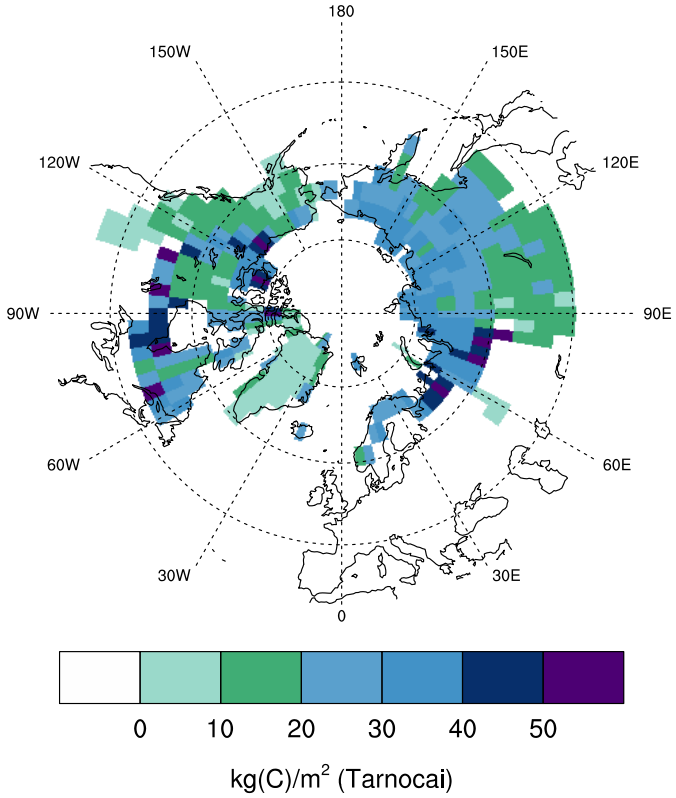

Fig. 11. Distribution of soil organic carbon contents (0–100 cm depth) based on the NCSCD published by Tarnocai et al. (2009), displayed in the model resolution.

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