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Uncertainties in modelling CH_4 emissions from northern wetlands in glacial climates: effect of hydrological model and CH_4 model structure

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Abstract. Methane (CH_4) fluxes from northern wetlands may have influenced atmospheric CH_4 concentrations at climate warming phases during the last 800 000 years and during the present global warming. Including these CH_4 fluxes in earth system models is essential to understand feedbacks between climate and atmospheric composition.

Attempts to model CH_4 fluxes from wetlands have previously been undertaken using various approaches. Here, we test a process-based wetland CH_4 flux model (PEATLAND-VU) which includes details of soil-atmosphere CH_4 transport. The model has been used to simulate CH_4 emissions from continental Europe in previous glacial climates and the current climate.

This paper presents results regarding the sensitivity of modeling glacial terrestrial CH_4 fluxes to (a) basic tuning parameters of the model, (b) different approaches in modeling of the water table, and (c) model structure. In order to test the model structure, PEATLAND-VU was compared to a simpler modeling approach based on wetland primary production estimated from a vegetation model (BIOME 3.5). The tuning parameters are the CH_4 production rate from labile organic carbon and its temperature sensitivity.

The modelled fluxes prove comparatively insensitive to hydrology representation, while sensitive to microbial parameters and model structure. Glacial climate emissions are also highly sensitive to assumptions about the extent of ice cover and exposed seafloor. Wetland expansion over low relief exposed seafloor areas have compensated for a decrease of wetland area due to continental ice cover.

1 Introduction

Due to its large Global Warming Potential (GWP), CH_4 plays an important role in the positive feedback mechanisms that amplify global warming (Denman et al., 2007). Most pre-industrial CH_4 emissions arose from wetlands which are situated in broad latitudinal belts in the humid tropics and boreal-arctic zones (Denman et al., 2007). The atmospheric CH_4 concentration (AMC) appears to be closely linked to climate change during the last 800 000 years (Loulergue et al., 2008). During glacial periods the AMC is low, while conversely it increases during interglacials, and rises even more sharply during phases of rapid climate warming. Furthermore besides the glacial-interglacial change, considerable variation also exists on a shorter (millennial) timescale, the stadial-interstadial cycles, where the interstadials are associated with sharp peaks in AMC (Brook et al., 1996; Flückiger et al., 2004).

Proposed mechanisms for the CH_4 concentration rise during interstadials are:

1. variations in the sink strength, caused mainly through CH_4 oxidation by the hydroxyl radical (OH) in the upper atmosphere (Kaplan et al., 2006; Harder et al., 2007),
2. reactions of wetland CH_4 emissions to changes in precipitation and soil temperature (Brook et al., 2000; Van Huissteden, 2004)
3. release of CH_4 from receding ice caps (Wadham et al., 2008) and
4. release of CH_4 from seafloor methane-hydrates (Kennet et al., 2000, 2003).

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Modelling has shown that fluctuations in the OH sink in the atmosphere can be considerable (Valdes et al., 2005; Kaplan et al., 2006; Harder et al., 2007), in particular during episodes of rapid climate change. This may be at least partly responsible for the observed AMC differences, in addition to variations in wetland sources. However, Harder et al. (2007) noted that more constraints are needed on the glacial wetland CH_4 source. The wetland source consisted of both tropical and temperate/high latitude wetlands. Brook et al. (2000) concluded that wetlands north of 30° degrees north are likely to have been a major source. Dällenbach et al. (2000) indicated both tropical and northern wetlands as sources, the latter being responsible for the AMC increases during interstadials preceding the Last Glacial Maximum (LGM). Van Huissteden (2004) showed that middle/high latitude wetlands during glacial times could have increased their source strength due to temperature change alone. The magnitude of third source, release of CH4 derived from subglacial methanogenesis, is very uncertain due to poorly quantified data about the originating microbial metabolism (Wadham et al., 2008). A marine hydrate source is less likely to be a cause of the pre-LGM AMC peaks, based on isotope evidence of glacially preserved CH_4 (Maslin and Thomas, 2003; Schaefer et al., 2006; Sowers, 2006; Fischer et al., 2008).

Present global warming is expected to increase CH_4 emissions from wetlands, particularly from the periglacial and boreal wetland belt. The present-day arctic is strongly influenced by global warming, relative to middle and low latitudes (Serreze et al., 2000; Hassol, 2004). A situation analogous to the last glacial warming episodes may be repeating itself now, due to (a) the thawing of permafrost soils rich in organic carbon, (b) the release of old CH_4 and (c) the conversion of old soil carbon to CH_4 and CO_2 (Zimov et al., 2006; Walter et al., 2007). In addition new CH_4 is being produced by hydrological shifts in wetlands and associated changes in vegetation. In this respect, processes during glacial warming phases may act as an analogue for future warming, although on a global scale it is necessary to take into account the extent of the ice sheets, which were covering the Northern Hemisphere in the past. The geological record contains abundant evidence of such changes in glacial-periglacial wetlands, including widespread melting of glacial permafrost in middle latitudes with thaw lake formation (Van Huissteden, 2004).

To understand the role of the CH_4 feedback mechanism within climate change more completely, improved global scale models of the interaction between climate and wetland CH_4 emissions are necessary. Various approaches modelling emissions at global or continental scale have been attempted (see Sect. 2.1). These models tend to focus on only some of the processes that influence CH_4 emissions (e.g. hydrology, primary production), using assumptions regarding other parts of the process chain. The results depend on the approach used, but only for the modern climate it is possible to assess which modeling approach is most accurate, due to the lack of data regarding CH_4 emissions for past climates.

The goal of this study is to test different modeling approaches, for both modern and past climates on a continental scale, in order to evaluate model structure and which sets of processes are relevant and should be included in large scale models of methane emission. We focus on the climate of the middle part of the Last Glacial – Marine Isotope Stage (MIS) 3 and 2, including the LGM and the present-day climate. Specific attention has been paid to the differences between stadial and interstadial climates.

Our results are based on a regional climate model simulation over Europe (see Sect. 2.1), to allow the model to be refined against available paleogeographic and paleoclimate information (Van Huissteden, 2004). This is a geographically restricted area that does not include all northern latitude wetlands during the Last Glacial, so a complete inventory of wetland CH_4 emission during the last glacial is not possible. However, it serves well for our purpose of model testing, because of comparably minor uncertainties in paleogeographic reconstruction and the availability of detailed climate model simulations.

2 Models

2.1 Previous modelling experiments

Several attempts have been made to model global CH_4 fluxes from wetlands using a bottom-up approach based on modeling the process of CH_4 emission (Christensen et al., 1996; Cao et al., 1996; Gedney et al., 2004; Valdes et al., 2005). Christensen et al. (1996) modelled CH_4 emission as a small (∼3%) percentage of heterotrophic soil respiration derived from the BIOME 3.5 predictive vegetation model (Haxeltine and Prentice, 1996), and an empirical equation (Lloyd and Taylor, 1994). The model of Cao et al. (1996) is process-based, and includes both soil organic matter decomposition and hydrology. Gedney et al. (2004) used a simple equation based on water table depth, soil carbon and temperature, coupled to a land surface hydrology model. However, the CH_4 flux equation includes a global constant that needs to be calibrated to known CH_4 emissions and is therefore not independent from top-down emissions estimates. Models estimating global scale emissions for past (glacial) times have been published by Kaplan, 2002 (for the LGM, based on the approach of Christensen et al., 1996); Van Huissteden, 2004 (LGM and MIS 3 stadials/interstadials for Europe); and Valdes et al., 2005 (LGM, stadials and interstadials, based on Cao et al., 1996). The models of Van Huissteden (2004) and Valdes et al. (2005) are coupled to climate model output. The majority of these models employ only a subset of the processes known to influence wetland CH_4 flux generation; the emphasis being on hydrology (soil water level and wetland extent) and soil temperature. Soil carbon is included in the Cao et al. (1996) model and implicitly by Christensen et al. (1996). Van Huissteden (2004) used a modified version of an existing model (Walter, 2000) which incorporates a more extensive process description, including gas transport in soil and vegetation.

Process models regarding CH_4 fluxes are generally at the plot scale (Granberg et al., 2001; Walter, 2000; Segers and Leffelaar, 2001; Segers et al., 2001). Their use for large-scale modeling of CH_4 fluxes is questionable, since these models place high demands on parameter requirements. These models include key processes such as the formation of CH_4 from labile organic compounds in the anaerobic parts of the soil profile, its oxidation in aerated parts of the soil, and its different transport routes: gas diffusion in soil pores, ebullition, and transport by plants through arenchymous tissues. Like the model of Walter (2000), the Cao's (1996) includes a number of process components, in particular modeling of the hydrology. Necessarily, (untested) assumptions have been made about essential process parameters and both vegetation and soil characteristics in the upscaling of these models.

2.2 Modelling experiments in this study

In this study two contrasting modelling methodologies are compared. First, the process-based plot-scale model of Walter (2000) as implemented in the PEATLAND-VU model (Van Huissteden et al., 2006a) is applied to grid cells of a regional climate model over Europe (see Sect. 2.2.1). This approach permits the testing of effects of different parameterizations of the detailed CH_4 emission processes. Second, a simplified approach is used, that assumes wetland CH_4 emissions are a fraction of wetland net primary production (NPP) as derived from the BIOME 3.5 model. In both cases the model output is the CH_4 flux that would result from a climate model grid cell if the complete cell area was covered with wetlands. To obtain the actual CH_4 emission, the model results are overlaid in GIS with a paleo-wetland map (Fig. 2).

2.2.1 PEATLAND-VU

PEATLAND-VU is a process-based model of CO_2 and CH_4 emissions from peat soils under various climate scenarios. It includes a modified version of the Walter et al. (1996) and Walter (2000) soil profile scale CH_4 flux model (Van Huissteden et al., 2006a). It consists of four sub-models: a soil physics sub-model to calculate temperature (including soil freezing) and water saturation of the soil layers, a CO_2 sub-model, a CH_4 sub-model and an organic production sub-model (Van Huissteden et al., 2006a).

The CH_4 sub-model includes:

1. CH_4 production depending on substrate availability;
2. CH_4 oxidation within the aerated topsoil and during transport of CH_4 in plants;
3. CH_4 transport by diffusion above and below the water table;
4. CH_4 transport by ebullition below the water table;
5. CH_4 transport through plants.

Although all relevant processes are included, some of the processes (in particular CH_4 production and plant transport/oxidation) are not parameterized in close detail as is the case in other models (e.g. Segers and Leffelaar, 2001; Segers et al., 2001). As such, the Walter (2000) model should be characterized as a semi-process model rather than as a full-scale process model.

The model requires as input (a) a soil profile description with organic matter content, dry bulk density and pF curves (soil moisture retention curves) for each soil horizon and (b) a time series for soil surface or air temperature, water table depth and snow cover for each model time step of 1–10 days. To reduce the influence of initial boundary conditions (soil temperature profile, CH_4 concentration profile) the model is run with one spin-up year. The output of the model consists of surface CH_4 fluxes, including contributions from the different transport pathways. The average of one year (excluding the spin-up year) is used for calculating the CH_4 fluxes for one climate model grid cell.

The input data for the PEATLAND-VU model can be obtained from generic data, for example soil profiles and weather station data or climate model output (Van Huissteden et al., 2006a). The model has been shown to be most sensitive to water table and soil temperature input, while sensitivity to variations in soil profile is comparatively little (Van Huissteden et al., 2006a).

According to Walter (2000) the production factor for CH_4 from labile organic compounds in the soil (R_0 in Walter's model description) should be regarded as a tuning parameter to adapt the model to different sites and climatic conditions. Vegetation parameters in PEATLAND-VU that strongly influence CH_4 emission in the model are net primary productivity (NPP), the rate of transport of CH_4 through plants and the fraction of CH_4 oxidized during transport through plant (P_{ox}) (Walter, 2000; Van Huissteden et al., 2006a). NPP influences substrate availability for CH_4 production. It is modelled using an optimum function of soil temperature (Van Huissteden et al., 2006a). Next, the fraction of NPP transferred to labile soil organic matter is determined by the fraction of below-ground organic production f_{roots}, the fraction of f_{roots} (f_{dep}) that is allocated to rhizodeposition (root exudates) and a root senescence factor that determines the amount of dead root material. Sensitivity analysis of vegetation parameters is the subject of a separate paper (Berrittella and Van Huissteden, 2009).

Both temperature and water table level are the strongest drivers for the modelled flux. On this basis the model has been used by Van Huissteden (2004) for simulation of paleo-CH_4 fluxes in Europe during the last glacial period and also to explore the effect that these factors may have on global-scale model simulations.

2.2.2 Water table simulation

The groundwater table strongly influences CH_4 fluxes (Bubier, 1995; Moore et al., 1993). Realistic modelling of hydrological processes, in particular water table position and active layer depth is therefore crucial. Van Huissteden (2004) used a simplified approach, assuming that the water table is lowest in summer, scaled according to seasonal precipitation deficit derived from the climate model. A more realistic approach is that of Cao et al. (1996), who simulated water table by including effects of snowmelt, precipitation and evapotranspiration. An improvement of the water table level has therefore been made by including the hydrology part of the model by Cao et al. (1996). This "bucket type" soil moisture model translates the climate model output of monthly precipitation and temperature into a water table time series used by PEATLAND-VU.

2.2.3 Simplified CH_4 emission model

Since the Walter-Heimann model is essentially plot-based and requires several input parameters that cannot be specified with certainty in large scale modelling, it is useful to compare its output to a more simplified model. Christensen et al. (1996) modelled CH_4 flux as a fixed percentage of ecosystem respiration, based on observations at several flux measurement sites. We adopted a similar approach to construct a simpler model as reference for the Walter-Heimann model.

The BIOME 3.5 output does not contain heterotrophic respiration output; therefore CH_4 flux is assumed to be a fixed percentage of NPP, provided by BIOME 3.5 itself. This assumption is justified by ^{14}C pulse labelling experiments on tundra vegetation by King et al. (2002), indicating that approximately 2–3% of assimilated C is emitted as CH_4. We modelled CH_4 fluxes as 2% of the NPP output of BIOME 3.5. To determine if wetlands could occur given the simulated climate, the water table was simulated as in the previous section. From the simulated water table depth a "dryness" index was derived, being the sum of the water table depths of months with a water table below the surface. If this sum was above -0.1 m, the climate in the related model grid cell was assumed to support extensive wetlands. A potential mismatch of this approach is an underestimation of the CH_4 fluxes. The model of Christensen et al. (1996) shows deviations between the calculated emissions and estimated emissions from an atmospheric inversion model. This is attributed to the presence of high emission hot spots present in arctic wetlands (Panikov et al., 1995). Such emission hotspots may be river plains (Van Huissteden et al., 2005) or thermokarst lakes (Walter et al., 2006, 2007).

3 Modelled climate changes

This study demonstrates not only modelled wetland CH_4 emissions for Last Glacial stadial and interstadial climates, but also for the current climate. However, the focus is on the interstadials of MIS 3, which show the most prominent changes in AMC in the ice core record. Furthermore, the wetland emissions during the LGM stadial are also modelled for comparison, while modelled Modern climate emissions serve to validate the model results against present-day measured emissions.

3.1 Paleogeography: climate and environment

The climate model simulations used here have been derived from the "Stage 3" project (Van Andel, 2002), aimed at simulating the paleo-environment of early modern human migration in Europe. The Stage 3 climate model simulations are based on a nested approach, with a global GCM simulation coupled to a Regional Climate Model (RCM) with 60 km grid cell size over Europe. Both models are coupled to the BIOME 3.5 vegetation model (see Sect. 2.1). The model experiments (Barron and Pollard, 2002) are:

LGM: Last Glacial Maximum conditions;

ST3COLD, simulating a typical "Stage 3 Cold" interval;

ST3ADHOC, similar to ST3COLD, but with forced lower sea surface temperatures;

ST3WARM, simulating a typical "Stage 3 Warm" interval;

MODERN, being a control experiment simulating the modern climate.

The paleogeography (ice distribution, sea level and coastlines) of the MIS 3 and LGM climates (Fig. 1) in the climate model simulations is derived from paleogeographical reconstruction and modeling of sea level and isostasy (Arnold et al., 2002; Barron and Pollard, 2002). We use the same paleogeography for our modeling study. Ice cover and exposed seafloor during glacial times have had a strong effect on wetland distribution.

Wetlands were abundant throughout Europe during the last glacial period wherever topography allowed wetland formation, as testified by peaty deposits particularly in the Northwest European lowlands and North Sea basin, peri-Alpine and intramontane basins (e.g. Van Huissteden, 2004). Basins fill successions in the Northwest European plain have been described in many studies (e.g. Kolstrup and Wijmstra, 1977; Ran and Van Huissteden, 1990; Kasse et al., 1995; Mol, 1997; Van Huissteden et al., 2001, and references therein; Bos et al., 2001). Valley fills with gravel-bed rivers in areas with more pronounced relief also contain intercalated fine-grained beds with organic deposits (Mol, 1997; Van Huissteden et al., 2001; Bos et al., 2001).

The organic deposits in these successions represent sedge mires dominated by *Cyperaceae spp.* and mosses (e.g. Ran, 1990; Bos et al., 2001). Water level was at, or above, the surface for much of the growing season; soil pH was around

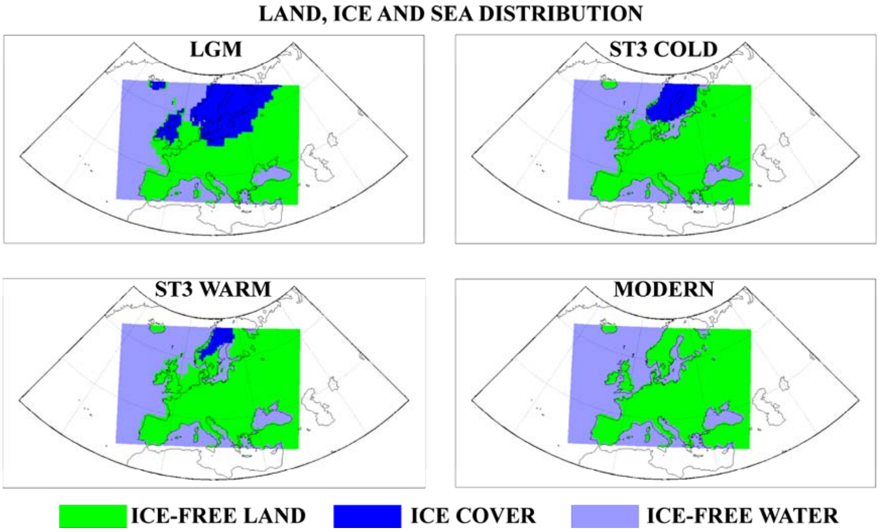

Fig. 1. Paleogeographic maps used for the "Stage 3 Project" climate model simulations and for this study. For references, see the text.

neutral (Ran, 1990; Bos et al., 2001) during this period. The soil pH was well buffered by the input of groundwater or river water, or by the presence of relatively unweathered deposits and deposition of carbonate-rich eolian dust (Van Huissteden, 1990). Reports of sphagnum peat in Middle Weichselian deposits are rare (Behre, 1989). Ombrotrophic sphagnum bogs therefore were largely absent during MIS 3, although temperature should not have been a limiting factor for sphagnum mosses growth.

Wet soils were not been restricted exclusively to topographic lows. Within loess sequences, particularly in Western Europe, abundant evidence has been found of, at least, temporary wet soil conditions in the form of "tundra gley" soils (e.g. Huijzer, 1993; Antoine et al., 2001). When a permafrost table was present any flat terrain was likely to develop poorly drained soils with potential CH_4 emission.

Paleobotanical data indicate a generally open, treeless landscape (Huntley et al., 2003). Organic beds were not only restricted to warm interstadials, but were also deposited also during stadials (Ran and Van Huissteden, 1990). Summer temperatures were generally low (average July temperatures between 7° to 10°C in the Netherlands), but warmer periods did occur (Kolstrup and Wijmstra, 1977; Ran, 1990; Ran et al., 1990; Coope, 2002) with temperatures even close to modern temperatures in Northern Finland (Helmens et al., 2007). These warm spikes, apparently, did not induce any northern immigration of trees or otherwise large-scale adjustment of the vegetation. Evidence of episodic presence of permafrost has been found in the shape of ice wedge casts or polygons and thermokarst lake deposits (Van Huissteden, 1990; Kasse et al., 1995; Van Huissteden et al., 2001).

3.2 Paleogeography: wetland distribution

The model described above results in an estimate of potential CH_4 flux, given the presence of wetlands. A wetland distribution map is therefore necessary to calculate the actual flux (Fig. 2). It is assumed that present-day low-lying and flat areas containing wetlands (also prior to cultivation) were wetlands as well during the last glaciation. This assumption is validated by the widespread occurrence of peat beds dated between 50 000 and 18 000 years in these areas as discussed above.

Delineation of flat areas is based on the GTOPO30 digital elevation model (DEM) which has 30 arc seconds resolution (Verdin and Greenlee, 1996). From this DEM, a slope map was produced.

Since it is difficult to establish a sharp limit between "flat" areas and slope classes that might have supported wetlands, and those that are too steep, a fuzzy classification has been applied, resulting in a map indicating the likeliness of wetland presence. For the same purpose, a sigmoid shaped membership function was also used to define boundaries between 0.05% and 0.25% slopes. A value between 0 and 1 is assigned to each grid cell, which indicates the degree of certainty that the grid cell is completely flat (0 degree slope) and is likely to support wetlands; 0 stands for not flat (no wetlands), 1 for completely flat and covered with wetland if the climate allows sufficiently high water table. The resulting map (Fig. 2) has been checked with the distribution of valleys and basins in The Netherlands and North-West Germany, which contain MIS 3 age deposits indicating wetland presence. Most of the grid cells representing wetlands are, in fact, located in valley and basin positions, while a relatively minor amount are situated in flat upland areas. For the exposed sea

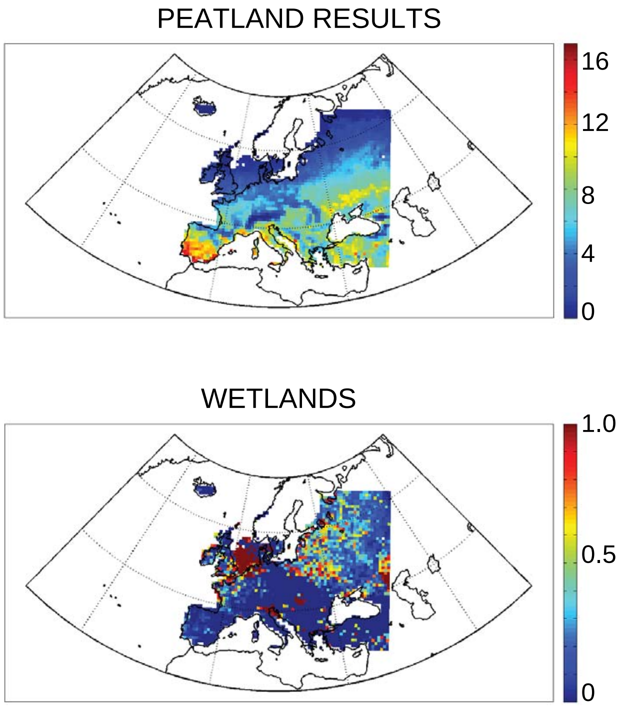

Fig. 2. Example of model output. The upper map displays fluxes of CH_4 as modelled by the PEATLAND-VU model for each climate gridcel (ST3ADHOC climate). Fluxes units are mg m^{-2} hr^{-1}. The lower map is the map for wetland distribution. The color scale ranges from 0 (no wetlands) to 1 (wetland). It indicates for each grid cell the fuzzy membership of the wetland class.

floor and other areas, the seafloor bathymetry based on the 2' ETOPO02 DEM version 2 (USDC/NOAA/NGDC 2006) has been used in a similar way. Both DEM-derived maps (land area and seafloor area) of likely wetland areas are combined into a wetlands map with the same resolution as the climate model grid (60 km grid cells). In this wetlands map only the topography determines the wetland extent; the effect of climate on water table is not included, since the water table is included in the CH_4 flux modelling.

The wetlands map is overlaid in GIS with the modelled fluxes maps based on the climate model grid to obtain a CH_4 flux map. The fuzzy membership values indicating wetland presence for each grid cell are multiplied with the flux calculated by the CH_4 flux model. The CH_4 flux models simulate seasonality; the fluxes are averaged over one year. The fluxes of each grid cell on this flux map are summed to obtain the total flux over the study area.

3.3 Present climate and environment and model validation

We modelled present-day wetland CH_4 fluxes for validation against present-day field data. However, in the model for the modern climate the effects of anthropogenic changes (e.g. widespread drainage of wetlands and agriculture) have not been included. Moreover, the current system is no longer in a steady state because of the forcing imposed by global climate change. We validate the model against point source (plot scale) measurement data because in this way we can restrict the validation to emission of natural wetlands only, excluding drained wetlands. Any larger scale data (e.g. tall tower data, remote sensing of atmospheric CH_4 concentration) would include anthropogenic CH_4 sources.

There is an important difference between present-day periglacial wetlands and the modelled paleo-periglacial wetlands. At present, *Sphagnum* mosses are geographically widespread and constitute a major component of wetlands, including boreal and arctic ones, while Sphagnum was largely absent in the wetlands during the studied part of the last glacial (see Sect. 3.1). An important effect of *Sphagnum sp.* is a reduction of the CH_4 emissions to the atmosphere by means of symbiosis with methanotrophic bacteria (Raghoebarsing et al., 2005). This enhanced CH_4 oxidation in *Sphagnum* mosses may have a marked effect on net emission, as large as 40% to 95% of the soil CH_4 production. This difference must be taken into account when modelled data are compared with present-day measured values. Sensitivity analysis of vegetation parameters will be the subject of a subsequent paper (Berrittella and Van Huissteden, 2009).

4 Results

4.1 Comparison of modelled values with data for MODERN climate

The comparison between modelled fluxes and those measured on northwest European flux measurement sites gives similar results. Although the sites for wetlands and mires are quite distant geographically, the model runs performed with standard values for all parameters, are in the same order of magnitude as the measured values and show a good approximation (Figs. 3 and 4). The model results agree better with the wetland data than with the hummocky mire data, because the above mentioned effect of CH_4 oxidation in *Sphagnum* mosses has not been taken into account in the model.

4.2 Sensitivity to CH_4 production parameters in PEATLAND

Figure 2 shows the topography-based estimate of wetland presence and the modelled CH_4 flux per climate model grid cell for LGM and modern climate, using PEATLAND-VU with modelled water table. Relatively large fluxes have been modelled for southern European sites. However, wetland extent in these areas is generally little, while in northern Europe extensive areas with flat topography have supported wetlands. During the glacial climates, extensive areas of flat seafloor, exposed by the low glacial sea level, are shown in the model output, while on the other hand large land areas are

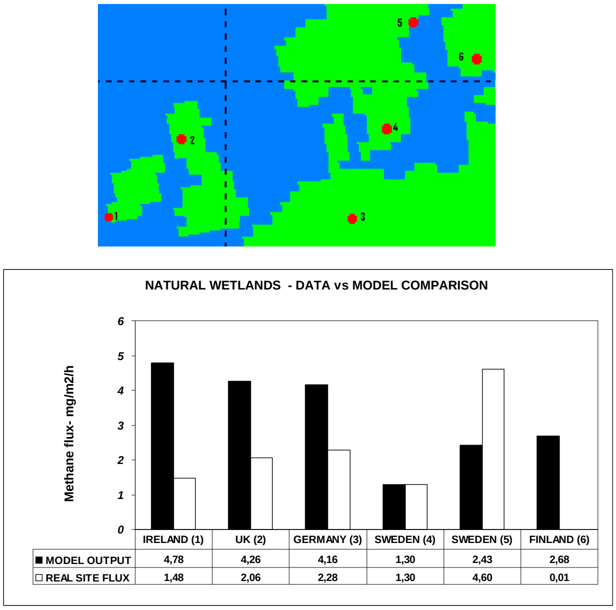

Fig. 3. Overview of measured fluxes versus modelled values. The wetland sites include swamps and hollows with shallow water table and dominant sedges and mosses. Site reference are: (1) Glencar, Ireland from Laine at al. (2007); (2) Loch More, Scotland from McDonald et al. (1998), (3) Mt. Broken, Germany from Tauchnitz et al. (2008); (4) ASA Exp. Forest, Sweden from Von Arnold et al. (2005), (5) Stor-Åmyran , Sweden from Sundh et al. (1995), (6) Vesijako, Finland from Minkkinen et al. (2007).

ice-covered and do not contribute to CH_4 sources. Figure 5 shows the modelled fluxes for the different climate model experiments.

The fluxes are least for the cold LGM climate, with its relatively large extent of ice cap. The fluxes of the ST3WARM and MODERN climate are roughly equal (ST3WARM being the largest), with a comparatively large contribution from exposed seafloor in ST3WARM.

The Q10 factor is defined as the relative increment in bacterial metabolism after an increase in temperature of 10°C (Van Hulzen et al., 1999). It is included in the Walter (2000) model for both CH_4 formation and consumption (related to methanogenic and methanotrophic bacteria) and it is therefore the model parameter representing a direct link between the modelled climates and the produced CH_4. The value of Q10 factor for CH_4 formation is generally higher than the one for CH_4 oxidation (Walter, 2000) so CH_4 formation is expected to be strongly influenced by climate change. However, a wide range of values (2–16) for Q10 related to CH_4 formation has been cited in the literature (Walter, 2000). Therefore we conducted a series of experiments with different Q10 values for the PEATLAND-VU/water table simulation combination for all climates. The fluxes for land areas and exposed seafloor areas have been calculated separately.

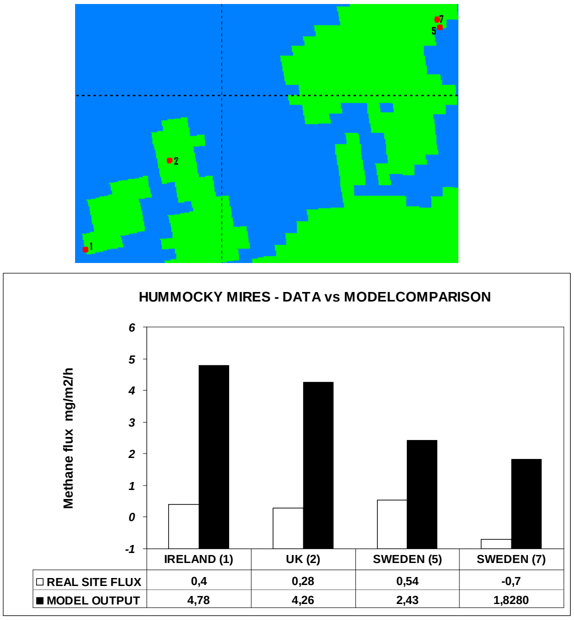

Fig. 4. Overview of mires measured fluxes versus modelled values. The hummocky mires include submerged Sphagnum vegetation in pools. Site reference are: (1) Glencar, Ireland from Laine at al. (2007); (2) Loch More, Scotland from McDonald et al. (1998), (5) Stor-Åmyran , Sweden from Sundh et al. (1995), (7) Vindeln, Sweden from Granberg et al. (2001).

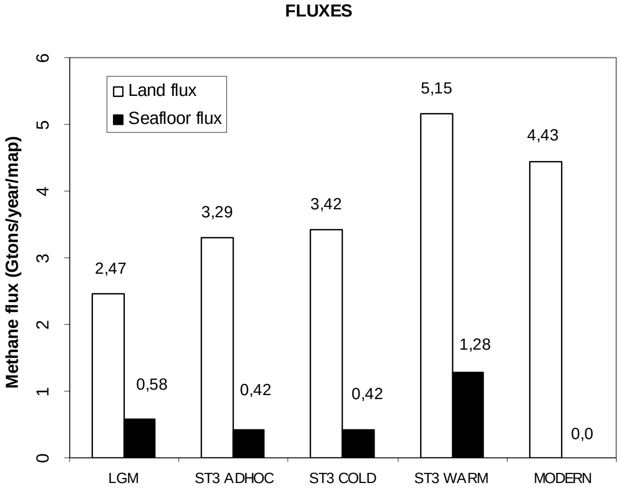

Fig. 5. Modelled fluxes using PEATLAND with modelled water table. Fluxes from present land areas and exposed seafloor areas are displayed separately.

In Fig. 5 the modelled yearly emission over the study area is shown for a CH_4 production Q10 of 3, a value that performs well for validations of PEATLAND-VU (Van Huissteden et al., 2006b). Figure 6 shows a simulation with different Q10 values for the MIS 3 Warm climate. The contribution of land areas rises with higher Q10; while the exposed seafloor areas do not display a strong increase.

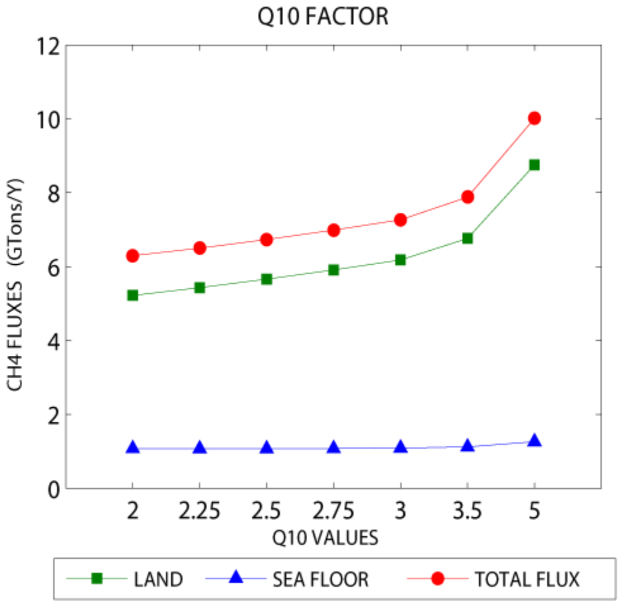

Fig. 6. MIS 3 Warm Climate. The two source areas (land and seafloor) show a contrasting reaction: the land flux increases exponentially, while the exposed seafloor flux hardly rises with higher Q10.

The R_0 factor (μM/h) relates CH_4 production to the labile organic matter fractions (exudates, dead roots, litter) in the model. It is used as a tuning parameter of the model by Walter (2000). In practice, it does not differ significantly when the model is calibrated with data from various wetland sites (Van Huissteden et al., 2006a; Van Huissteden et al., 2009). To test the influence of this parameter, runs have been performed with a fixed water table (cf. Van Huissteden, 2004). The result (Fig. 7) shows a linear increase of CH_4 flux for low values of R_0. This increase diminishes with higher values. The increase with higher R_0 is somewhat stronger for the land areas than for the seafloor areas.

4.3 Sensitivity to hydrology and CH_4 emission model structure

Methane fluxes in periglacial wetlands are highly sensitive to the level of the water table (e.g. Van Huissteden et al., 2005; Bubier, 1995; Moore et al., 1993). On the other hand the water table position is difficult to model accurately for paleoclimate simulations (Cao et al., 1996). The results of the two different approaches to water table modelling outlined in Sect. 2.2.2 (“Simple Hydrology” after Van Huissteden, 2004 and “Modeled water table” after Cao et al., 1996) are displayed in Fig. 8. For all climates, the total fluxes are very similar, although the simple water table model results in lower emissions, 6 to 18% less, that those of the Cao et al. (1996) model water table.

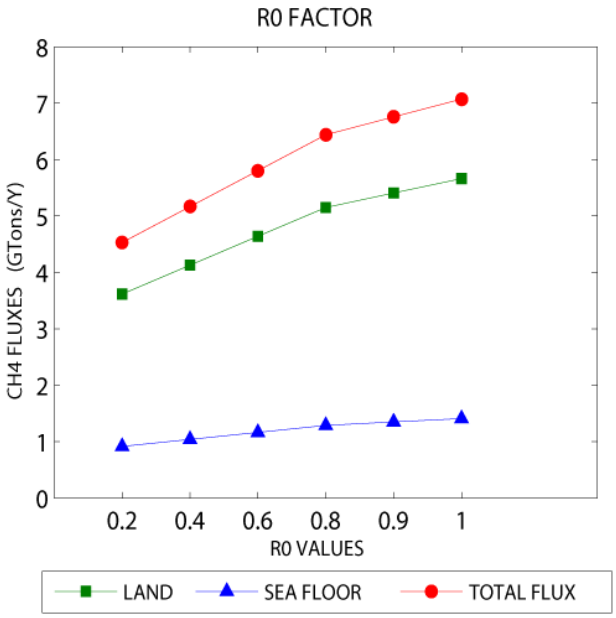

Fig. 7. Model runs indicating the influence of the CH_4 production rate factor R_0. The runs have been performed with a Q10=3.0, for the warm MIS 3 climate.

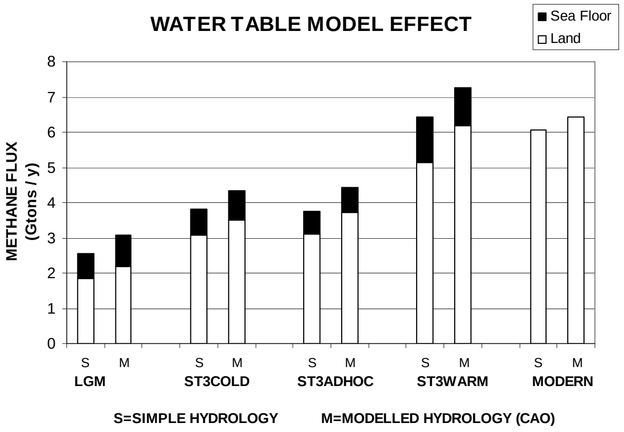

Fig. 8. Effects of water table model. Simple hydrology as applied by Van Huissteden (2004); water table model cf. Cao et al. (1996). Values refer to the total study area.

The effects of the structure of the CH_4 emissions model was investigated by comparing the simple CH_4 emission model outlined in section 2.2 with PEATLAND-VU. Results for the same climate (Fig. 8) differ by at least 1 GTon compared with emissions from the simple model. The pattern of differences among the climates also changes. With the simple model, (Fig. 9) emissions during the modern climate are twice as much as those of the glacial climates, while among the glacial climates the differences are hardly perceptible (few decimals, see Table 1) compared to PEATLAND-VU.

Table 1. Comparison between a simple BIOME NPP-based model of CH_4 fluxes and fluxes modelled using PEATLAND-VU and modelled water table. Corresponding values are reported in Fig. 1.

SIMPLE MODEL	Land flux	Seafloor flux	PEATLAND	Land flux	Seafloor flux
LGM	1.55	0.61	LGM	2.46	1.55
ST3 ADHOC	1.23	0.80	ST3 ADHOC	3.29	1.23
ST3 COLD	1.45	0.64	ST3 COLD	3.42	1.45
ST3 WARM	1.72	0.86	ST3 WARM	5.15	1.72
MODERN	6.09	0	MODERN	4.43	0

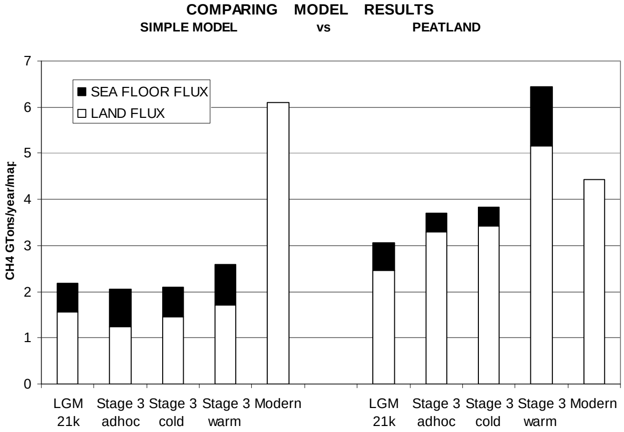

Fig. 9. Comparison between a simple BIOME NPP-based model of CH_4 fluxes and fluxes modelled using PEATLAND-VU and modelled water table (Cao et al., 1996). Corresponding values are reported in the Table 1.

5 Discussion

It has been assumed that one of the causes of low CH_4 emission during glacial stadials was the extent of large ice sheets (e.g. Harder et al., 2007). However, exposed seafloor wetlands may have compensated at least partly for this loss of wetland area as is shown by our model. These areas probably consisted of largely low relief lowlands, capable of supporting extensive wetlands. Indeed, in the North Sea basin and northern Adriatic basin, glacial peats have been found with an MIS 3 age (Van Huissteden, 1990; Amorosi et al., 1999).

The two most important parameters through which climate change is expected to influence wetland CH_4 emission are temperature and water table changes. In our model setup temperature effects are governed by the CH_4 production Q10 relation in the PEATLAND-VU model and by the water table by the way in which the relationship between water table and climate is modelled.

It is surprising that the Q10 value specifically enhances the fluxes from the present-day land areas, but not the ones from the exposed seafloor areas for the glacial climates. The reason is the much larger variation of the elevation of the land areas compared to the exposed seafloors, with colder and more continental climates. In the land areas there are considerable areas of higher elevation with a corresponding colder climate. In particular, elevated plateau areas (e.g. the Ardennes) and intramontane basins may have sustained considerable wetland areas that contributed to CH_4 fluxes. Fluxes from areas with a colder climate will be more closely affected by a higher Q10.

Two sets of model runs were carried out using common environmental parameters and one of the two water table models ('Simple hydrology cf. Van Huissteden, 2004 and water table model of Cao et al., 1996). With the water table simulated by the Cao et al. (1996) model, the fluxes of all glacial climates are slightly higher, with the ST3WARM CH_4 fluxes moderately (11%) larger than those of the modern climate (Fig. 8). The differences between the colder glacial climates are relatively small in both cases.

Apparently, the Cao model favors higher water tables or more extensive wetlands for the glacial climates. The small differences between the simple and modelled water table simulations suggest that the PEATLAND-VU model is not very sensitive to water table input as long as the amplitude and average values for the yearly water table variation are modelled correctly. The values for both approaches are consistent with those published by Van Huissteden (2004), although there is a general increase in the land fluxes and a decrease in the seafloor fluxes.

5.1 Model structure

A comparison of the output of the simpler model with that of PEATLAND shows the considerable influence of model structure. With the simple model, the contrasts between the glacial climates are smaller. The largest flux is generated by the modern climate. The proportion of fluxes from exposed seafloor is relatively large, varying between 39 to 65% of the values coming from land. With PEATLAND the fluxes of the glacial climates are higher, there are larger differences between warm and cold climates, and the proportion of exposed seafloor fluxes is smaller, as illustrated in Fig. 9 and Table 1.

The difference is generated by the dependency of the simple model on the BIOME 3.5 NPP estimates, which are considerably higher for the Modern climate than for the glacial climates. The "MIS Warm" climate shows fluxes that are higher than that of the modern climate. This difference between ST3WARM and MODERN is partly caused by the addition of fluxes from exposed seafloor areas; in the paleogeography of the ST3WARM climate the Scandinavian ice cap is very small, as confirmed by paleodata. Helmens et al. (2007) indicate the existence of ice-free conditions in Arctic Finland during an OIS3 interstadial. Furthermore, the simulated water tables in the lowlands of Southeastern

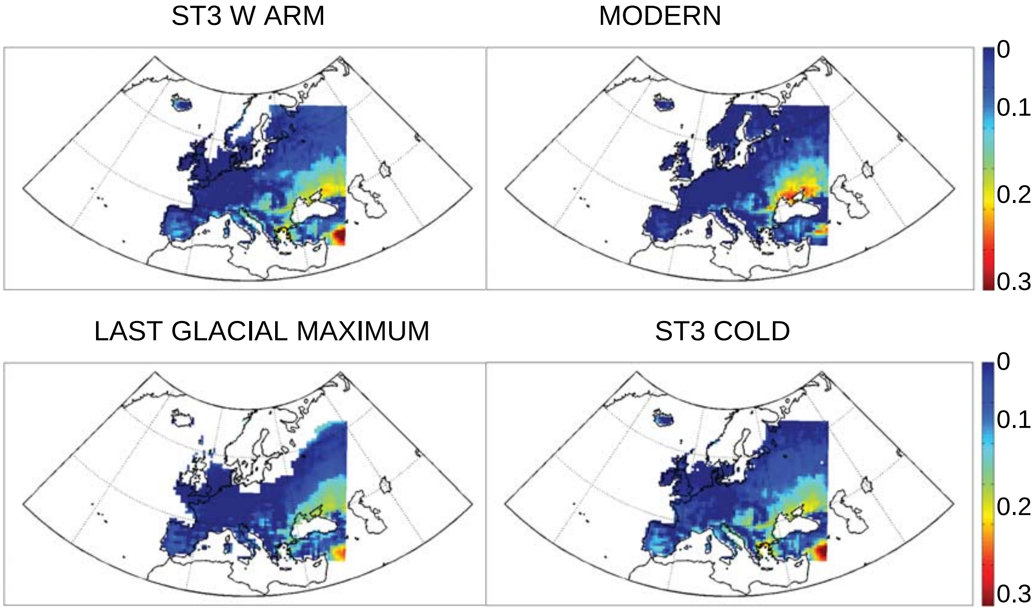

Fig. 10. Simulated water table for the climate scenarios based on the Cao et al. (1996) model. Units are meters below soil surface.

Europe are somewhat higher during the glacial climates than those for the modern climate, which causes larger fluxes in these areas (Fig. 10).

6 Conclusions

In previous attempts to model global and continental scale CH_4 fluxes, the effects of model structure and parameterization have rarely been considered. This study shows that, in particular, model structure can generate large differences. This is not unexpected. However, the differences also affect modeling of fluxes for different climates in unequal ways. Using a simple NPP-based approach causes smaller difference between glacial climates and a stronger contrast between glacial interstadial climates and modern warm climate.

The hydrological part of the model chain has a smaller effect. Modelling of water table position and wetland extent should be as realistic as possible, given the availability of topographic and soil data, and should provide the right timing of the minimum, maximum and average of the water table depth, but smaller temporal differences apparently do not have a conspicuous effect.

In addition, paleogeography seems to have a considerable influence on modelled emissions. Our model shows that the contribution of exposed seafloor wetlands may be large. On the one hand, wetland area is decreased by ice cap extension in glacial climates; on the other it is expanded by wetlands on the exposed seafloor. This holds in particular for glacial climates older than the LGM. For the LGM, the extent of ice caps, glacial lakes and shorelines is relatively well known, but for older stadials and interstadials this paleogeography is less precisely defined.

Basic parameters relating microbial CH_4 production and oxidation to climate are also important. However, the effect of methanogenesis Q10 is relatively small; there is more uncertainty in the CH_4 production rate itself. So far, past experience with modeling fluxes from different wetland sites do not indicate large between-site differences (Van Huissteden, 2006).

Despite these uncertainties of large scale CH_4 flux modeling, the results converge in a range of values that suggest that order-of-magnitude approaches through modelling of CH_4 fluxes under different climate conditions are possible. Our study has been restricted to Europe because it serves as a model sensitivity test. For a full comparison of modeled values with ice core data (e.g. Brook et al., 2000; Harder et al., 2007), glacial wetlands over the Asian continent and North America should be included as well as Europe. However, in that case a larger amount of paleogeographic uncertainty also arises, in particular with respect to ice sheet extent, adding further to the model uncertainty indicated in our study.

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