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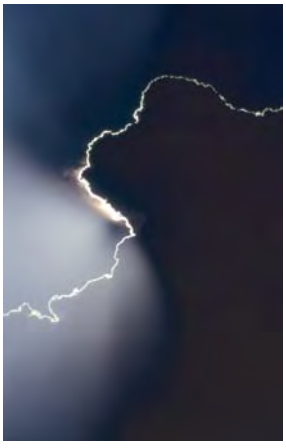
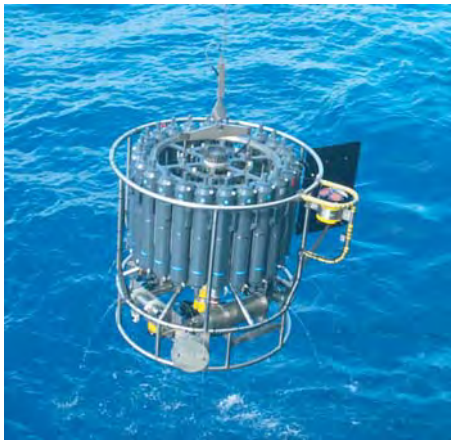
Modelling interactions between boreal wetlands, carbon cycle and climate

Robert J. Schuldt





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Abstract

Since the last glaciation, boreal wetlands have accumulated substantial amounts of peat, estimated at 180 to 621 Pg of carbon (C). Over the same period of time these wetlands have emitted methane (CH_4), the second most important greenhouse gas (GHG) next to carbon dioxide (CO_2). Present day estimates range from 32 to 112 Tg CH_4 per year. With these emissions boreal wetlands significantly affect the global cycling of carbon and the CH_4 concentration in the atmosphere. By storing carbon and taking up CO_2 from the atmosphere, boreal wetlands have had a cooling effect on climate in the past. Undisturbed boreal wetlands are likely to continue functioning as a net carbon sink. In the future, particularly with regard to future climate change, the carbon balance could be significantly changed since biogeochemical processes of boreal wetlands are sensitive to biotic and abiotic environmental conditions. Earth system models are state of the art tools to investigate carbon cycle dynamics in past and future climates. However, these global models usually neglect biogeochemical processes of boreal wetlands. In order to investigate how boreal wetlands interact with the carbon cycle and with the climate, I developed a model that accounts for the characteristic biogeochemical processes of boreal wetlands (the peatBALANCE model) and implemented it into the land surface model of the Max Planck Institute Earth System Model (MPI-ESM) and also incorporated a CH_4 emission model into it. This dissertation focuses on the peat accumulation and CH_4 emission of boreal wetlands and it describes which processes and parameters are needed to model the carbon cycle dynamics of boreal wetlands in past, present and future times. I analyzed results from numerous model simulations and compared results against data from measurements and other modelling approaches. My research produced a number of key findings: The peatBALANCE model has accumulated 240 Pg of catotelm peat carbon in areas north of 35° during the last 6000 yr of model simulation. The peat accumulation rate for present day to 2100 is 48.88 Tg C yr^{-1}. The model simulates CH_4 emissions of 49.3 Tg CH_4 yr^{-1} for 6000 yr BP and 51.5 Tg CH_4 yr^{-1} for pre-industrial times. At the present day the CH_4 emissions are in the range of 48 to 58 Tg CH_4 yr^{-1} while showing an annual variability of 10 Tg CH_4 yr^{-1}. The model predicts large increases of CH_4 emissions up to 78 Tg CH_4 yr^{-1} in 2100, using the emissions scenario RCP8.5. The main conclusions drawn from this research were that boreal wetlands experience extensive changes and, as boreal wetlands, are complex adaptive systems: they respond to a changing external forcing by adapting C accumulation and CH_4 emission rates. The net effect, however, is more than a combination of impacts, as these drivers interact in complex ways. The results presented in this thesis highlight the importance of boreal wetlands for simulations of the global carbon cycle. My study adds processes to the land surface model of the MPI-ESM and I recommend accounting for these boreal wetland processes when investigating global carbon cycle dynamics with ESMs in past, present and future climates, particularly in the next generation of ESMs.

Key words: boreal wetlands, carbon cycle, peat accumulation, methane emission, peatBALANCE, Earth System Model, MPI-ESM.

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List of Abbreviations

alpha	Soil moisture
AMIP	Atmospheric Model Intercomparison Project
AR5	Fifth Assessment Report of the IPCC
AS	Asia
C	Carbon
CBALANCE	Carbon cycle module of the JSBACH
CH_4	Methane
CLIMBER-LPJ	CLIMate and BiosphERe with LPJ
CMIP5	Coupled Model Intercomparison Project Phase 5
CO_2	Carbon dioxide
DGVM	Dynamic Global Vegetation Model
DJF	Winter season
ECMWF	European Centre for Medium-Range Weather Forecasts
ESM	Earth System Model
EU	Europe
g	Gramm
GEOS-Chem	GEOS - Chemical transport model
GHG	Greenhouse gas
HAdCM3	UK Met Office climate model
HBL	Hudson Bay Lowlands
IPCC	Intergovernmental Panel on Climate Change
JJA	Summer season
JSBACH	Land surface component of the MPI-ESM
K	Kelvin
kg	Kilogramm
LAI	Leaf area index

LPJ	Lund Potsdam Jena Dynamic Global Vegetation Model
MAM	Spring season
MERLIN	MEthane Remote Sensing LIDAR MissioN
MPI-ESM	Max Plack Institute Earth System Model
MPI-ESM-LR	MPI-ESM Low Resolution
NA	North America
NH	Northern hemisphere
NOAA	National Oceanic and Atmospheric Administration
GMD	Global Monitoring Division
NPP	Net primary production
PB	Before present
peatBALANCE	Carbon cycle module of the JSBACH, accounting for
PFT	Plant function type
PgC	Petagramm of carbon
ppb	Parts per billion
ppm	Parts per million
Q_{10}	Temperature coefficient
RCP8.5	Representative concentration pathway (8.5)
SH	Southern hemisphere
SON	Autumn season
Tg CH_4	Teragramm of CH_4
TOPMODEL	Hydrologic basin model
topSoilTemp	Soil temperature of the uppermost soil layer
WETCHIMP	WETland and Wetland CH_4 Intercomp. of Models Project
WSL	West Siberian Lowlands
yr	year
ZOTTO	ZOtino Tall Tower Observatory

Chapter 1

1 Introduction

1.1 Boreal wetlands carbon cycle and climate

For the last 800000 yr, the climate has evolved cyclical and glaciers spread regularly over the Earth. Approximately every 100000 yr, the glaciers are so large that they become unstable and retreat to the high mountains. Ice-core reconstructions show that temperature has co-evolved with greenhouse gas (GHG) concentrations in concert (Lüthi et al., 2008). Over the last 800000 yr, natural factors have caused the atmospheric carbon dioxide (CO_2) concentration as well as the atmospheric methane (CH_4) concentration to vary within a range of about 170 to 300 parts per million (ppm) and 400 to 700 parts per billion (ppb) respectively (Forster et al., 2007). From ice core reconstructions it can be derived further that the atmospheric carbon dioxide content increased strongly at the beginning of each interglacial. This warm situation, however, allows for a global onset of biological and geological processes which alter the carbon cycle substantially (Brovkin et al., 2012).

One of these processes altering the carbon cycle is the establishment of boreal wetlands. Human induced climate change reinforces the biological processes, which in most cases feedback to the climate, and amplifies the warming. In this thesis I focus on the peat accumulation and CH_4 emission of boreal wetlands above 35° N and investigate their interactions with climate with respect to the carbon cycle.

Boreal wetlands are peat moss dominated ecosystems. Peat mosses are very special plants, particularly adapted to acid, cool, wet and extremely nutrient-poor conditions (Rydin et al., 2006). Their common features are waterlogged conditions, slow decomposition and slow rates of subsurface flow that allow the partly decayed organic matter to accumulate in place (Dise, 2009). The processes

of anaerobic decomposition that allow carbon to accumulate also produce the strong greenhouse gas CH_4. The boreal wetlands are further subdivided into bogs and fens, according to their nutrient regime. Further subdivisions according to their moisture regime, soil or substrate are common. As the key features of these ecosystems, carbon accumulation and GHG emission, will be investigated in this study, these ecosystems will be referred to hereinafter as boreal wetlands.

Boreal wetlands are the ecosystems with the highest carbon density, even though they cover only 3 % of the land surface. Boreal wetlands are the largest single source of methane emissions and have a large share of the global atmospheric methane budget (Denman et al., 2007; O'Connor et al., 2010). Approximately 40 % of current global methane sources are natural (Heimann et al., 2010).

Previous studies suggest that the size of the boreal peat carbon stock is as large as 180 to 621 Petagramm C (PgC) (Gorham, 1991; Smith et al., 2004; Turunen et al., 2002; Yu et al., 2010) and CH_4 emissions are in the range of 32 to 112 Teragramm (Tg CH_4) per year (Bergamaschi et al., 2007; McGuire et al., 2010; Zhuang et al., 2004). By storing carbon and taking up CO_2 from the atmosphere, boreal wetlands have had a cooling effect on climate during the last millennium (Frolking and Roulet, 2007; Roulet et al., 2007). The carbon cycling in boreal wetlands is highly influenced by climatic conditions (Dorrepaal et al., 2009). Undisturbed boreal wetlands are likely to continue functioning as a net carbon sink (Smith et al., 2004; Tolonen and Turunen, 1996; Turunen et al., 2002).

These carbon pools might be destabilized in the future because 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 wetlands 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). Scenarios for future climate change predict that high northern latitudes will experience increased temperatures but also higher mean precipitation (Belyea and Malmer, 2004; Malmer and Wallen, 2004). Overall it has been investigated that climate change will significantly impact northern wetlands (Limpens et al., 2008). Among the largest uncertainties in current projections of future climate is the feedback between the terrestrial carbon cycle and climate (Dorrepaal et al., 2009). Little, however, is known of the response of boreal wetlands to future climate change with respect to strength and temporal characteristics. A closer look at the processes that happened in the past is important to gain a better understanding of climate-biogeosphere interactions and feedbacks happening today and expected in the future.

The interaction between boreal wetlands and climate can be investigated with the help of models. More than that, the interaction between vegetation and climate in particular must be considered an important component in climate system dynamics (Claussen, 2009). Earth System Models (ESMs) are the state of the art tools to investigate the interactions of the different components, such as atmosphere and biosphere. The results presented in this study help us to understand the role of boreal wetlands in the climate system and provide the basis for further research.

As mentioned above, there is abundant evidence of the different processes involved in the interaction of boreal wetlands, carbon cycle and climate. Their strength and temporal properties, however, are not well known and still subject to large uncertainties. This thesis aims to improve the understanding and to provide a quantification of these interactions.

Therefore, the following research questions arise:

(1) Which processes and parameters are needed to model the carbon cycle dynamics of boreal wetlands for the last 6000 yr?

(2) How does the carbon peatBALANCE/CH_4 emission model perform compared to pre-industrial peat accumulation and present day CH_4 emission rates?

(3) How have the carbon accumulation and CH_4 emissions evolved from 6000 yr BP to pre-industrial and the present day?

(4) How will the carbon cycle dynamics of boreal wetlands evolve in the future?

1.2 Outline of this thesis

Chapters 2 and 3 of this thesis are written in the style of journal publications. As a consequence, they contain their own introductions and conclusions. Chapter 2 is in review by Biogeosciences, an international scientific and open access journal, and is reproduced here with editorial adjustments (Schuldt et al., 2012).

The remaining chapters of this thesis are structured as follows:

In the second chapter of this thesis an overview of existing models of peat dynamics and CH_4 emissions is given. Following this a new model for peat accumulation and decay is presented and a CH_4 emission model that model is combined with is described. A description of the simulation conducted follows. In the Chapter 2, the research questions (1), (2) and (3) as defined above are addressed.

Chapter 3 is currently being prepared for submission. This chapter concentrates on the present day and future CH_4 emissions. Trends and variability are investigated, addressing the research question (3) and elaborating on research question (4).

The fourth chapter contains a summary of the major findings of this study and the conclusions one can draw from these as well as a discussion of perspectives for future research.

Chapter 2

2 Modelling Holocene carbon accumulation and methane emissions of boreal wetlands. An Earth System Model approach

2.1 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 (Pg C) (Gorham, 1991; Smith et al., 2004; Turunen et al., 2002; Yu et al., 2010) and CH_4 emissions are in the range of 32 to 112 Teragramm per year (Tg CH_4 yr^{-1}) (Bergamaschi et al., 2007; McGuire et al., 2010; Zhuang et al., 2004). By storing carbon and taking up carbon dioxide (CO_2) from the atmosphere, boreal wetlands have had a cooling effect on climate during the last millennium (Frolking and Roulet, 2007; Roulet et al., 2007). This positive carbon balance also applies to the greenhouse gas (GHG) emissions, in particular CH_4 emissions of boreal wetlands. Undisturbed boreal wetlands are likely to continue functioning as a net carbon sink (Smith et al., 2004; Tolonen and Turunen, 1996; Turunen et al., 2002). 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 wetlands 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).

2.1.1 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 g C m^{-2} yr^{-1} (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.

In the soil column of wetlands 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 (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 boreal wetlands 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 (Kamal and Varma, 2008; Sundh et al., 1994). The production depends on the composition of the microbial community and several abiotic factors such as the availability 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 (Dinsmore et al., 2009; Wille et al., 2008). 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, boreal wetlands are characterized by environmental gradients in the horizontal plane: patterns of vegetation variation can be found everywhere in boreal wetlands. 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).

2.1.2 Models of peat dynamics

2.1.2.1 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 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. (Denman et al., 2007; 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.

2.1.2.2 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 Pg C 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 boreal wetlands 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.

2.1.3 Methane emission models

The importance of boreal wetlands 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 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; 2001b). 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 et al. (Wania, 2007; Wania et al., 2009a; 2009b) 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.

2.1.4 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 Tg CH_4 yr^{-1} (pre-industrial) to 170–200 Tg CH_4 yr^{-1} at the end of the 21st century. Meng et al. 2012 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 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.

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	✗	✓	✗	✓	✓	✗
This study	CO_2 and CH_4 emissions on millennial time scales	Wetlands extent, water table position	✓	✓	✓	✗	✓	(✓)

2.1.5 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 (section 2.1). 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 (section 2.2).

We compare the results of this model with observations and results from an inversion model for the present-day situation (section 2.3). 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 (section 2.4). We end with a conclusion in section 2.5.

2.2 Methods

2.2.1 Model description

JSBACH is the modular land surface scheme of the MPI-ESM (Raddatz et al., 2007; Roeckner et al., 2003). 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

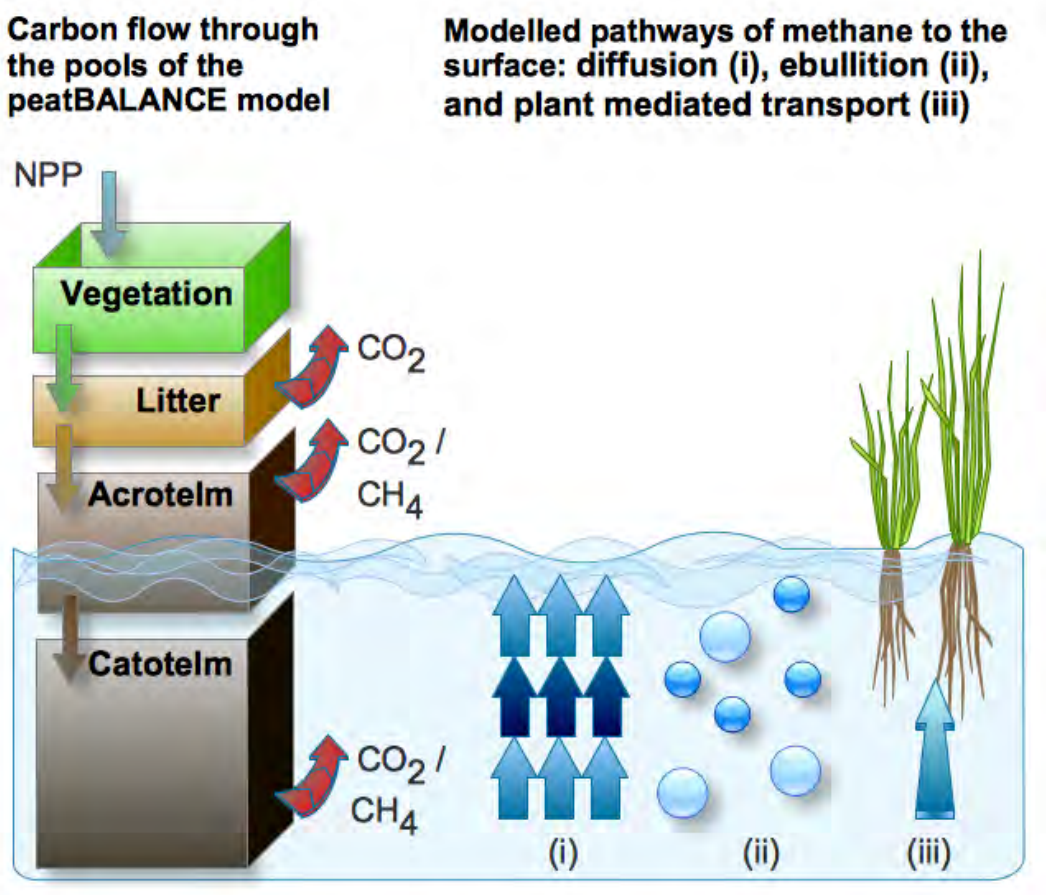

Figure 1: Diagrammatic sketch of the carbon fluxes in the peatBALANCE model. The transport pathways of CH_4 fluxes are shown at the right.

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).

2.2.1.1 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 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.

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

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

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

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

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

$$R_L = \alpha \frac{Q_{10}^{(Tsoil-Tref)/10}}{\tau_L} \quad (6)$$

$$R_S = \alpha \frac{Q_{10}^{(Tsoil-Tref)/10}}{\tau_S} \quad (7)$$

Table 2: Model variables 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^{-1}	Carbon flux to the carbon pool X
k_X	-	mol C m^{-2}(canopy) s^{-1}	Decomposition flux from carbon pool X
NPPx	-	mol C m^{-2}(canopy) s^{-1}	Part of NPP allocated to carbon pool X
R_X	-	mol C m^{-2}(canopy) s^{-1}	Respiration flux from carbon pool X
β_X	-	Beta	Fraction of the respiration flux that goes into the carbon pool X
Υ_X	1.7	-	Factor relating leaf carbon to the carbon content of the whole pool X
f_{ae}	-	-	Fraction indicates the oxic fraction of the acrotelm carbon pool
h_A	-	-	Height of acrotelm carbon pool
P_{CH_4}	-	-	Potential CH_4 flux
ρ_A	4579.14	mol C m^{-3}	Density of acrotelm pool
ρ_C	6277.73	mol C m^{-3}	Density of catotelm pool
$\tau_{A_{an}}$	42.64	$years^{-1}$	Turn over time of anoxic acrotelm pool
$\tau_{A_{ea}}$	14.92	$years^{-1}$	Turn over time of oxic acrotelm pool
τ_C	30000	$years^{-1}$	Turn over time of catotelm pool
τ_L	660	$days^{-1}$	Turn over time of litter carbon pool
τ_S	150	$years^{-1}$	Turn over time of soil carbon pool
C_f	0.52	-	Carbon fraction of biomass pools
f_m	0.4	-	Factor to determine the methane production flux
LAI	-	-	Leaf Area Index
Q_{10}	1.8	-	Base for temp. dependence of respiration
sla	0.451	m^{-2} (leaf) mol C	Specific leaf area
T_{ref}	273.15	K	Q_{10} reference temperature
T_{soil}	-	K	Temperature of the uppermost soil layer
α	-	Alpha	Mean water stress factor

2.2.1.2 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 (eq. 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 τ_C = 30000 yr for the catotelm. The anaerobic respiration k_C is modelled through a Q_{10} model (eq. 13).

$$\frac{dC_A}{dt} = \beta_L R_L C_L - k_A C_A \quad (8)$$

$$\frac{dC_C}{dt} = \beta_A C_A - k_C C_C \quad (9)$$

$$h_A = C_A \,/\, (\rho_A \, C_f) \quad (10)$$

$$f_{ae} = 1 - \frac{wt}{h_A} \quad (11)$$

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

$$k_C = \alpha \frac{Q_{10}^{(T_{soil}-T_{ref})/10}}{\tau_C} \quad (13)$$

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

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_{CH4}, eq. 14) is transferred to the methane emission model. The peatBALANCE model has a daily time step.

2.2.1.3 Methane transport model

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

(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.

2.2.2 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 (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 pre-industrial control run. Kleinen et al. (2012) showed that changes in the peatland area are rather small over the time period 8000 yr BP to pre-industrial, so that we neglect changes in peatland area in the present study.

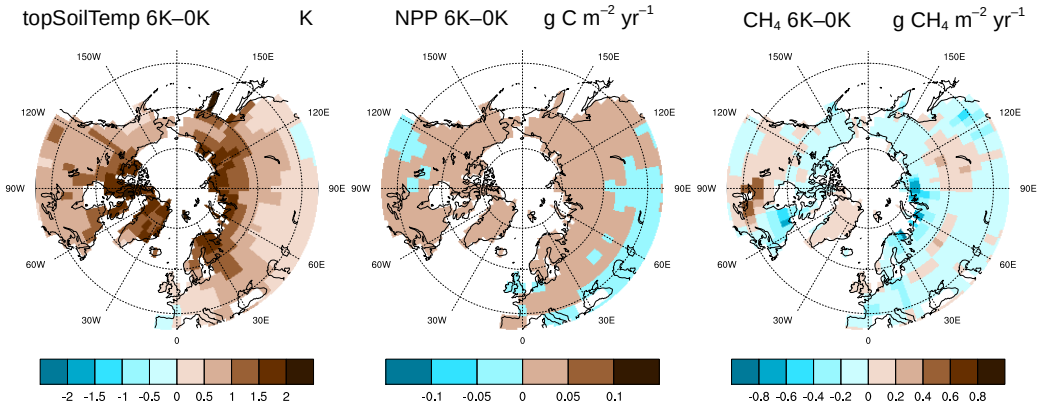

Figure 2: Left and middle panel: Changes of variables simulated by the MPI-ESM and used here for driving the peatBALANCE model. Shown are 10-yr averages for pre-industrial (0 yr BP) minus 6000 yr BP. Annual temperatures of the uppermost soil layer (Kelvin, left). NPP (g C m^{-2} yr^{-1}, middle). Right panel: Modelled CH_4 emissions (g CH_4 m^{-2} yr^{-1}) for pre-industrial (0 yr BP) minus 6000 yr BP.

Using these boundary conditions we conducted Holocene simulations (6000 yr BP to pre-industrial) of the peatBALANCE model accompanied by time-slice simulations with the coupled Walter model (runs of 30 yr every 1000 yr).

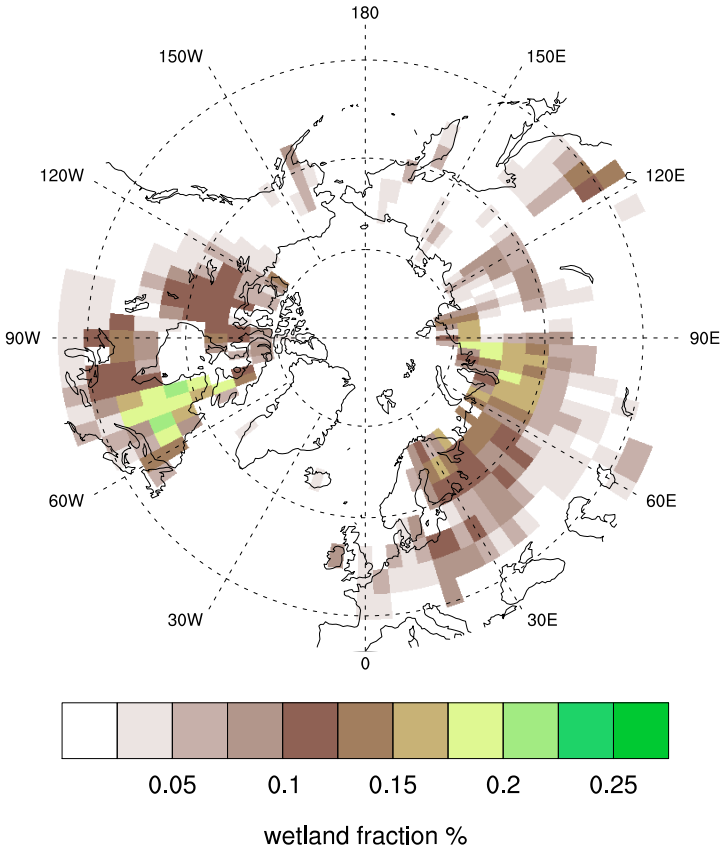

Figure 3: Wetland fraction displayed in the model resolution used in the transient simulations (as published by Kleinen et al., 2012).

The peatBALANCE model runs at truncation T31, corresponding to a horizontal resolution of a 3.75° × 3.75° longitude-latitude grid (approx. 400 x 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° N, subdivided into: Europe (EU), Asia (AS), and North America (NA). For comparison with data we defined smaller wetland areas as defined in

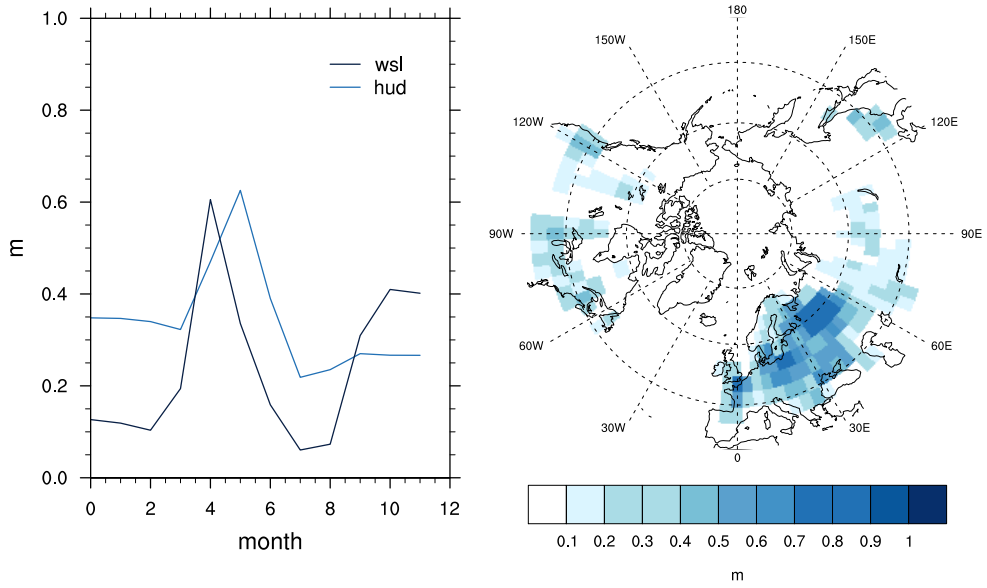

Figure 4: Left panel: Seasonal dynamics of water table (m) for 2 different sites (Table 2). Right panel: Amplitude of changes in water table between spring season (MAM) and autumn (SON). All plots are for pre-industrial conditions, data as published by Kleinen et al. (2012).

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.

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

2.3 Results

2.3.1 Results for peat accumulation

Results from the transient 6000 yr Holocene experiment show an accumulation of 240 Pg C 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.

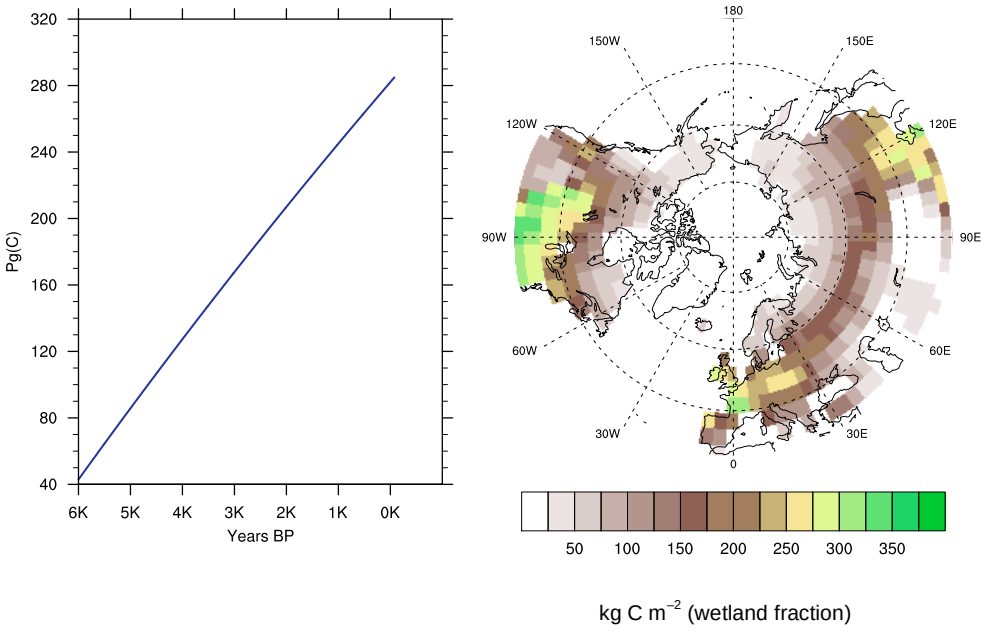

Figure 5: Peat carbon (Pg C) accumulated during a 6000 yr peatBALANCE model run. Left panel: boreal wetlands above 40° N. Right panel: Peat carbon (kg C m^{-2}) in the wetland fraction of the model grid cells.

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.

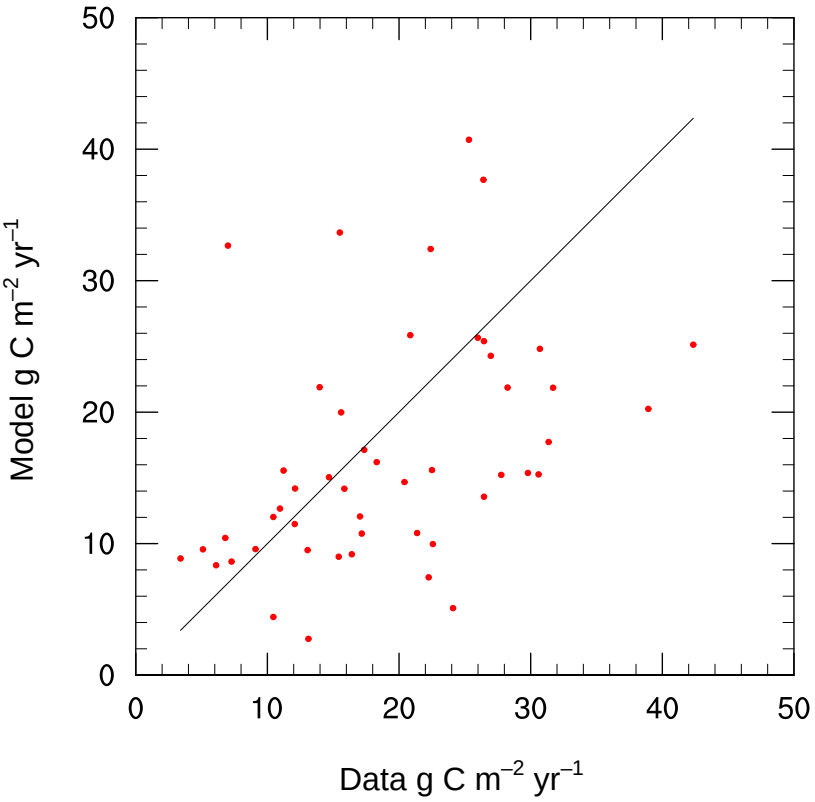

Figure 6: Modelled peat accumulation rates for pre-industrial times and at different sites compared to a dataset of site scale peat accumulation rate measurements compiled by Kleinen et al. 2012 with data from Gorham et al. (2003), Kremenetzki (2003), Beilman et al. (2009), and Yu et al. (2010).

2.3.2 Results for CH_4 emission

2.3.2.1 Pre-industrial times

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

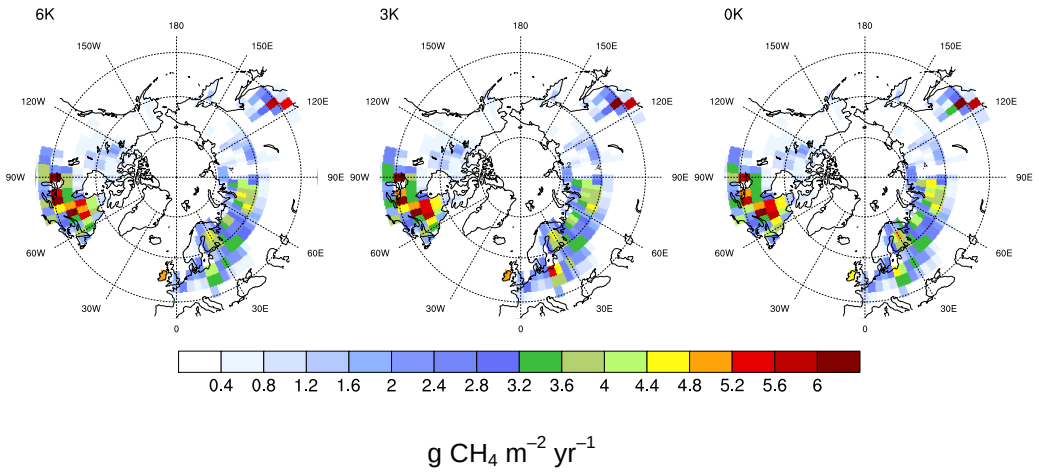

Figure 7: Methane emissions (g CH_4 m^{-2} yr^{-1}) from the time slice simulations for 6000 yr BP (left), 3000 yr BP (middle) and pre-industrial (right), averaged over 10 yr of model simulation. Carbon fluxes are represented with respect to grid box area.

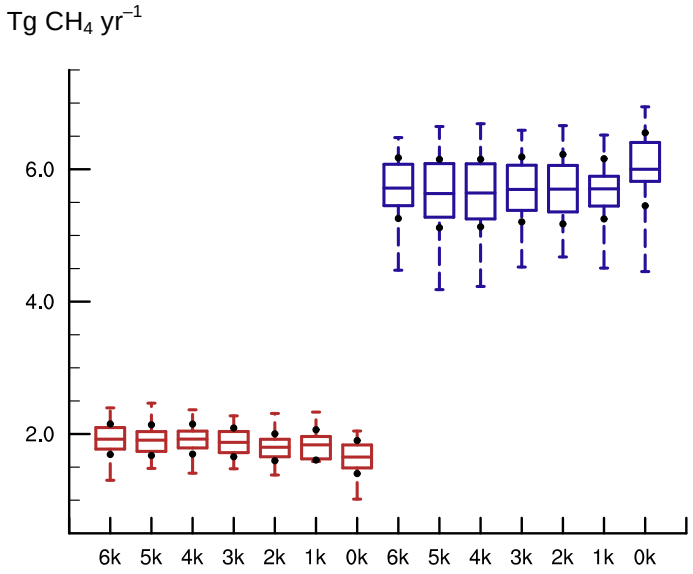

Figure 8: Box-and-whisker plots for CH4 emissions (Tg CH_4 yr^{-1}) averaged over the regions of Hudson Bay (left, red) and West Siberian Planes (left, blue) as defined by Picket-Heaps (2011) and Winderlich (2011) for 6000 yr BP to pre-industrial. The tailored box plots show the mean, minimum value, maximum value, and the 25th and 75th percentiles of a 30-yr time series.

Our model results show CH_4 emissions for the West Siberian Lowlands of 6 Tg CH_4 yr^{-1} (Fig. 8, blue). Based on the atmospheric concentration data from four tower stations in this region (ZOTTO (Sasakawa et al., 2012; Winderlich et al., 2010)), an atmospheric transport inversion results in emissions of 6.89 Tg CH_4 yr^{-1} 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 g CH_4 m^{-2} yr^{-1}) 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 CH_4 yr^{-1} for pre-industrial 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 CH_4 yr^{-1} in the year 2008.

2.3.2.2 Holocene time slices

Apart from the pre-industrial 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 figure 7) change in pre-industrial times 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.

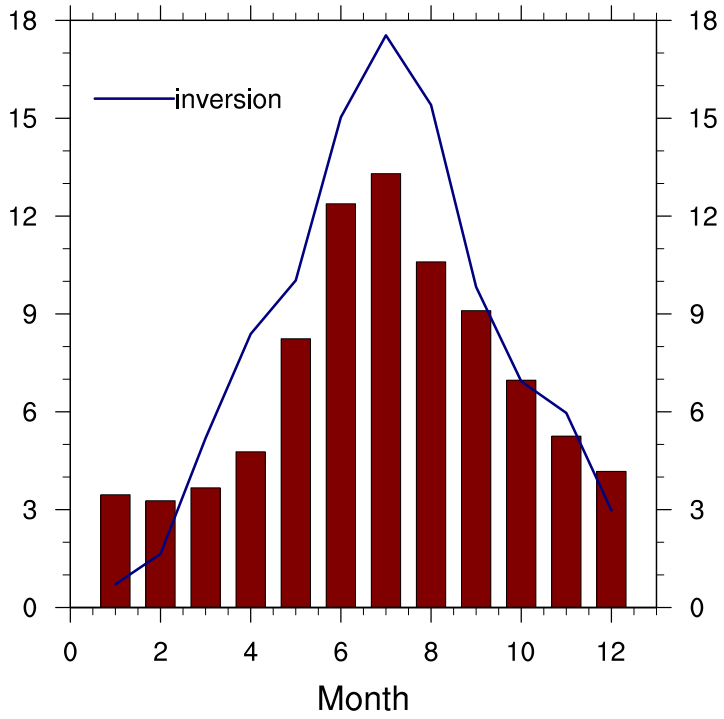

Figure 9: Sum of monthly CH_4 emissions (g CH_4 m^{-2} yr^{-1}) in the West Siberian Lowlands: Bar chart represents 30 year mean at present day, solid line shows results from an data-driven inversion study for the year 2009 (Winderlich, 2011).

Adding up the emissions for circumpolar boreal regions (above 40° N) results in 49.3 (+/– 2.3) Tg CH_4 yr^{-1} at 6000 yr BP, which increases to 51.5 (+/– 2.75) Tg CH_4 yr^{-1} in pre-industrial times. In general, the boreal emissions show an increase over the last 6000 yr, with some variability (Fig. 10,

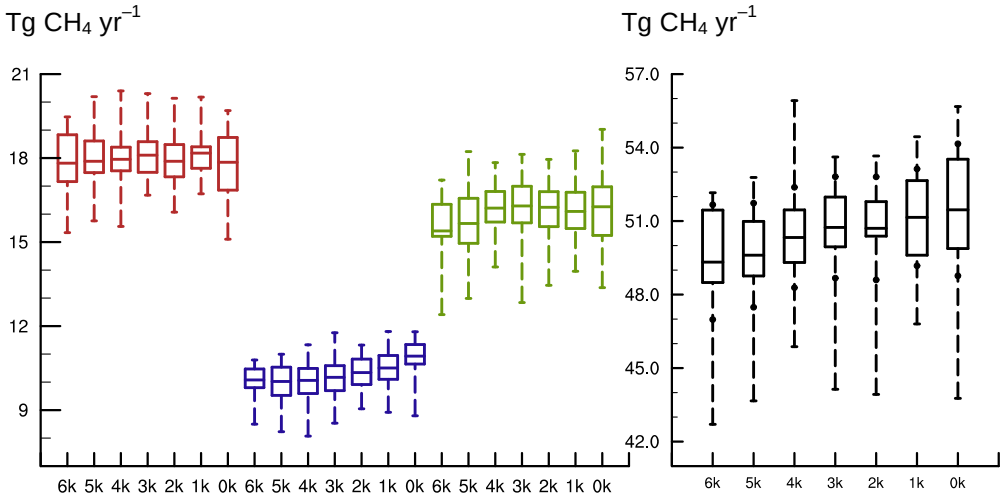

Figure 10: Left panel: Box-and-whisker plots for CH_4 emissions (Tg CH_4 yr^{-1}) averaged over the domains of North America (left, red), Asia (left, blue), and Europe (left, green), for the years 6000 BP until pre-industrial. The tailored box plots show the mean, minimum value, maximum value, and the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

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 pre-industrial times. (ii) In the Asian domain we find an increase of CH_4 emissions from 6000 yr BP (10 Tg CH_4 yr^{-1}) to pre-industrial times

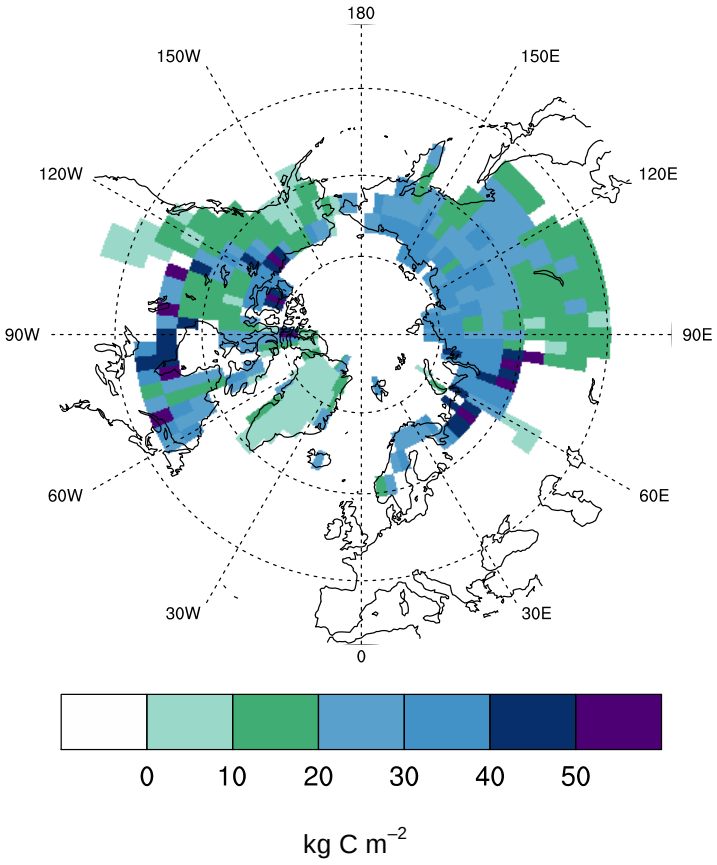

Figure 11: Distribution of soil organic carbon contents (0–100 cm depth) based on the NCSCD published by Tarnocai et al. 2009, displayed in the model resolution.

(11 Tg CH_4 yr^{-1}). (iii) In Europe we see an increase between 6000 and 4000 yr BP, followed by a stable phase until pre-industrial times.

2.4 Discussion

2.4.1 Peat accumulation

Comparing the areas where data of soil organic carbon content suggest present-day boreal wetlands (e.g. Tarnocai et al., 2009) the wetland area determined by the model, we see that the modelled wetland distribution contains most areas

where Tarnocai et al. (2009) 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 boreal wetlands 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.

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. (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 wetlands.

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 Pg C within 6000 yr of simulation. Considering the initialisation and expansion of boreal wetlands in the early Holocene between 11000 and 8000 yr BP (Jones and Yu, 2010; Korhola et al., 2010; MacDonald et al., 2006; Yu et al., 2010) and an estimated size of the accumulated carbon from the last glacial until pre-industrial times of 180 to 621 Pg C (Gorham, 1991; Smith et al., 2004; Turunen et al., 2002; 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 (McGuire et al., 2010; Tarnocai et al., 2009).

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 Pg C 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 (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, boreal wetlands 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

(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 boreal wetlands 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 boreal wetlands is a non-equilibrium system. Presumably, it will take much longer than 60000 yr for these boreal wetlands 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.

2.4.2 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 CH_4 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 CH_4 yr^{-1} (McGuire et al., 2010; Mikaloff Fletcher et al., 2004) for pre-industrial times.

Our results show CH_4 emissions in the range of 49.3 to 51.5 Tg CH_4 yr^{-1} for boreal wetlands north of 40° over the course of our Holocene experiment from 6000 yr BP to pre-industrial. 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 Tg CH_4 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 pre-industrial 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 CH_4 $yr^{-1}$and the maximum values of the European domain rise from 17 to 19 Tg CH_4 yr^{-1}.

For two selected regions, the Hudson Bay Lowlands and the West Siberian Lowlands – two major areas of wetlands today – the modelled pre-industrial 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 ~ 50 Tg CH_4 yr^{-1} for the boreal zone, we would expect emissions of about 5 Tg CH_4 yr^{-1} for the HBL accordingly. If we choose the HBL exactly as defined by Pickett Heaps et al. (2011) we get emissions of 1.6 Tg CH_4 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.

2.4.3 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 CH_4 yr^{-1} estimated by (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 (Parmentier et al., 2011b; van Winden et al., 2010) 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).

2.5 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 pre-industrial wetland fraction and water table levels from CLIMBER-LPJ simulations by Kleinen et al. (2012). The peatBALANCE simulation yields an accumulation of 240 Pg C 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 pre-industrial CH_4 emissions are 51.5 Tg CH_4 yr^{-1} for boreal wetlands above 40° North, which is in the range of estimates of 15–112 Tg CH_4 yr^{-1} for boreal wetlands. The model run suggests that CH_4 emissions were slightly lower at 6000 year BP than at pre-industrial. Emissions rise until pre-industrial times with some variability. These dynamics in boreal CH_4 emissions resemble the minimum in the atmospheric CH_4 concentration around 5000–4000 year 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.

Chapter 3

3 Modelling present day and future natural methane emissions of boreal wetlands: Trends and interannual variability

3.1 Introduction

Natural methane (CH_4) emissions from boreal wetlands contribute significantly to the present day global CH_4 budget. CH_4 is an important greenhouse gas (GHG) that has a comparably short lifetime of 12 yr but a Global Warming Potential (GWP) of 25, given a time horizon of 100 yr (Denman et al., 2007). Globally, wetlands in general are the single largest CH_4 source and emit 100–231 Tg CH_4 yr^{-1} (Denman et al., 2007). Boreal wetlands north of 45° N account for 27–46 Tg CH_4 yr^{-1} (Bartlett and Harriss, 1993; Bousquet et al., 2006; Gorham, 1991; Hein et al., 1997; Wang et al., 2004) and have the highest carbon density among all terrestrial ecosystems (Reddy and DeLaune, 2008).

The amount of CH_4 emitted to the atmosphere depends on the CH_4 production, oxidation and transport in the soil. Water table depth is one of the key factors governing CH_4 emission from boreal wetlands and also temperature can exert considerable influence on CH_4 dynamics in northern wetlands (Lai, 2009). Lowering of the water level of the highly organic wetland soils will increase decomposition rates and elevate fluxes of carbon dioxide (CO_2) to the atmosphere (Denman et al., 2007; Reddy and DeLaune, 2008). A decrease in water availability to wetlands can also lead to a decrease in methane formation in wetlands since methane formation in the soil is dependent on anaerobic conditions. Increased temperatures in the peat profile on the other hand will lead to increased methane production in soils that remain flooded (Clair et al., 1998). Consequently, climate affects the net CH_4 exchange since it changes ecosystem hydrology, soil and vegetation characteristics (Spahni et al., 2011). Elevated temperatures will

increase ecosystem productivity (Dorrepaal et al., 2009) and intensify peat decomposition, which in general will accelerate carbon emissions to the atmosphere. In summary it can be said, that climate change will significantly impact northern wetlands (Limpens et al., 2008).

The major sinks of CH_4 are oxidation by OH in the troposphere, biological CH_4 oxidation in drier soils and loss to the stratosphere (Denman et al., 2007). The resulting CH_4 concentrations in the atmosphere have been measured frequently at a wide variety of sites in both hemispheres over the last 25 yr (network of 40 surface air flask sampling sites operated by NOAA/GMD (Bousquet et al., 2006) or five sites in the NH and SH by the AGAGE network (Rigby et al., 2008). In 2005, the global average abundance of CH_4 was 1,774.62 ± 1.22 ppb.

In pre-industrial times (e.g. from 1700 to 1800) the global CH_4 concentration in the atmosphere was 715 ± 4 ppb, based on ice core measurements of CH_4 (Etheridge et al., 1988). The increase to present day values was followed by a period of little change from 1999 (Dlugokencky et al., 2001). In 2007 and 2008 the concentration of methane in the atmosphere increased again. Rigby et al. (2008) attribute this increase to increased emissions from Northern Hemispheric sources and Bousquet et al. (2006) suggested that atmospheric methane levels could increase in the near future, after a period of stabilization, if wetland emissions return to their mean 1990s levels. Past observations indicate large interannual variations in CH_4 growth rates (Dlugokencky et al., 2001). The mechanisms causing these variations are poorly understood and the role of climate is not well known (Denman et al., 2007).

While temperature and carbon content of the soil have been identified as the main controls of the CH_4 emissions, the relationship between CH_4 emissions and these variables is not yet well understood (Melton et al., 2012). The uncertainty in total natural CH_4 emissions is also due to a lack of knowledge of the geographical distribution and interannual variability of CH_4 emissions from wet ecosystems,

which are the largest natural CH_4 source (Denman et al., 2007). An inverse modelling study (Bousquet et al., 2006) found that fluctuations in wetland emissions are the dominant contribution to interannual variability in surface emissions (± 12 Tg CH_4 yr^{-1}), explaining 70% of the global emission anomalies over the past two decades (1984–2003).

3.1.1 Scientific questions and outline of this chapter

In chapter 2 of this thesis it was shown that the modelling approach using the peatBALANCE model in combination with a CH_4 emission model is able to represent the processes of peat accumulation and methane emission in boreal wetlands over the Holocene and performs well for pre-industrial times. This newly developed process based carbon accumulation and decay model in combination with the mentioned CH_4 emission model (see chapter 2 for a detailed description of the peatBALANCE and the CH_4 emission model) now allows to asses the trends and interannual variability of CH_4 emission of natural boreal wetlands at the present day (1979 to 2008) and in future times until the year 2100.

Three subordinated research questions were posed in this third chapter in order to answer the research questions (3) and (4) posed in the first chapter of this thesis:

(1) What is the spatial and temporal variability of methane emissions?

(2) What is the susceptibility of the CH_4 emissions from boreal wetlands to climate change?

The chapter 3 contains the following sections:

The section 3.2 describes the experimental setup. Results are presented in section 3.3, subdivided into sections regarding trends and variability at the present day (3.3.1), spatial patterns (3.3.2), seasonal variability (3.3.3) and future CH_4 emissions (3.3.4). The discussion of the CH_4 fluxes is presented in section 3.4 and the conclusions can be found in section 3.5.

3.2 Methods

The natural CH_4 emissions of boreal wetlands were evaluated by using a process-based model for CH_4 production and emission. The simulations were performed at a spatial resolution of T63 ca. 1.5° × 1.5° latitude and longitude. The peatBALANCE model developed within this research was implemented into the land surface component (JSBACH) of the MPI-ESM (Raddatz et al., 2007; Roeckner et al., 2003). The CH_4 emission model (Walter et al., 2001b) was combined with the peatBALANCE model. It simulates the three most dominant pathways of CH_4 to the surface, diffusion, ebullition and plant mediated transport. A detailed description of both models is given in the second chapter of this thesis, section 2.1 or by Schuldt et al. (2012).

3.2.1 Experimental setup, analyzed regions and investigation period

The peatBALANCE model was forced with results from the CMIP5 simulations performed with the MPI-ESM (Giorgetta et al., n.d.; Taylor et al., 2012). Three sets of experiments were performed to investigate natural boreal CH_4 emissions (see Table 1 for an overview of conducted simulations): 1. A spin-up run to fill up the soil carbon pools (S1). 2. An ensemble of three present day climate AMIP simulations (A1, A2, A3). 3. A future simulation on the basis of the RCP8.5 high emissions scenario (F1). A detailed description of the setup for the three experiments is given below.

In all three types of experiments the peatBALANCE model is driven by four variables such as the soil temperature of the uppermost soil layer (topSoilTemp), the net primary production (NPP), the leaf area index (LAI) and the soil moisture (alpha). These driving data were extracted from relevant MPI-ESM model runs conducted for the CMIP5 project, which in turn were set up to investigate the

historical as well as present day AMIP period (AMIP, the Atmospheric Model Intercomparison Project is now an integral part of CMIP (Gates et al., 1999), see below) and future times with high emission RCP8.5 scenarios (Vuuren et al., 2011). The Coupled Model Intercomparison Project Phase 5 (CMIP5) promotes a set of coordinated climate model experiments for the evaluation in the Fifth Assessment Report (AR5) of the IPCC.

Table 4: **Experimental setup.** Experiment: Abbreviation used for the conducted experiments. Description: more information on the CMIP5 experiments can be found in Taylor et al. (2012). Forcing: from which CMIP5 experiments the driving data were taken. Cpool: experiment from which the carbon pools of the peatBALANCE model were initialized. Years: length of run or date of simulated years.

Exp.	Description	Forcing	Cpool	Years
S1	Spin-up simulation, CMIP5 historical	CMIP5 historical	-	6000 yrs
A1	AMIP simulation, 1st realization	CMIP5 AMIP (R1)	S1	1979–2008
A2	AMIP simulation, 2nd realization	CMIP5 AMIP (R2)	S1	1979–2008
A3	AMIP simulation, 3rd realization	CMIP5 AMIP (R3)	S1	1979–2008
F1	Future simulation, CMIP5 RCP8.5	CMIP5 RCP8.5	A1	2009–2100

For the spin-up procedure of the peatBALANCE model a driver from a ‚historical' MPI-ESM run is used that was driven by CO_2 emissions rather than concentrations. A corresponding forcing was used from a freely evolving MPI-ESM simulation of the historical period, carried out with atmosphere-ocean setup and a carbon cycle model. The peatBALANCE model run for 6000 yr in order to

get 292.3 Pg C of catotelm peat, which represents today's peat carbon stock in the boreal zone (Schuldt et al., 2012).

For the present day period (1979 to 2008) the forcing used by the peatBALANCE model is based on MPI-ESM simulations with corresponding forcing from “time-slice” experiments with atmosphere-only setup forced by prescribed SSTs and sea ice. The AMIP protocol described by Gates et al. (1999) for the years 1979 to 2008 again provide the bases for this setup.

The future CH_4 emission simulations are based on results of CMIP5 MPI-ESM-LR model forced with a high emissions scenario (RCP8.5) for the years 2009 to 2100 (Taylor et al., 2012). The methane transport model according to Walter et al. (2001b) was used in all experiments but the spin up simulations (S1) (see second chapter of the thesis, section 2.1 for a description of the spin-up simulations).

The peatBALANCE model uses prescribed but fixed grid cell wetland fractions as well as the position of the water table within the peatland fraction hat has a temporal resolution of one month, as determined by the CLIMBER2-LPJ model in a simulation with historical, AMIP and RCP8.5 forcing respectively (see Fig. 12 for wetland fraction in model resolution). These experiments are based on the CLIMBER-LPJ experimental setup as published by Kleinen et al. (2012).

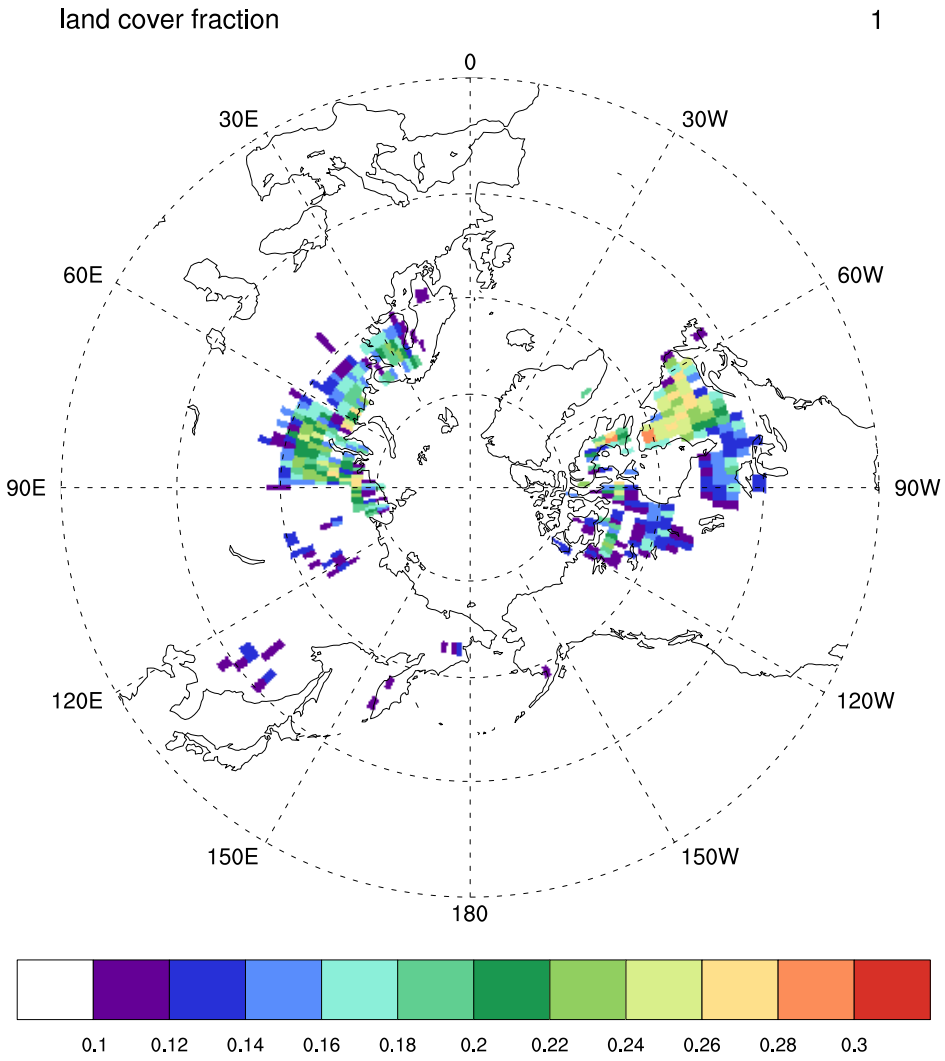

Figure 12: Wetland fraction in T63 resolution of MPI-ESM-LR used for experiments S1, A1–3 and F1.

3.3 Results

Boreal wetland emissions were calculated in the peatBALANCE / CH_4 emissions model driven with results from three different MPI-ESM-LR CMIP5 simulations: ‚historical', ‚AMIP', and RCP8.5. Wetland fraction and water table (wt) were taken from a CLIMBER/LPJ model run that was based on the model configuration described by Kleinen et al. (2012). As this study focuses on the peat accumulation and CH_4 emissions out of natural boreal wetlands, the analysis is focused on areas above 40° North. Three domains are analyzed in more detail: Europe (eu), Asia (as), and North America (na).

3.3.1 Trend and variability of CH_4 emission at the present day

Annually averaged CH_4 emissions from the boreal zone north of 40° N display a very weak increasing trend from 1979 to 2008 (Fig. 13a). This is true for the three model realizations (A1, A2, and A3). However, in the case of the forcing variables considered in the model setup, an increasing trend – if present – appears more pronounced in the driving variables soil temperature, NPP and LAI (Fig. 13b to 13e). What is apparent is the interannual variability of both the CH_4 emissions and the forcing variables. The interannual variability of CH_4 emissions is about 5 to 8 Tg(CH_4)/yr. Especially the influence of the Mt. Pinatubo eruption in 1991, but also the occurrence of El Niño events in the years 1982/83, 1986/87, 1991/92, 1993, 1994, and 1997/98 may be noted in the forcing variables propagating to the wetland CH_4 emissions. As El Niño events affects weather in large parts of the world, the effects depend strongly on the location and season. The effects regarding precipitation in boreal areas are less rainfall in NA during DJF and in AS during MAM. Temperature decreases almost circumpolar, except for increases in NA during DJF and MAM. These effects alter plant growth, water table and soil decomposition.

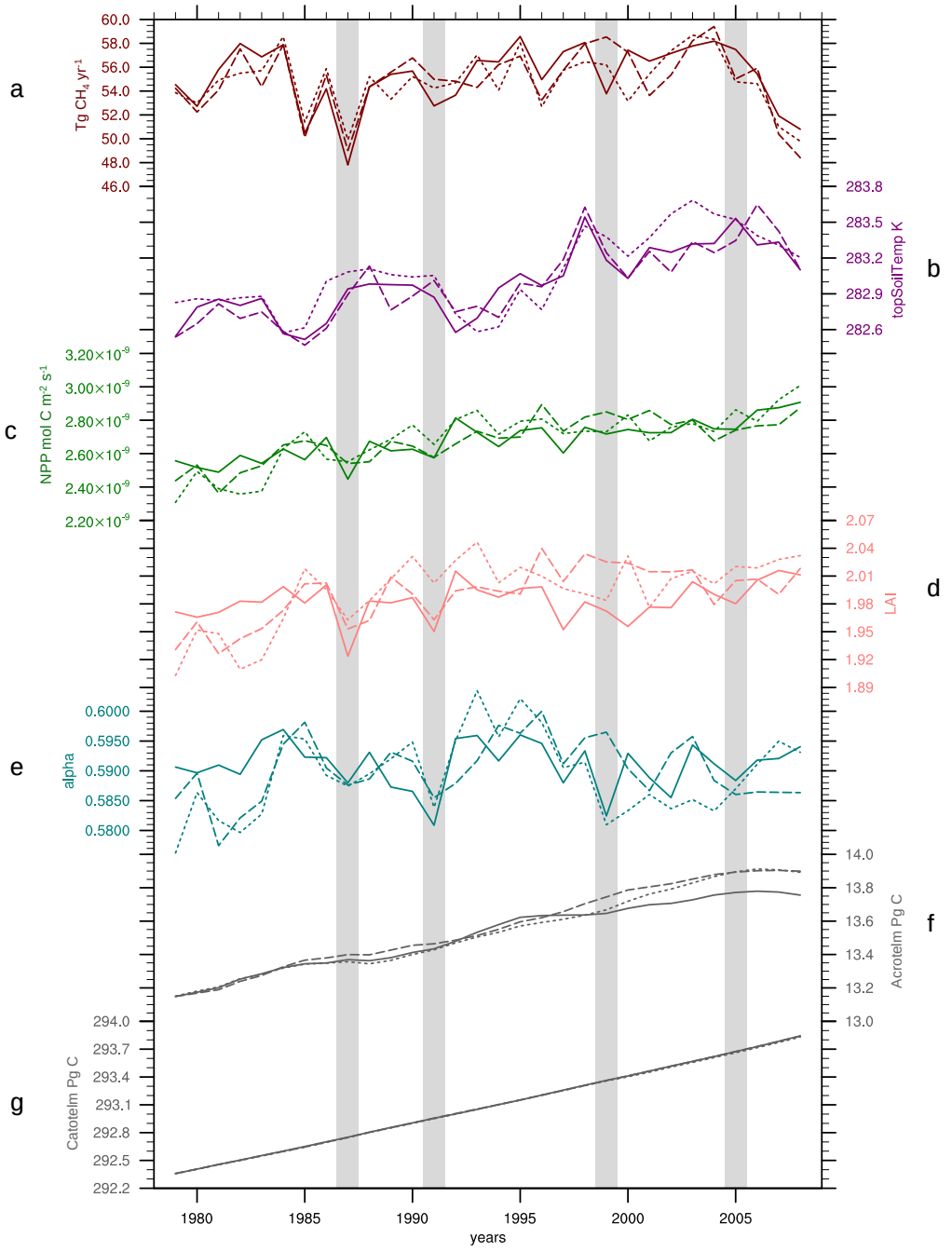

Figure 13: Natural boreal wetland CH_4 emissions of areas above 35° N and associated driving variables from the experiments A1, A2, and A3. The peatBALANCE model was driven by output from MPI-ESM with AMIP forcing. Displayed are yearly values, grey-filled bars are added for emphasis. The three model realizations are displayed as solid (A1), coarse dashed (A2) and fine dashed (A3) lines. Panels b) to e) display the forcing variables used for the model simulations: soil temperature in degree K (purple), NPP in g C m^{-2} yr^{-1} (green), Leaf Area Index (orange) and the soil moisture alpha (cyan). Panels e) and f) show the accumulated peat in the acrotelm and catotelm carbon pools

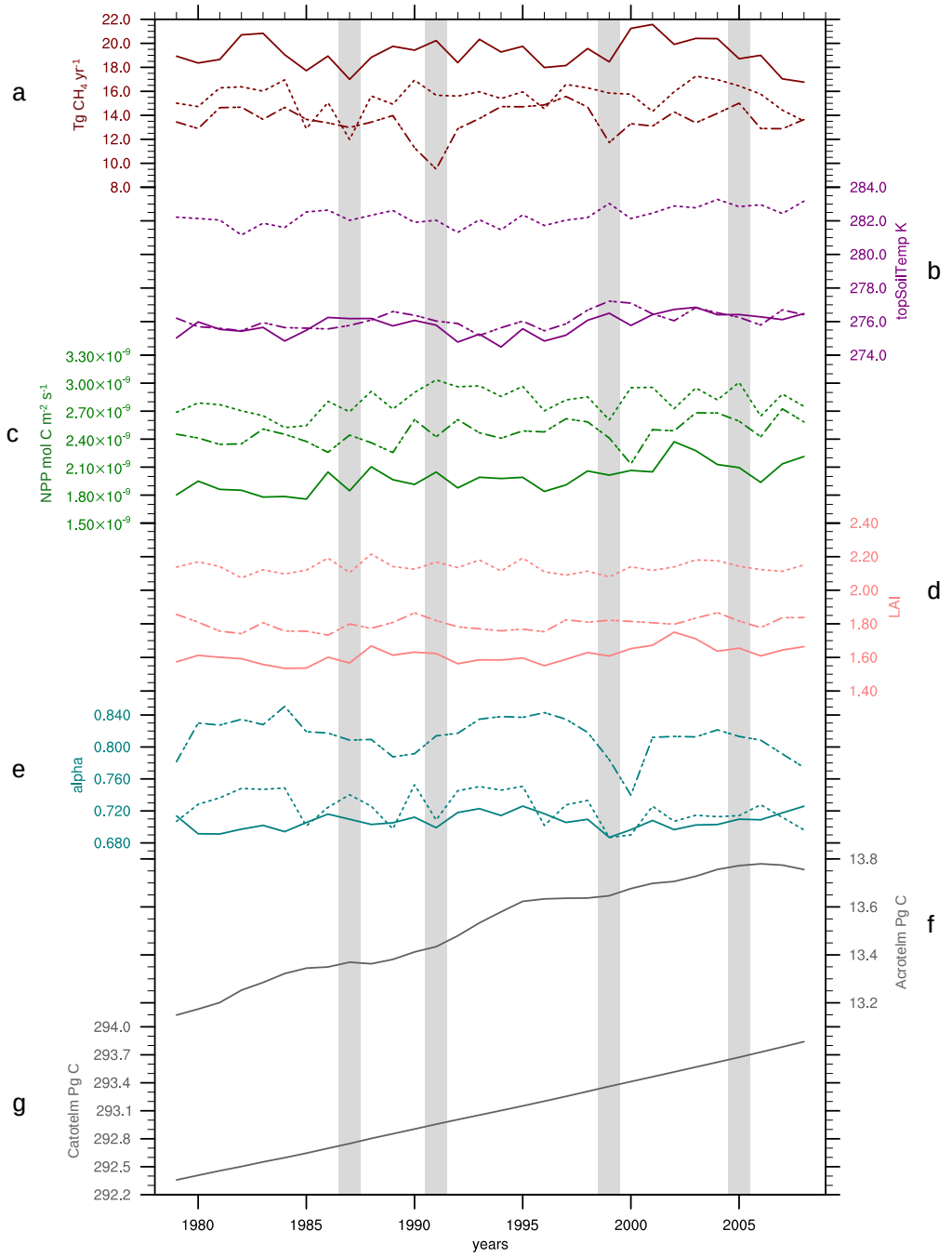

Figure 14: Natural boreal wetland CH_4 emissions of three evaluated areas, North America (solid), Asia (variable dashed) and Europe (dashed), and associated driving variables. The peatBALANCE model was driven by output from MPI-ESM with AMIP forcing. Displayed are yearly values from the A1 experiment, grey-filled bars are added for emphasis. Panel a) shows the boreal wetland CH_4 emissions of the three different areas above 35°N. Panels b) to e) display the forcing variables used for the model simulations, separated according to the areas analyzed: soil temperature in degree K (purple), NPP in g C m^{-2} yr^{-1} (green), Leaf Area Index (orange) and the soil moisture alpha (cyan). Panels f) and g) show the accumulated peat in the acrotelm and catotelm carbon pools respectively.

In 1991, the year of the Mt. Pinatubo eruption, the model shows the lowest CH_4 emissions of the whole A1 experiment in the Asian area (9.5 Tg CH_4 yr^{-1}, Fig. 14a). The global yearly mean emission is comparably low in 1991 with 53–54 Tg CH_4 yr^{-1} depending on the ensemble member (Fig. 13a). The decrease in CH_4 emissions in 2007/2008 is matched by a decrease in soil temperatures in combination with constant LAI and soil moisture.

3.3.2 Spatial patterns of CH_4 emissions

In addition to the global CH_4 emissions shown in Fig. 13a, it is interesting to see how the interannual variability differs among the different peatland areas. The analysis (Fig. 14) is based on the first model realization A1.

The contributions of the three large areas, Europe (EU, 10° W–60° E, 40° N–80° N), Asia (AS, 60° E–120° E, 40° N–80° N), and North America (NA, 55° W–165° W, 40° N–80° N), to the global CH_4 emissions are shown in Fig. 14a. Quantitatively, NA (solid line) contributes most to the total CH_4 emissions with ~19 Tg CH_4 yr^{-1}. EU (dashed line) contributes ~15 Tg CH_4 yr^{-1} and AS (variable dashed) least with ~13 Tg CH_4 yr^{-1}. The fact that NA has the largest CH_4 emissions but comparatively small values in all four driving variables is remarkable. The interannual variability is about 2 to 3 Tg CH_4 yr^{-1} and shows largest deviation in 1991 for the AS region with 4.5 Tg CH_4 yr^{-1}.

The spatial distribution of the mean modelled CH_4 emission over the whole AMIP period simulation from 1979 to 2008 between 40 °N – 90 °N is presented in Fig. 15 (multi year, seasonal means). As expected from the distribution of boreal wetlands (Fig. 12), large CH_4 emissions can be found in North America around the Hudson Bay, in Russia at the West Siberian Lowlands with values as high as 15 g CH_4 m^{-2} yr^{-1} (Fig. 15). In Europe, Finland shows the most dominant CH_4 emissions.

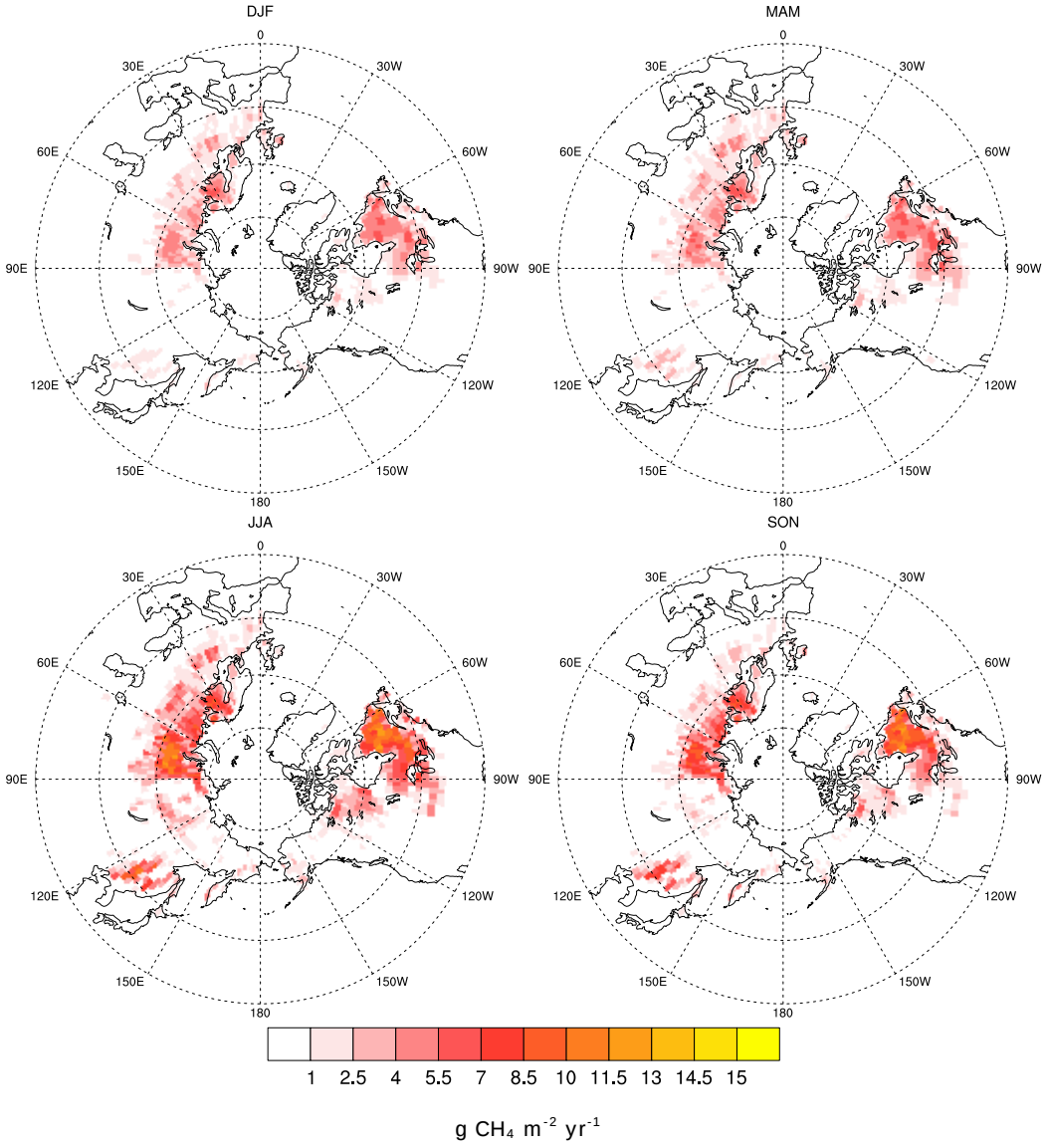

Figure 15: Long term monthly mean CH_4 emissions from boreal wetlands between 35° N – 90° N. Images are produced from the monthly output of the A1 model run ranging from 1979 to 2008. Displayed are seasonal means

3.3.3 Seasonal variability

Seasonal changes in the terrestrial CH_4 emissions are most evident at northern latitudes between 50° N to 70° N (Fig. 16), where a vast area of northern wetland

actively emits CH_4 during the summer growing period (Fig. 15). The zonally averaged seasonal cycle of CH_4 emissions indicates a late onset of emissions in May that lasts until September in the high latitudes. The figure displayed is the long-term monthly mean from the AMIP experiments (1979 to 2008).

The seasonal distribution of mean CH_4 emissions indicates highest emissions in summer and autumn with values up to 15 g CH_4 yr^{-1} (Fig. 15). Lower emissions are present in winter and spring with values as high as 6 g CH_4 yr^{-1}. The monthly standard deviation, or variability (see Fig. 17), is largest in autumn (up to 5 g CH_4 yr^{-1}). Similar values are present in the summer. Almost no deviation from the mean exists in boreal winter (<1.5 g CH_4 yr^{-1}) and spring.

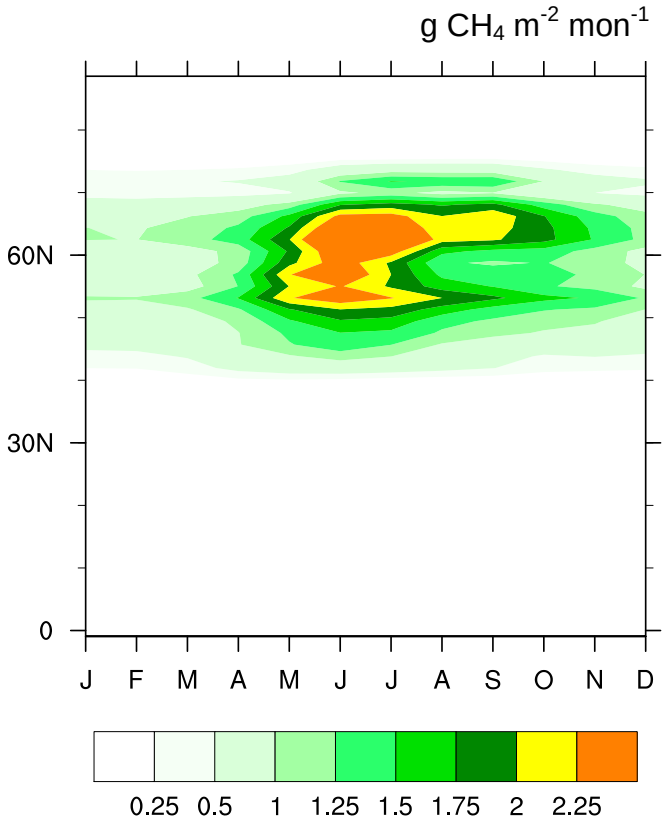

Figure 16: Zonally averaged seasonal cycle of CH_4 emissions. Displayed is the long-term monthly mean from the A1 experiment (1978 to 2008).

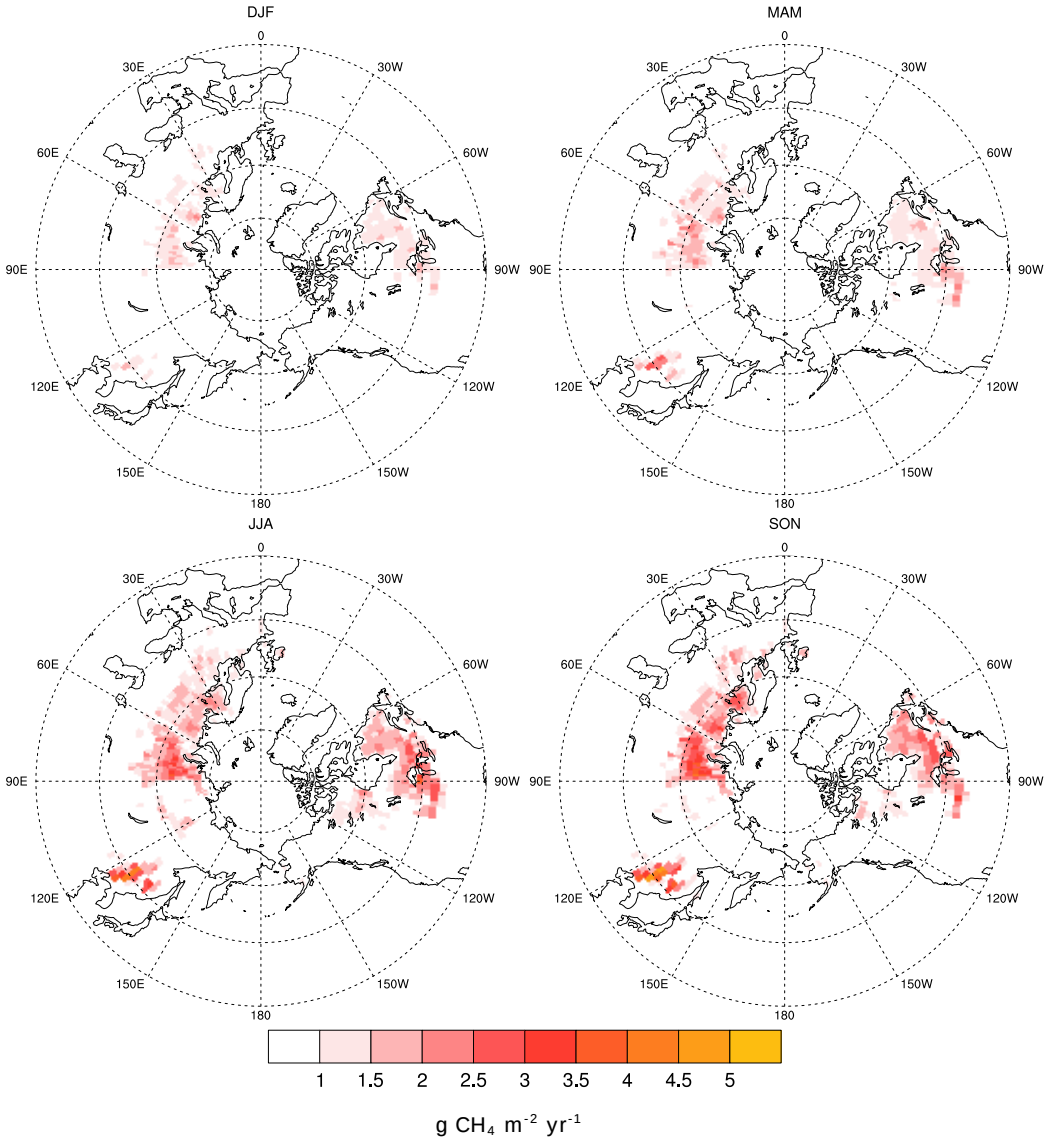

Figure 17: Monthly interannual variability of CH_4 emissions from boreal wetlands between 35° N – 90° N. Displayed are the standard deviations of monthly means from the A1 experiment. This example derives the climatology based on the entire time period. Displayed are seasonal means.

The spatial distribution of the variability, depicted here as the monthly standard deviation, follows the distribution of wetlands again (Fig. 17) and spreads particularly in the Great Lakes area as well as from Finland to the West Siberian

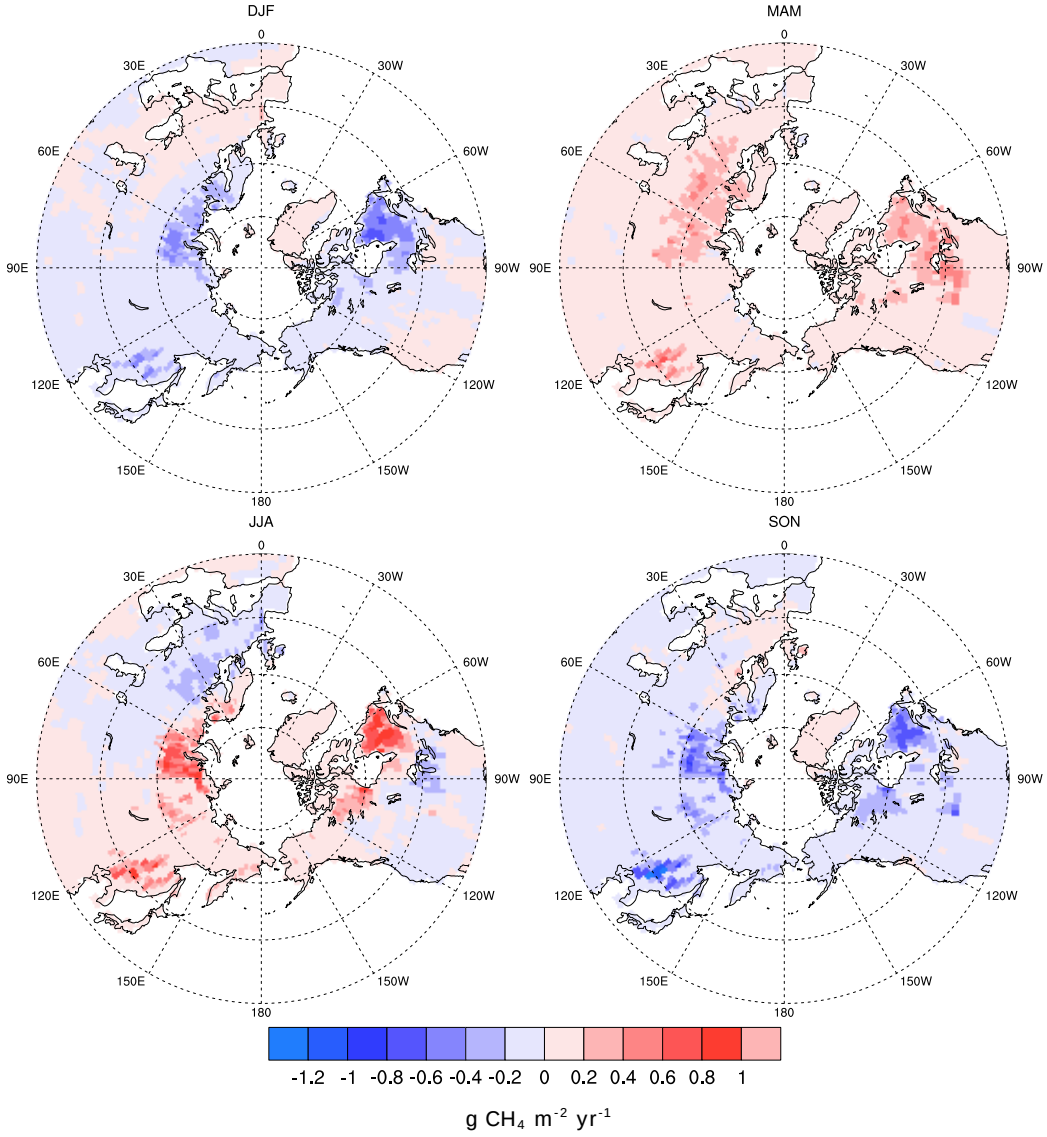

Figure 18: Monthly anomalies of CH_4 emissions from boreal wetlands between 35° N – 90° N Anomalies are calculated by subtracting the long term mean from each point. Displayed are seasonal means of the A1 experiment.

Lowlands. Another small-scale but well pronounced spot of interannual variability can be found in the Far East (see Fig. 17).

The monthly anomalies are presented in Fig. 18. The climatological anomalies were calculated by subtracting the long term mean from monthly data. Whereas

the anomalies in the spring and summer are both positive, the anomalies of the winter and spring season are either negative. Summer and autumn anomalies show stronger anomalies than winter and spring. The spatial distribution follows the distribution of wetlands again (Fig. 12).

3.3.4 Future CH_4 emissions until 2100

The future simulation F1 is based on a CMIP5 MPI-ESM simulation driven by the RCP8.5 scenario from 2009 to 2100. Modelling results show that boreal natural CH_4 emissions increase drastically from 57 up to 71 Tg CH_4 yr^{-1} (see Fig. 19a). The four driving variables (Fig. 19b to 19e) show different progressions: whereas soil temperature and NPP are constantly increasing, LAI and alpha stabilize and decrease respectively. The soil temperatures increase from 283 to 288 K (10 year running mean).

The interannual variability is about 5 to 8 Tg CH_4 yr^{-1}. Very pronounced year-on-year changes of up to 14 Tg CH_4 yr^{-1} occur especially in the last decade of the simulation.

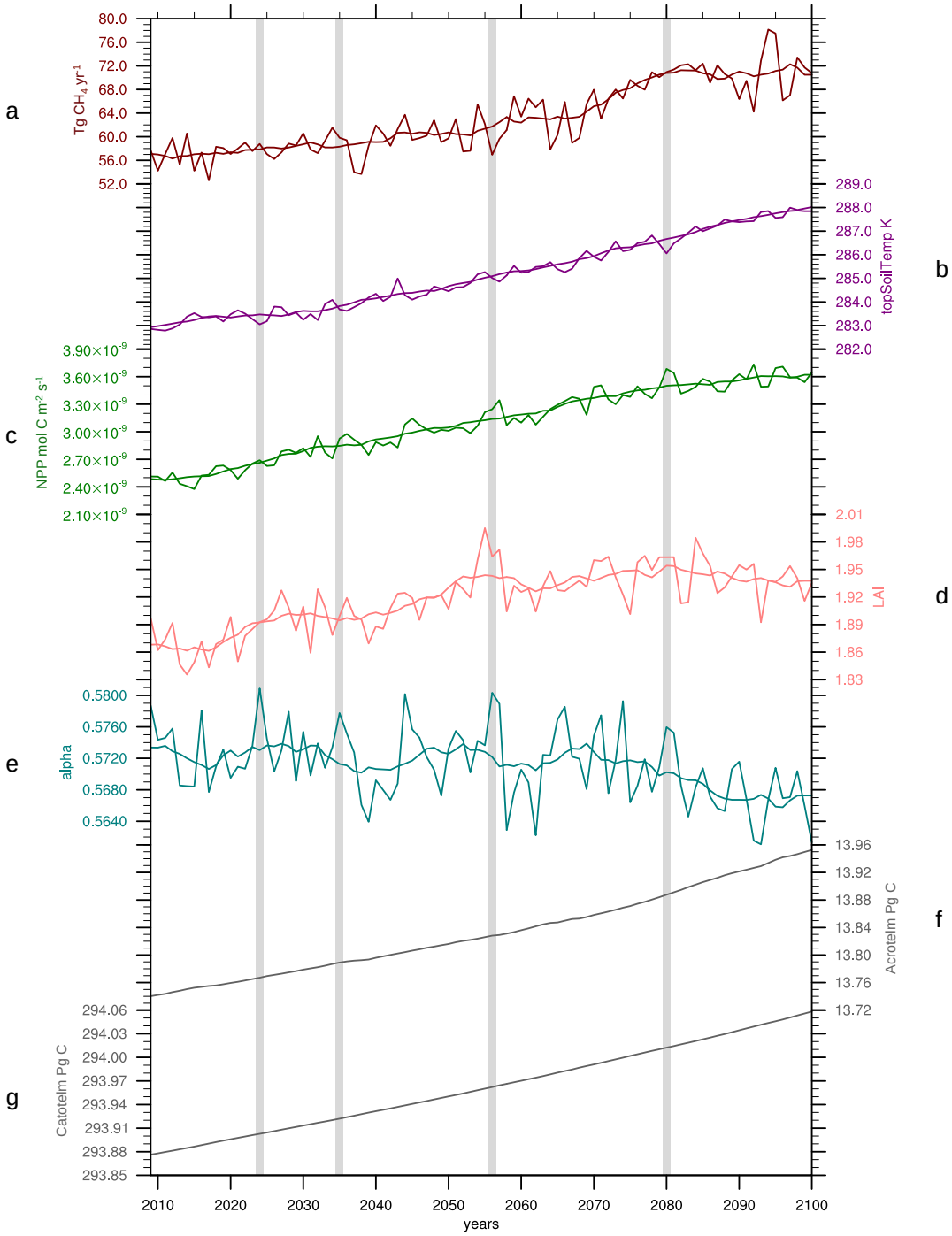

Figure 19: Natural boreal wetland CH_4 emissions of areas above 35° N and associated driving variables. The peatBALANCE model was driven by output from MPI-ESM with RCP8.5 forcing from 2010 to 2100. Displayed are yearly values and a 10-year running mean for the experiment F1. Panel a) shows CH_4 emissions. Panels b) to e) display the forcing variables used for the model simulations: soil temperature in degree K (purple), NPP in g C m^{-2} yr^{-1} (green), Leaf Area Index (orange) and the soil moisture alpha (cyan). Panels f) and g) show the accumulated peat in the acrotelm and catotelm carbon pool respectively.

3.4 Discussion

3.4.1 Present day CH_4 emissions

Modelling results from the present day experiments A1 to A3 (AMIP period from 1979 to 2008) show year-on-year changes of up to 8 Tg CH_4 yr^{-1}. The total boreal CH_4 emissions range from 47.5 to 59.5 Tg CH_4 yr^{-1} in 1991 and 2004 respectively. The amount of CH_4 emitted, however, shows only a small increasing trend. Using an inversion model Bousquet et al. (2006) found even larger fluctuations in wetland emissions (12 Tg CH_4 yr^{-1}).

The interannual variation of CH_4 emissions is assumed to be a characteristic of boreal wetlands through climatic controls. The most important environmental parameters controlling the production and release of wetlands CH_4 to the atmosphere are the availability of organic carbon to bacteria, plant cover, water table depth and soil temperature (Walter et al., 1996). These factors, except for the plant cover, are represented in the model either by calculation of the model itself or affecting the model as a driving variable.

In a recently published modelling study by Ito et al. (2012) global natural wetlands accounted for the largest terrestrial CH_4 source, producing 170 to 192 Tg CH_4 yr^{-1} (from 1996 to 2005). The present day methane flux from the soil of northern ecosystems (north of 40° N), however, is 31–72 Tg CH_4 yr^{-1} (Volodin, 2008). For an overview of results from other modelling studies see Table 2.

Regarding the range of wetland data and emission calculation schemes that were considered, these values were within the range of values estimated in previous studies (see Table 2). This finding is also consistent with those of a sensitivity analysis by Petrescu et al. (2010). However, the actual range of estimation uncertainty may be even larger, because the present study did not fully explore uncertainties in sensitive parameter values and predicted changes in wetland

extent in response to global climate change, which can span a wide range (Riley et al., 2011).

Results from a chemical transport model based on re-analysis meteorological data (ECMWF) suggest an even stronger decrease of global CH_4 emissions of about 13 Tg CH_4 yr^{-1} in the years following the eruption (Dentener et al., 2003). Zhuang et al. (2004) for example estimate that the 50 Tg CH_4 emissions in 1991 decrease to 40 and 45 Tg CH_4 yr^{-1} in 1992 and 1993, respectively.

The period of the Mt. Pinatubo eruption coincides with a positive Niño-3 index that indicates an El Niño Event. As the forcing used for the present day experiments (A1 to A3) is based on MPI-ESM simulations driven by observed sea surface temperatures it is possible to link the effects of El Niño conditions to the carbon cycle in the model, even though this approach may be limited by atmospheric variability, which is not tightly coupled to SSTs (Taylor et al., 2012).

Zhuang et al. (2004) and Dlugokencky et al. (2001) assign large positive anomalies in the global growth rate of atmospheric CH_4 concentrations at least in parts to increased boreal wetlands CH_4 emissions resulting from warm conditions based on strong El Niño phenomena in 1998. Modelling results from Zhuang et al. (2004) indicate wetlands across the Pan-Arctic CH_4 emissions of 55 Tg CH_4 yr^{-1} in 1998, an amount that is 8–11 Tg higher than emissions in 1999 and 1997. The result (A1) shows 58 Tg CH_4 yr^{-1} in 1998 followed by only 53.5 Tg CH_4 yr^{-1} in 1999. A recent regional modelling study for Alaska suggests more emitted CH_4 in El Niño than in La Niña events (Lu and Zhuang, 2012). This may be explained by CH_4 emissions that are positively correlated with temperature (Lai, 2009; Segers, 1998; Strack and Waddington, 2008). Only in the year 1987 a different effect can be observed as soil temperature increases but CH_4 emission show a strong minima.

Table 5: Wetland CH_4 emission results from different modelling studies

Authors	Emissions (Tg CH_4 yr^{-1})	Time	Area
Walter et al., 2001	260	1982–1993	global
" "	66	" "	>30° N
Gedney et al., 2004	297*	1990–1999	global
Eliseev et al., 2008	133–139	1961–1990	global
" "	34–39	" "	>30° N
" "	191–199**	2100	global
" "	70**	" "	>30° N
Wania et al., 2009	29.7–46.5	1991–2000	>45° N
Ito et al., 2012	125–160	1901–2001	global
WETCHIMP***	190±39	1993–2004	Global
" "	51±15	1993–2004	>35° N
This study	48–58	1979–2008	>40° N
" "	78****	2100	>40° N

*fitted to atm. concentrations, **SRES A2, ***Melton et al. (2012), ****RCP8.5

The degree of seasonal variability (3.3.3) may be a consistent feature of particular boreal wetlands reflecting peat quality, water table fluctuation or other factors (Dise, 1993). Next to temperature and water table, Dise (1993) identified nutrients as the main control on boreal wetland CH_4 emissions. These controlling variables,

especially the nutrients, however, are not consistent among the published studies (Dise, 1993).

Our approach assumes that the degree of aeration is the most important constraint on methanogenesis in wetlands. Laboratory studies indicate that substrate supply is the primary control once anaerobic conditions have been achieved (Whalen, 2005). The substrate, namely the acrotelm and catotelm carbon pools, are growing constantly during the experiments. Since CH_4 emissions do not increase to the same extent as the soil carbon pool, it could be assumed that temperature is an additional, important control on methanogenesis (Whalen, 2005). Increased temperatures in turn may increase NPP (Riley et al., 2011).

Riley et al. (2011) conclude that the overall temperature sensitivity of net CH_4 emissions is the result of the temperature sensitivity of the component processes of primary productivity – production of methanogenesis substrate from soil and litter organic matter, methanogenesis, CH_4 methanotrophy and transport. As a result, projecting future climate effects from terrestrial CH_4 emissions is difficult.

The comparison of modelling results against observational data causes certain difficulties because of the episodic and spatially heterogeneous nature of the fluxes (Riley et al., 2011). A different approach would be to compare modelling results against atmospheric data.

3.4.2 Atmospheric growth rate

Measurements of atmospheric CH_4 emissions are available from 1984 onwards. The growth rate, that was up to 14 ppb yr^{-1} in the early 1980s (Blake and Rowland, 1988), slowed down to less than zero in 2001, 2004 and 2005 (Denman et al., 2007). If ones assumes that the CH_4 emissions from boreal wetlands have an impact on the atmospheric CH_4 concentrations, the results are in line with

observations. Several studies emphasize the impact of wetlands CH_4 emissions on the atmospheric CH_4 concentration.

Inversions carried out by Bousquet et al. (2006) showed that fluctuations in wetland emissions are the dominant contribution to interannual variability in surface emissions (12 Tg CH_4 yr^{-1}). Furthermore, they explained 70% of the global emission anomalies from 1884 to 2004 by wetland CH_4 emissions. One has to consider that boreal wetland CH_4 emissions are just one part of the global CH_4 budget, especially since man-made activities produce considerable amounts of CH_4. This kind of comparison, however, allows for evaluating the role of natural boreal wetlands.

3.4.3 Future CH_4 emissions

Our results from the future simulation F1 based on the RCP8.5 emission scenario show increased CH_4 emissions by 13.5 Tg CH_4 yr^{-1} in the year 2100 (57 to 70.5 Tg CH_4 yr^{-1}).

Several studies suggest that the wetland temperature response and not the change in wetlands extent will dominate the change in natural CH_4 emissions (Eliseev et al., 2008; Gedney et al., 2004). The strength of the change of emissions however ranges strongly. Gedney et al. (2004) expect a major increase of CH_4 .emissions by 2100, with 500–600 Tg CH_4 yr^{-1}, whereas Eliseev et al. (2008) expect CH_4 emissions in the range of 168–170 Tg CH_4 yr^{-1} in scenario SRES B1, 179–183 Tg CH_4 yr^{-1} in SRES A1B and 191−199 Tg CH_4 yr^{-1} in SRES A2. Both studies, however, do not restrict their study area to boreal wetlands but analyze the global emissions.

Given that temperature and NPP are the driving variables and soil carbon stocks as modelling results increase in the future simulation one would assume that an increase in methane emissions from wetland ecosystems is determined mainly by

the temperature dependence of methane production. This is in line with the modelling results from Eliseev et al. (2008).

A number of studies suggest that methanogenesis seems to have an especially high sensitivity to temperature (Segers, 1998; Walter and Heimann, 2000; Zhuang et al., 2004). The relationship between a certain increase of methanogenesis per 10° C temperature increase is known as the Q_{10} factor. A wide range of values (2–16) for this Q_{10} factor related to CH_4 formation has been cited in the literature (Walter and Heimann, 2000). To be consistent with the CBALANCE model a comparable low value of 1.8 was used for the peatBALANCE model as well. Therefore, the sensitivity to temperature is closer to the mean value used in Ringeval et al. (2010) or Meng et al. (2011) than the range reported by Segers et al. (1998), which covers values from 1.5 to 28. However it is not clear how effective this temperature sensitivity will be in future, since the substrate availability may also be a limiting factor in the boreal wetlands (Basiliko et al., 2007). Friedlingstein et al. (2006) state that in future times soil organic matter decomposition might increase faster than NPP increases as temperatures rise. This scenario would lead to less supply of fresh organic material and could limit the production of CH_4.

Considering that the CH_4 emissions are to a large extent temperature driven it is obvious that boreal wetlands will play an increasingly important role as future climatic change affects the boreal land areas significantly (Meehl et al., 2007).

3.4.4 Limitations of this study

The simulated CH_4 emissions depend on several assumptions outside of the peatBALANCE model. This is true for soil temperature, NPP, LAI, alpha and water table heights. For example the process of CH_4 production through the degradation of dead plant organic matter is strongly simplified. This allows us to

run the model at the global scale for long times, but on the other hand leads to uncertainties. Riley et al. (2011) point out that simulated below-ground respiration serves as the driver of CH_4 production in their model, errors in NPP propagate to errors in CH_4 production. This affects the peatBALANCE/CH_4 emission model as well.

Another detail leading to uncertainties is the representation of PFTs (Plant function types) in the present model. Wetlands are represented only by one type of plant. Experiments assuming dominance of one vegetation type (Sphagnum vs. Carex vs. Shrubs) show that Carex-dominated vegetation can increase CH_4 emissions by 50 % to 78 % over Sphagnum-dominated vegetation, depending on the modelled climate, while for shrubs this increase ranges from 42 % to 72 % (Berrittella and van Huissteden, 2011).

An example is the prescribed ratio of CH_4 to CO_2 production in the drained soil that was applied in the study. Assuming a constant ratio (that has been measured in the Lab) makes modelling a lot easier. In the field, however, the ratio is everything but fixed (Keller and Bridgham, 2007).

Although the projections of future CH_4 emissions are subject to a range of uncertainties one can be confident that the major mechanisms are represented well by the peatBALANCE/CH_4 emission model. The simplification of the set of complex processes that is involved in boreal wetland CH_4 emissions has true advantages for applying the model for global and long term simulations. At the same time this simplification leads to uncertainties in the modelling results.

3.5 Conclusions

A CH_4 production and emission model was combined with the peatBALANCE model as part of the land surface model JSBACH that is part of the MPI-ESM. The model includes representations of CH_4 production, oxidation, aerenchyma

transport, ebullition, diffusion through the soil and fractional inundation. Present day CH_4 emissions range from 48 to 58 Tg CH_4 yr^{-1} with a variability of 10 Tg CH_4 yr^{-1}.

In a hypothetical future warming scenario (RCP8.5) until the year 2100, the model predicted large increases in CH_4 emissions up to 78 Tg CH_4 yr^{-1}. Given model limitations and missing processes (e.g. permafrost dynamics), it should be emphasized that the results must be interpreted with caution. In reality feedbacks between CH_4 emissions and climate do not only base on soil temperature and NPP but also on sophisticated spatial processes so that further model improvement is much needed.

Chapter 4

4 Conclusions and Outlook

4.1 Summary of findings

This section provides a summary of the findings from the two previous chapters and answers the research questions posed in the introduction. In view of these findings conclusions are drawn in the following section.

1) Which processes and parameters are needed to model the carbon cycle dynamics of boreal wetlands for the last 6000 yr?

The interactions between boreal wetlands, carbon cycle and climate were evaluated on millennial timescales using the newly developed peatBALANCE model which was implemented into the land surface module of the Max Planck Institute Earth System Model (MPI-ESM), JSBACH. The strategy was pursued of using an approach defined by the need to cope with the global application over long timescales and the detailed representation of the processes that define the boreal wetlands carbon cycle. In addition to the available processes in the CBALANCE model the following processes and parameters were identified as mandatory: 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), a moving water table which defines the boundary of these functional layers, and, as an outcome of the interaction of the components listed above, the accumulation of carbon in the catotelm as well as outgoing fluxes of CO_2 and CH_4. To account for the latter, the newly developed peatBALANCE model was combined with a CH_4 transport model as described by Walter et al. (2001b). Moreover, the model used prescribed grid cell peatland fractions as well as the position of the water table within the peatland fraction. Only very few parameters were used, namely turnover times, densities and carbon fraction of the carbon pools and a factor to determine the CH_4 production flux.

2) How does the peatBALANCE/CH_4 emission model perform compared to pre-industrial peat accumulation and present day CH_4 emission rates?

The modelled catotelm peat accumulation rates were compared to observations of catotelm peat accumulation rates from Gorham et al. (2003), Kremenetzki et al. (2003), Beilman et al. (2009) and Yu et al. (2010). The measured carbon accumulation rates are slightly higher, which could possibly be explained by a measurement bias (Korhola et al., 2010) since the model represents a substantially larger area than a local peat site.

Results from the CH_4 emission model were compared to data for the West Siberian Lowlands. Based on the atmospheric concentration data from four tower stations in this region (ZOTTO (Sasakawa et al., 2012; Winderlich et al., 2010)), an atmospheric transport inversion model shows almost similar results (6.89 Tg CH_4 yr^{-1}) compared to 6 Tg CH_4 yr^{-1} simulated with the peatBALANCE/CH_4 model for the year 2009 (Winderlich, 2011)). The seasonal cycle of the modelling results compares well with the results of the data-driven inversion. However, the modelled summer emissions are smaller (peatBALANCE/CH_4 shows 13.2, the inversion model 17.5 g C m^{-2} yr^{-1} in July) than the atmospheric data implies. For the Hudson Bay Lowlands area the peatBALANCE/CH_4 emission model gives CH_4 emissions of 1.6 Tg CH_4 yr^{-1} for pre-industrial times, whereas Pickett-Heaps et al. (2011) published observational data for this area of 2.3 Tg CH_4 yr^{-1} in the year 2008.

3) How have the carbon accumulation and CH_4 emissions evolved from 6000 yr BP to pre-industrial and the present day?

Results from a 6000 yr simulation of the peatBALANCE model show an accumulation of 240 Pg C catotelm peat in areas above 35° N. This is corroborated by earlier studies by Gorham (1991), Turunen et al. (2002), Smith et al. (2004) and Yu et al. (2010), who estimate the size of the accumulated carbon from the last glacial until pre-industrial times to be 180 to 621 Pg C. The acrotelm

carbon pool reached an equilibrium state with a size of 16 Pg C 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).

The CH_4 emissions for circumpolar boreal regions (above 40° N) result in 49.3 (+/– 2.3) Tg CH_4 yr^{-1} at 6000 yr BP and increase to 51.5 (+/– 2.75) Tg CH_4 yr^{-1} in pre-industrial times. At the present day, simulated with a different set of experiments based on AMIP simulations and with a higher model resolution, CH_4 emissions range from 47.5 to 59.5 Tg CH_4 yr^{-1} with a variability of 10 Tg CH_4 yr^{-1}. These results are corroborated by earlier studies by who showed that wetlands CH_4 emissions show a rising trend over the course of the Holocene.

4) How will the carbon cycle dynamics of boreal wetlands evolve in the future?

With results from a simulation until the year 2100, which is based on a high emission scenario (RCP8.5), the peatBALANCE/CH_4 emission model predicts a large increase of CH_4 emissions of 13.5 Tg CH_4 yr^{-1} (57 to 70.5 Tg CH_4 yr^{-1}). This increase is accompanied by very pronounced year-on-year changes of up to 14 Tg CH_4 yr^{-1}. These findings indicate that boreal wetlands presumably will increase their share of atmospheric CH_4 concentrations in the future. Being the largest single source of natural CH_4 emissions, the increasingly important role of boreal wetlands is emphasized by this investigation. The soil carbon pools show only minor changes during this comparably short period of time.

4.2 Conclusions and Assessment

In view of the findings summarized in the section before, conclusions are drawn below, which are followed by an outlook on possible future directions of research. This thesis assesses the interactions between boreal wetlands, carbon cycle and

climate over the last 6000 yr, during the present day and until the year 2100. Within this research project a process-based carbon accumulation and decay model for boreal wetlands, peatBALANCE, was developed and applied in combination with a CH_4 emission model to assess the carbon cycle dynamics of natural boreal wetlands. The present study suggests that during the past 6000 yr BP CH_4 emissions rose with pronounced variability until pre-industrial times. These dynamics in boreal CH_4 emissions resemble the minimum in the atmospheric CH_4 concentration around 5000 yr BP with the subsequent increase. The rising trend of atmospheric CH_4 concentrations (reconstructed from ice-cores) over the last several thousand years, therefore, may be explained not only with the inclusion of anthropogenic factors (CH_4 emissions from landuse (see Ruddiman, 2003)) but also by natural processes. This study demonstrated, furthermore, that large amounts of carbon have accumulated in the catotelm over the past 6000 yr. All, carbon accumulation and emission, but also the trends and variability indicate the close link between boreal wetlands, carbon cycle and the climate. Several studies emphasize the impact of wetlands CH_4 emissions on the atmospheric CH_4 concentration (Mitra et al., 2003; Worthy et al., 2000). These findings are corroborated with studies carried out by Bousquet et al. (2006), who explained 70 % of the global emission anomalies from 1884 to 2004 by wetland CH_4 emissions. The atmospheric CH_4 budget, however, is composed of CH_4 not only from natural boreal wetlands but also from termites, CH_4 hydrates, wildfires and geologic sources. A range of human related sources such as the decomposition of wastes in landfills, ruminant digestion and manure management associated with domestic livestock, natural gas and oil systems, and coal mining contribute their share to the atmospheric CH_4 concentration as well. The main CH_4 sink that determines the atmospheric CH_4 concentrations is the depletion by ozone.

The links between boreal wetlands CH_4 emissions and atmospheric CH_4 concentration mentioned above demonstrate the complex nature of the

interactions leading to the climate relevant GHG concentrations. However, the quantitative investigation of the atmospheric CH_4 concentrations will only be possible by further research done using process-based atmospheric chemistry models. These models will have to explicitly consider the ozone sink and different CH_4 sources to describe the atmospheric CH_4 budget completely.

The analysis of the qualitative relationships between the processes involved in regard to natural boreal wetlands suggests that a changing climate will affect these wetlands considerably. Therefore, an implementation of the presented model into an ESM and further research are needed. Both the model development and the results obtained provide the basis for further investigations. This is important as boreal wetlands are a significant component of the carbon and methane cycles that cannot be neglected in investigations of global warming.

Apart from the investigated climate related long-term changes that are altering boreal wetlands carbon cycle, there are several other anthropogenic factors leading to a reduction of boreal wetlands today: the agricultural conversion and drainage of natural boreal wetlands and peat mining for horticulture and fuel. These man-made changes alter the boreal wetlands substantially on the short-term. For a comprehensive study of boreal wetlands it would make sense though, to include human-induced changes when modelling boreal wetlands carbon cycle climate interactions.

The simulation of the interactions of natural boreal wetlands, carbon cycle and climate, represented in this thesis by the combined peatBALANCE/CH_4 emission model that was implemented into the land surface module of the MPI-ESM, requires the consideration of many processes that all contribute to the complexity of boreal wetlands. The perspectives for further research on these interactions are manifold.

The simulations performed depend on several variables from outside the peatBALANCE model. The calculation of wetland fractions and corresponding

water tables within the peatBALANCE model would allow for spatial dynamics, like the initialization or expansion of wetlands (Jones and Yu, 2010; Korhola et al., 2010; Yu et al., 2010).

Further improvements with regard to a better representation of boreal wetlands would be the integration of more wetland specific PFTs (Plant Function Types). The wetlands as defined in this study are represented only by one type of plant. Experiments assuming dominance of one vegetation type (Sphagnum vs. Carex vs. Shrubs) show that Carex-dominated vegetation can increase CH_4 emissions significantly over Sphagnum-dominated vegetation (Berrittella and van Huissteden, 2011).

Some other processes altering the carbon cycle of boreal wetlands were not considered in the current version of the peatBALANCE/CH_4 emission model: sulfate deposition, Sphagnum-associated methane oxidation and permafrost. Boreal wetlands have always been strong CH_4 sources. With increases in CO_2 and temperature, and the associated increases in wetland productivity, CH_4 fluxes would be expected to increase. However, sulfate 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). Sphagnum-associated methane oxidation occurs ubiquitously across the globe (Parmentier et al., 2011a; van Winden et al., 2010) and could reduce the amount of CH_4 significantly. And last but not least, permafrost, which covers some parts of boreal wetlands in the northern boreal zone (Robinson and Moore, 1999) inhibits soil decomposition, thus leading to a huge build up of frozen organic carbon and hindering methane production (Anisimov, 2007; Khvorostyanov et al., 2008a; 2008b; Schuur et al., 2008). Permafrost then again is subject to future climate change, possibly leading to a reduction of its extend and carbon stocks (Avis et al., 2011; Yu, 2012). An inclusion of one or more of these processes could improve the reliability of the simulations.

A comparison of modelling results from other wetland models as carried out in the model intercomparison project WETCHIMP (WETland and Wetland CH_4 Intercomparison of Models Project (Melton et al., 2012)) would help to gain knowledge about the model performance. A further comparison against currently planned satellite observations (e.g. the MERLIN MEthane Remote Sensing LIDAR MissioN) would also help to improve insights about the distribution and strengths of boreal CH_4 emissions.

The modelling of boreal wetlands carbon cycling in the context of Earth System Models remains challenging. Although the simulations of peat accumulation and CH_4 emissions with the peatBALANCE/CH_4 emission model are subject to a range of uncertainties and certain processes have not been included yet, it has been shown that the major mechanisms that are represented by the peatBALANCE model lead to plausible results that which makes a decisive contribution to understanding past, present and future of boreal wetlands carbon cycle climate interactions. The approach described in this study does not only add processes to the land component of the MPI-ESM that were important for carbon balance in the past, but also provides a new scheme for accounting for wetland response to future climate change. This is important, as over long timescales boreal wetlands are a significant component of the carbon and methane cycles that could either dampen or amplify human-induced global warming. The results presented in this thesis highlight the importance of boreal wetlands for simulations of the global carbon cycle and I recommend accounting for these boreal wetland processes when investigating global carbon cycle dynamics with ESMs in past, present and future climates.

Bibliography

Anisimov, O. A.: Potential feedback of thawing permafrost to the global climate system through methane emission,, 1–7, 2007.

Avis, C. A., Weaver, A. J. and Meissner, K. J.: Reduction in areal extent of high-latitude wetlands in response to permafrost thaw, Nature Geosci, 4(7), 444–448, doi:10.1038/ngeo1160, 2011.

Bartlett, K. B. and Harriss, R. C.: Review and assessment of methane emissions from wetlands, Chemosphere, 26(1-4), 261–320, doi:10.1016/0045-6535(93)90427-7, 1993.

Basiliko, N., Blodau, C., Roehm, C., Bengtson, P. and Moore, T.: Regulation of decomposition and methane dynamics across natural, commercially mined, and restored northern peatlands, Ecosystems, 2007.

Bauer, I.: Modelling effects of litter quality and environment on peat accumulation over different time-scales, J Ecol, 92(4), 661–674, doi:10.1111/j.0022-0477.2004.00905.x, 2004.

Beilman, D. W., MacDonald, G. M., Smith, L. C. and Reimer, P. J.: Carbon accumulation in peatlands of West Siberia over the last 2000 years, Global Biogeochem Cy, 23(1), GB1012, doi:10.1029/2007GB003112, 2009.

Belyea, L. and Malmer, N.: Carbon sequestration in peatland: patterns and mechanisms of response to climate change, Glob Change Biol, 10(7), 1043–1052, 2004.

Bergamaschi, P., Frankenberg, C., Meirink, J. F., Krol, M., Dentener, F., Wagner, T., Platt, U., Kaplan, J. O., Körner, S., Heimann, M., Dlugokencky, E. J., et al.: Satellite chartography of atmospheric methane from SCIAMACHY on

board ENVISAT: 2. Evaluation based on inverse model simulations, J Geophys Res, 112(D2), D02304, doi:10.1029/2006JD007268, 2007.

Berrittella, C. and van Huissteden, J.: Uncertainties in modelling CH4 emissions from northern wetlands in glacial climates: The role of vegetation parameters, Clim. Past, 7(4), 1075–1087, 2011.

Beven, K. J. and Kirkby, M. J.: A physically based, variable contributing area model of basin hydrology / Un modèle à base physique de zone d“appel variable de l”hydrologie du bassin versant, Hydrol Sci Bull, 24(1), 43–69, doi:10.1080/02626667909491834, 1979.

Blake, D. R. and Rowland, F. S.: Continuing worldwide increase in tropospheric methane, 1978 to 1987, Science, 239(4844), 1129–1131–1131, doi:10.1126/science.239.4844.1129, 1988.

Blodau, C.: Carbon cycling in peatlands-A review of processes and controls, Environ Rev, 10(2), 111–134, doi:10.1139/a02-004, 2002.

Blunier, T., Chappellaz, J., Schwander, J., Stauffer, B. and Raynaud, D.: Variations in atmospheric methane concentration during the Holocene epoch, Nature, 374(6517), 46–49, doi:10.1038/374046a0, 1995.

Bohn, T. J., Lettenmaier, D. P., Sathulur, K., Bowling, L. C., Podest, E., McDonald, K. C. and Friborg, T.: Methane emissions from western Siberian wetlands: heterogeneity and sensitivity to climate change, Environ. Res. Lett., 2(4), –, doi:10.1088/1748-9326/2/4/045015, 2007.

Borren, W., Bleuten, W. and Lapshina, E.: Holocene peat and carbon accumulation rates in the southern taiga of western Siberia, Quaternary Research, 61(1), 42–51, doi:10.1016/j.yqres.2003.09.002, 2004.

Bousquet, P., Ciais, P., Miller, J. B., Dlugokencky, E. J., Hauglustaine, D. A.,

Prigent, C., Van der Werf, G. R., Peylin, P., Brunke, E. G., Carouge, C., Langenfelds, R. L., et al.: Contribution of anthropogenic and natural sources to atmospheric methane variability, Nature, 443(7110), 439–443, doi:doi:10.1038/nature05132, 2006.

Bretagnon, P. and Francou, G.: Planetary theories in rectangular and spherical variables - VSOP 87 solutions, Astron Astrophys, 202, 309–315, 1988.

Brovkin, V., Ganopolski, A., Archer, D. and Munhoven, G.: Glacial CO2 cycle as a succession of key physical and biogeochemical processes, Clim. Past, 8(1), 251–264, doi:10.5194/cp-8-251-2012, 2012.

Cao, M., Marshall, S. and Gregson, K.: Global carbon exchange and methane emissions from natural wetlands: application of a process-based model, J Geophys Res, 101, 14–14, 1996.

Charman, D. J.: Peatlands and environmental change, Wiley. 2002.

Christensen, T.: Response of methane emission from Arctic tundra to climatic change: results from a model simulation, Tellus B, 1995.

Clair, T., Warner, B. G., Robarts, R., Murkin, H., Lilley, J., Mortsch, L. and Rubec, C.: Chapter 3, in Canada Country Study: Climate Impacts and Adaptation, edited by G. Koshida and W. Avis, National Sectoral Volume. 1998.

Claussen, M.: Late Quaternary vegetation-climate feedbacks, Clim. Past, 5(2), 203–216, 2009.

Clymo, R. S.: The Limits to Peat Bog Growth, Philos T Roy Soc B, 303(1117), 605–654, 1984.

Denman, K., Brasseur, G., Chidthaisong, A., Ciais, P., Cox, P., Dickinson, R., Hauglustaine, D., Heinze, C., Holland, E., Jacob, D., Lohmann, U., et al.: Couplings Between Changes in the Climate System and Biogeochemistry, in

Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, edited by S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. Averyt, M. Tignor, and H. Miller, Cambridge University Press. 2007.

Dentener, F., van Weele, M., Krol, M., Houweling, S. and van Velthoven, P.: Trends and inter-annual variability of methane emissions derived from 1979-1993 global CTM simulations, Atmos Chem Phys, 3(1), 73–88, 2003.

Dinsmore, K. J., Skiba, U. M., Billett, M. F. and Rees, R. M.: Effect of water table on greenhouse gas emissions from peatland mesocosms, Plant Soil, 318(1-2), 229–242, doi:10.1007/s11104-008-9832-9, 2009.

Dise, N. B.: Methane emission from Minnesota peatlands: Spatial and seasonal variability, Global Biogeochem. Cycles, 7(1), 123–142, 1993.

Dise, N. B.: Peatland Response to Global Change, Science, 326(5954), 810–811, doi:10.1126/science.1174268, 2009.

Dlugokencky, E., Walter, B., Masarie, K., Lang, P. and Kasischke, E.: Measurements of an anomalous global methane increase during 1998, Geophys Res Lett, 28(3), 499–502, 2001.

Dorrepaal, E., Toet, S., Logtestijn, R. S. P. V., Swart, E., Weg, M. J. V. de, Callaghan, T. V. and Aerts, R.: Carbon respiration from subsurface peat accelerated by climate warming in the subarctic, Nature, 460(7255), 616–619, doi:10.1038/nature08216, 2009.

Eliseev, A. V., Mokhov, I. I., Arzhanov, M. M., Demchenko, P. F. and Denisov, S. N.: Interaction of the methane cycle and processes in wetland ecosystems in a climate model of intermediate complexity, Izv. Atmos. Ocean. Phys., 44(2), 139–152, doi:10.1134/S0001433808020011, 2008.

Etheridge, D. M., Pearman, G. I. and De Silva, F.: Atmospheric trace-gas variations as revealed by air trapped in an ice core from Law Dome, Antarctica, Ann Glaciol, 1988.

Fischer, N. and Jungclaus, J. H.: Evolution of the seasonal temperature cycle in a transient Holocene simulation: orbital forcing and sea-ice, Clim. Past, 7(4), 1139–1148, doi:10.5194/cp-7-1139-2011, 2011.

Flückiger, J., Monnin, E., Stauffer, B., Schwander, J., Stocker, T. F., Chappellaz, J., Raynaud, D. and Barnola, J.-M.: High-resolution Holocene N2O ice core record and its relationship with CH4 and CO2, Global Biogeochem Cy, 16(1), 10–1–10–8, 2002.

Forster, P. M., Ramaswamy, V., Artaxo, P., Berntsen, T., Betts, R., Fahey, D. W., Haywood, J., Lean, J., Lowe, D. C., Myhre, G., Nganga, J., et al.: Changes in Atmospheric Constituents and in Radiative Forcing, in Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, edited by S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller, Cambridge University Press, Cambridge, New York. 2007.

Frankenberg, C., Meirink, J. F., van Weele, M., Platt, U. and Wagner, T.: Assessing Methane Emissions from Global Space-Borne Observations, Science, 308(5724), 1010–1014, doi:10.1126/science.1106644, 2005.

Friedlingstein, P., Bopp, L., Rayner, P., Cox, P., Betts, R., Jones, C., Bloh, von, W., Brovkin, V., Cadule, P. and Doney, S.: Climate–carbon cycle feedback analysis: results from the C4MIP model intercomparison, J Climate, 19, 3337–3353, 2006.

Frolking, S. and Roulet, N. T.: Holocene radiative forcing impact of northern peatland carbon accumulation and methane emissions, Glob Change Biol,

13(5), 1079–1088, doi:10.1111/j.1365-2486.2007.01339.x, 2007.

Frolking, S., Roulet, N. and Lawrence, D.: Issues related to incorporating northern peatlands into global climate models, in Geophys. Monogr. Ser., vol. 184, pp. 19–35, AGU, Washington, DC. 2009.

Frolking, S., Roulet, N., Tuittila, E., Bubier, J., Quillet, A., Talbot, J. and Richard, P.: A new model of Holocene peatland net primary production, decomposition, water balance, and peat accumulation, Earth Syst Dynam, 1, 1–21, doi:10.5194/esd-1-1-2010, 2010.

Gates, W. L., Boyle, J. S., Covey, C., Dease, C. G., Doutriaux, C. M., Drach, R. S., Fiorino, M., Gleckler, P. J., Hnilo, J. J., Marlais, S. M., Phillips, T. J., et al.: An Overview of the Results of the Atmospheric Model Intercomparison Project (AMIP I), http://dx.doi.org/10.1175/1520-0477(1999)080<0029:AOOTRO>2.0.CO;2, 1999.

Gedney, N., Cox, P. and Huntingford, C.: Climate feedback from wetland methane emissions, Geophys Res Lett, 31(20), L20503, doi:10.1029/2004GL020919, 2004.

Giorgetta, M. A., Jungclaus, J., Reick, C., Legutke, S., Brovkin, V., Crueger, T., Esch, M., Fieg, K., Glushak, K., Gayler, V., Haak, H., et al.: Climate change from 1850 to 2100 in MPI-ESM simulations for the Coupled Model Intercomparison Project 5, Journal of Advances in Modeling Earth Systems, n.d.

Glaser, P., Hansen, B., Siegel, D., Reeve, A. and Morin, P.: Rates, pathways and drivers for peatland development in the Hudson Bay Lowlands, northern Ontario, Canada, J Ecol, 92(6), 1036–1053, doi:10.1111/j.0022-0477.2004.00931.x, 2004.

Gorham, E.: Northern Peatlands: Role in the Carbon Cycle and Probable Responses

to Climatic Warming, Ecol Appl, 1(2), 182, doi:10.2307/1941811, 1991.

Gorham, E., Janssens, J. and Glaser, P.: Rates of peat accumulation during the postglacial period in 32 sites from Alaska to Newfoundland, with special emphasis on northern Minnesota, Can J Bot, 81(5), 429–438, doi:10.1139/B03-036, 2003.

Heimann, M.: How stable is the Methane Cycle. Science, 327(5970), 2010

Hein, R., Crutzen, P. J. and Heimann, M.: An inverse modeling approach to investigate the global atmospheric methane cycle, Global Biogeochem. Cycles, 11(1), 43, doi:10.1029/96GB03043, 1997.

Heinemeyer, A., Croft, S., Lomas, M. and Garnett, M.: Modelling UK upland peatland carbon dynamics-past, present and future, adsabs.harvard.edu, 2010.

Hilbert, D., Roulet, N. and Moore, T.: Modelling and analysis of peatlands as dynamical systems, J Ecol, 88(2), 230–242, 2000.

Ingram, H. A. P.: Soil Layers in Mires: Function and Terminnology, J Soil Sci, 29(2), 224–227, doi:10.1111/j.1365-2389.1978.tb02053.x, 1977.

Ingram, H. A. P.: Size and shape in raised mire ecosystems: a geophysical model, Nature, 297(5864), 300–303, doi:10.1038/297300a0, 1982.

Ito, A. and Inatomi, M.: Use of a process-based model for assessing the methane budgets of global terrestrial ecosystems and evaluation of uncertainty, Biogeosciences, 9(2), 759–773, doi:10.5194/bg-9-759-2012, 2012.

Jones, M. C. and Yu, Z.: Rapid deglacial and early Holocene expansion of peatlands in Alaska, P Natl Acad Sci Usa, 107(16), 7347–7352, 2010.

Kamal, S. and Varma, A.: Peatland microbiology, in Soil Biolology - Microbiology of Extreme Soils, edited by P. Dion and C. S. Nautiyal, pp. 177–203,

Springer. 2008.

Kayranli, B., Scholz, M. and Mustafa, A.: Carbon storage and fluxes within freshwater wetlands: a critical review, Wetlands, 2010.

Keller, J. K. and Bridgham, S. D.: Pathways of anaerobic carbon cycling across an ombrotrophic-minerotrophic peatland gradient, Limnology and Oceanography, 52(1), 96–107, 2007.

Khvorostyanov, D. V., Ciais, P., Krinner, G., Zimov, S. A., Corradi, C. and Guggenberger, G.: Vulnerability of permafrost carbon to global warming. Part II: Sensitivity of permafrost carbon stock to global warming, Tellus B, 60 B(2), 265–275, 2008a.

Khvorostyanov, D. V., Krinner, G., Ciais, P., Heimann, M. and Zimov, S. A.: Vulnerability of permafrost carbon to global warming. Part I: Model description and role of heat generated by organic matter decomposition, Tellus B, 60 B(2), 250–264, 2008b.

Kleinen, T., Brovkin, V. and Schuldt, R. J.: A dynamic model of wetland extent and peat accumulation: results for the Holocene, Biogeosciences, 9(1), 235–248, doi:10.5194/bg-9-235-2012, 2012.

Korhola, A., Ruppel, M., Seppa, H., Valiranta, M., Virtanen, T. and Weckstrom, J.: The importance of northern peatland expansion to the late-Holocene rise of atmospheric methane, Quaternary Sci Rev, 29(5–6), 611–617, doi:10.1016/j.quascirev.2009.12.010, 2010.

Kremenetski, K., Velichko, A., Borisova, O., MacDonald, G., Smith, L., Frey, K. and Orlova, L.: Peatlands of the Western Siberian lowlands: Current knowledge on zonation, carbon content and Late Quaternary history, Quaternary Sci Rev, 22(5-7), 703–723, 2003.

Lai, D. Y. F.: Methane Dynamics in Northern Peatlands: A Review, Pedosphere, 19(4), 409–421, doi:10.1016/S1002-0160(09)00003-4, 2009.

Limpens, J., Berendse, F., Blodau, C., Canadell, J. G., Freeman, C., Holden, J., Roulet, N., Rydin, H. and Schaepman-Strub, G.: Peatlands and the carbon cycle: From local processes to global implications - A synthesis, Biogeosciences, 5(2), 1379–1419, 2008.

Lu, X. and Zhuang, Q.: Modeling methane emissions from the Alaskan Yukon River basin, 1986–2005, by coupling a large-scale hydrological model and a process-based methane model, J Geophys Res, 117(G2), G02010, doi:10.1029/2011JG001843, 2012.

Lüthi, D., Le Floch, M., Bereiter, B., Blunier, T., Barnola, J.-M., Siegenthaler, U., Raynaud, D., Jouzel, J., Fischer, H., Kawamura, K. and Stocker, T. F.: High-resolution carbon dioxide concentration record 650,000–800,000 years before present, Nature, 453(7193), 379–382, doi:10.1038/nature06949, 2008.

MacDonald, G., Beilman, D. and Kremenetski, K.: Rapid early development of circumarctic peatlands and atmospheric CH4 and CO2 variations, Science, 2006.

Malmer, N. and Wallen, B.: Input rates, decay losses and accumulation rates of carbon in bogs during the last millennium: internal processes and environmental changes, The Holocene, 14(1), 111–117, doi:10.1191/0959683604hl693rp, 2004.

McGuire, A. D., Anderson, L. G., Christensen, T. R., Dallimore, S., Guo, L., Hayes, D. J., Heimann, M., Lorenson, T. D., Macdonald, R. W. and Roulet, N.: Sensitivity of the carbon cycle in the Arctic to climate change, Ecol Monogr, 79(4), 523–555, 2009.

McGuire, A. D., Macdonald, R. W., Schuur, E. A., Harden, J. W., Kuhry, P., Hayes,

D. J., Christensen, T. R. and Heimann, M.: The carbon budget of the northern cryosphere region, Curr Opin Env Sustain, 2(4), 231–236, doi:doi: 10.1016/j.cosust.2010.05.003, 2010.

Meehl, G. A., Stocker, T. F., Collins, W. D. and Friedlingstein, P.: Global Climate Projections, in Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, edited by S. Solomon, D. Quin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller, … Solomon and others. 2007.

Melton, J. R., Wania, R. and Hodson, E. L.: Present state of global wetland extent and wetland methane modelling: conclusions from a model intercomparison project (WETCHIMP), Biogeosciences, 2012.

Meng, L., Hess, P., Mahowald, N., Yawitt, J., Riley, W., Subin, Z., Lawrence, D., Swenson, S., Jauhiainen, J. and Fuka, D.: Sensitivity of wetland methane emissions to model assumptions: application and model testing against site observations, Biogeosciences Discuss, 2011.

Mikaloff Fletcher, S. E., Tans, P. P., Bruhwiler, L. M., Miller, J. B. and Heimann, M.: CH4 sources estimated from atmospheric observations of CH4 and its 13C/12C isotopic ratios: 1. Inverse modeling of source processes, Global Biogeochem Cy, 18(4), 1–17, 2004.

Mitra, S., Wassmann, R. and Vlek, P. L. G.: Global Inventory Of Wetlands And Their Role In The Carbon Cycle, Discussion Papers, 2003.

O'Connor, F. M., Boucher, O., Gedney, N., Jones, C. D., Folberth, G. A., Coppell, R., Friedlingstein, P., Collins, W. J., Chappellaz, J., Ridley, J. and Johnson, C. E.: Possible role of wetlands, permafrost, and methane hydrates in the methane cycle under future climate change: A review, Rev Geophys, 48(4), 2010.

Parmentier, F. J. W., van Huissteden, J., Kip, N., Op Den Camp, H. J. M., Jetten, M. S. M., Maximov, T. C. and Dolman, A. J.: The role of endophytic methane-oxidizing bacteria in submerged Sphagnum in determining methane emissions of Northeastern Siberian tundra, Biogeosciences, 8(5), 1267–1278, doi:10.5194/bg-8-1267-2011, 2011a.

Parmentier, F. J. W., van Huissteden, J., Van Der Molen, M. K., Schaepman-Strub, G., Karsanaev, S. A., Maximov, T. C. and Dolman, A. J.: Spatial and temporal dynamics in eddy covariance observations of methane fluxes at a tundra site in northeastern Siberia, J Geophys Res, 116(G3), G03016, 2011b.

Petrescu, A. M. R., Van Beek, L.P.H., van Huissteden, J., Prigent, C., Sachs, T., Corradi, C. A. R., Parmentier, F. J. W. and Dolman, A. J.: Modeling regional to global CH 4emissions of boreal and arctic wetlands, Global Biogeochem Cy, 24(4), GB4009–, doi:10.1029/2009GB003610, 2010.

Pickett-Heaps, C. A., Jacob, D. J., Wecht, K. J., Kort, E. A., Wofsy, S. C., Diskin, G. S., Worthy, D. E. J., Kaplan, J. O., Bey, I. and Drevet, J.: Magnitude and seasonality of wetland methane emissions from the Hudson Bay Lowlands (Canada), Atmos Chem Phys, 11(8), 3773–3779, doi:10.5194/acp-11-3773-2011, 2011.

Raddatz, T. J., Reick, C. H., Knorr, W., Kattge, J., Roeckner, E., Schnur, R., Schnitzler, K. G., Wetzel, P. and Jungclaus, J.: Will the tropical land biosphere dominate the climate–carbon cycle feedback during the twenty-first century? Climate Dynamics, 29(6), 565–574, doi:10.1007/s00382-007-0247-8, 2007.

Reddy, K. R. and DeLaune, R. D.: Biogeochemistry of Wetlands, CRC Press. 2008.

Rigby, M., Prinn, R. G., Fraser, P. J., Simmonds, P. G., Langenfelds, R. L., Huang, J., Cunnold, D. M., Steele, L. P., Krummel, P. B., Weiss, R. F., O'Doherty, S., et al.: Renewed growth of atmospheric methane, Geophys Res Lett,

35(22), L22805, doi:10.1029/2008GL036037, 2008.

Riley, W. J., Subin, Z. M., Lawrence, D. M., Swenson, S. C., Torn, M. S., Meng, L., Mahowald, N. M. and Hess, P.: Barriers to predicting changes in global terrestrial methane fluxes: analyses using CLM4Me, a methane biogeochemistry model integrated in CESM, Biogeosciences, 8(7), 1925–1953, doi:10.5194/bg-8-1925-2011, 2011.

Ringeval, B., de Noblet-Ducoudré, N., Ciais, P., Bousquet, P., Prigent, C., Papa, F. and Rossow, W. B.: An attempt to quantify the impact of changes in wetland extent on methane emissions on the seasonal and interannual time scales, Global Biogeochem Cy, 24, GB2003, doi:10.1029/2008GB003354, 2010.

Robinson, S. and Moore, T.: Carbon and peat accumulation over the past 1200 years in a landscape with discontinuous permafrost, northwestern Canada, Global Biogeochem Cy, 1999.

Roeckner, E., Bäuml, G., Bonaventura, L., Brokopf, R., Esch, M., Giorgetta, M., Hagemann, S., Kirchner, I., kornblueh, L., Manzini, E., Rhodin, A., et al.: The atmospheric general circulation model ECHAM 5. PART I: Model description, Report No. 349 [online] Available from: http://en.scientificcommons.org/8586047, 2003.

Roulet, N. T., Lafleur, P. M., Richard, P. J. H., Moore, T. R., Humphreys, E. R. and Bubier, J.: Contemporary carbon balance and late Holocene carbon accumulation in a northern peatland, Glob Change Biol, 13(2), 397–411, doi:10.1111/j.1365-2486.2006.01292.x, 2007.

Ruddiman, W. F.: The anthropogenic greenhouse era began thousands of years ago, Climatic Change, 61(3), 261–293, 2003.

Rydin, H., K Jeglum, J. and Hooijer, A.: The biology of peatlands,, 343, 2006.

Sasakawa, M., Ito, A., Machida, T., Tsuda, N., Niwa, Y., Davydov, D., Fofonov, A. and Arshinov, M.: Annual variation of CH4 emissions from the middle taiga in West Siberian Lowland (2005–2009): a case of high CH4 flux and precipitation rate in the summer of 2007, Tellus B, 64(0), doi:10.3402/tellusb.v64i0.17514, 2012.

Scanlon, D. and Moore, T.: Carbon Dioxide Production From Peatland Soil Profiles: the Influence of Temperature, Oxic/Anoxic Conditions and Substrate, Soil Sci, 165(2), 2000.

Schimel, J.: Playing scales in the methane cycle: From microbial ecology to the globe, P Natl Acad Sci Usa, 101(34), 12400–12401, doi:10.1073/pnas.0405075101, 2004.

Schneider, J., Grosse, G. and Wagner, D.: Land cover classification of tundra environments in the Arctic Lena Delta based on Landsat 7 ETM+ data and its application for upscaling of methane emissions, Remote Sens Environ, 113(2), 380–391, doi:10.1016/j.rse.2008.10.013, 2009.

Schuldt, R. J., Brovkin, V., Kleinen, T., and Winderlich, J.: Modelling Holocene carbon accumulation and methane emissions of boreal wetlands – an Earth system model approach, Biogeosciences, 10, 1659-1674, doi:10.5194/bg-10-1659-2013, 2013.

Schuur, E., Bockheim, J. and Canadell, J.: Vulnerability of permafrost carbon to climate change: Implications for the global carbon cycle,, 2008.

Segers, R.: Methane Production and Methane Consumption: A Review of Processes Underlying Wetland Methane Fluxes, Biogeochemistry, 41(1), 23–51, 1998.

Smith, L., MacDonald, G., Velichko, A., Beilman, D., Borisova, O., Frey, K., Kremenetski, K. and Sheng, Y.: Siberian Peatlands a Net Carbon Sink and Global Methane Source since the Early Holocene, Science, 303(5656), 353–

356, 2004.

Spahni, R., Wania, R., Neef, L., van Weele, M., Pison, I., Bousquet, P., Frankenberg, C., Foster, P. N., Joos, F., Prentice, I. C. and van Velthoven, P.: Constraining global methane emissions and uptake by ecosystems, Biogeosciences, 8(6), 1643–1665, doi:10.5194/bg-8-1643-2011, 2011.

Stacke, T. and Hagemann, S.: Development and validation of a global dynamical wetlands extent scheme, Hydrol. Earth Syst. Sci. Discuss., 9(1), 405–440, doi:10.5194/hessd-9-405-2012, 2012.

Strack, M. and Waddington, J.: Spatiotemporal variability in peatland subsurface methane dynamics, J Geophys Res, 113(G2), G02010, 2008.

Sundh, I., Nilsson, M., Granberg, G. and Svensson, B. H.: Depth distribution of microbial production and oxidation of methane in northern boreal peatlands, Microb Ecol, 27(3), doi:10.1007/BF00182409, 1994.

Tarnocai, C., Canadell, J. G., Schuur, E. A. G., Kuhry, P., Mazhitova, G. and Zimov, S.: Soil organic carbon pools in the northern circumpolar permafrost region, Global Biogeochem Cy, 23(2), GB2023, doi:10.1029/2008GB003327, 2009.

Taylor, K. E., Stouffer, R. J. and Meehl, G. A.: An overview of CMIP5 and the experiment design, Bulletin of the American Meteorological Society, 93(4), 485, 2012.

Tolonen, K. and Turunen, J.: Accumulation rates of carbon in mires in Finland and implications for climate change, Holocene, 6(2), 171–178, doi:10.1177/095968369600600204, 1996.

Turunen, J., Tomppo, E., Tolonen, K. and Reinikainen, A.: Estimating carbon accumulation rates of undrained mires in Finland – application to boreal and

subarctic regions, The Holocene, 12(1), 69–80, doi:10.1191/0959683602hl522rp, 2002.

van Huissteden, J., van den Bos, R. and Alvarez, I. M.: Modelling the effect of water-table management on CO2 and CH4 fluxes from peat soils, Neth J Geosci, 85(1), 3, 2006.

van Winden, J. F., Kip, N., Reichart, G.-J., Jetten, M. S. M., Op den Camp, H. J. M. and Damste, J. S. S.: Lipids of symbiotic methane-oxidizing bacteria in peat moss studied using stable carbon isotopic labelling, Org Geochem, 41(9), 1040–1044, doi:10.1016/j.orggeochem.2010.04.015, 2010.

Volodin, E.: Methane cycle in the INM RAS climate model, Izvestiya Atmospheric and Oceanic Physics, 2008.

Vuuren, D. P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G. C., Kram, T., Krey, V., Lamarque, J.-F., Masui, T., et al.: The representative concentration pathways: an overview, Climatic Change, 109(1-2), 5–31, doi:10.1007/s10584-011-0148-z, 2011.

Walter, B. and Heimann, M.: A process-based, climate-sensitive model to derive methane emissions from natural wetlands: Application to five wetland sites, sensitivity to model parameters, and climate, Global Biogeochem Cy, 14(3), 745–765, 2000.

Walter, B. P., Heimann, M. and Matthews, E.: Modeling modern methane emissions from natural wetlands 1. Model description and results, J Geophys Res, 106(D24), 34189–34206, doi:10.1029/2001JD900165, 2001a.

Walter, B. P., Heimann, M. and Matthews, E.: Modeling modern methane emissions from natural wetlands 2. Interannual variations 1982–1993, J Geophys Res, 106(D24), 34207–34219, doi:10.1029/2001JD900164, 2001b.

Walter, B. P., Heimann, M., Shannon, R. D. and White, J. R.: A process-based model to derive methane emissions from natural wetlands, Geophys Res Lett, 23(25), 3731, doi:10.1029/96GL03577, 1996.

Wang, J. S., Logan, J. A., McElroy, M. B., Duncan, B. N., Megretskaia, I. A. and Yantosca, R. M.: A 3-D model analysis of the slowdown and interannual variability in the methane growth rate from 1988 to 1997, Global Biogeochem Cy, 18(3), GB3011, doi:10.1029/2003GB002180, 2004.

Wania, R.: Modelling northern peatland land surface processes, vegetation dynamics and methane emissions, Ph. D. thesis, University of Bristol, United Kingdom. 2007.

Wania, R., Ross, I. and Prentice, I. C.: Integrating peatlands and permafrost into a dynamic global vegetation model: 1. Evaluation and sensitivity of physical land surface processes, Global Biogeochem Cy, 23(3), GB3014, doi:10.1029/2008GB003412, 2009a.

Wania, R., Ross, I. and Prentice, I. C.: Integrating peatlands and permafrost into a dynamic global vegetation model: 2. Evaluation and sensitivity of vegetation and carbon cycle processes, Global Biogeochem Cy, 23(3), GB3015, doi:10.1029/2008GB003413, 2009b.

Whalen, S.: Biogeochemistry of methane exchange between natural wetlands and the atmosphere, Environ Eng Sci, 22(1), 73–94, 2005.

Wildi, O.: Simulating Development of Peat Bogs, Vegetatio, 37(1), 1–17, 1978.

Wille, C., Kutzbach, L., Sachs, T., Wagner, D. and Pfeiffer, E.: Methane emission from Siberian arctic polygonal tundra: eddy covariance measurements and modeling, Glob Change Biol, 14(6), 1395–1408, doi:10.1111/j.1365-2486.2008.01586.x, 2008.

Winderlich, J.: Setup of a CO2 and CH4 measurement system in Central Siberia and modeling of its results, Ph. D. thesis, University of Hamburg, Germany, 9 January. 2011.

Winderlich, J., Chen, H., Gerbig, C., Seifert, T., Kolle, O., Lavric, J. V., Kaiser, C., Höfer, A. and Heimann, M.: Continuous low-maintenance CO 2/CH 4/H 2O measurements at the Zotino Tall Tower Observatory (ZOTTO) in Central Siberia, Atmos. Meas. Tech., 3(4), 1113–1128, doi:10.5194/amt-3-1113-2010, 2010.

Worthy, D., Levin, I., Hopper, F., Ernst, M. K. and Trivett, N.: Evidence for a link between climate and northern wetland methane emissions, J Geophys Res, 105(D3), 4031–4038, 2000.

Yu, Z. C.: Northern peatland carbon stocks and dynamics: a review, Biogeosciences, 9(10), 4071–4085, doi:10.5194/bg-9-4071-2012, 2012.

Yu, Z., Beilman, D. W. and Jones, M. C.: Sensitivity of northern peatland carbon dynamics to Holocene climate change, in Geophys. Monogr. Ser., vol. 184, pp. 55–69, AGU, Washington, DC. 2009.

Yu, Z., Loisel, J., Brosseau, D. P., Beilman, D. W. and Hunt, S. J.: Global peatland dynamics since the Last Glacial Maximum, Geophys Res Lett, 37(13), L13402, doi:10.1029/2010GL043584, 2010.

Zhuang, Q., Melillo, J. M., Kicklighter, D. W., Prinn, R. G., McGuire, A. D., Steudler, P. A., Felzer, B. S. and Hu, S.: Methane fluxes between terrestrial ecosystems and the atmosphere at northern high latitudes during the past century: A retrospective analysis with a process-based biogeochemistry model, Global Biogeochem Cy, 18(3), GB3010, doi:10.1029/2004GB002239, 2004.

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