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Uncertainties in modeling 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 800 000 years and at 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 been undertaken previously 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 different glacial climates and the present climate.

This paper displays results on the sensitivity of modeling glacial terrestrial CH_4 fluxes to basic tuning parameters of the model, to different approaches in modeling of the water table, and to model structure. For testing the model structure, PEATLAND-VU has been compared to a simpler modeling approach based on wetland primary production estimated from a vegetation model (BIOME). 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, and sensitive to microbial parameters and model structure. Glacial climate emissions are also highly sensitive to assumptions on the extent of ice cover and exposed seafloors. Wetland expansion on low relief exposed seafloor areas, may 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 as a positive feedback to global warming (Denman et al., 2007). Most pre-industrial CH_4 emission arises from wetlands, 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 strongly linked to climate change during the last 800 000 years (Loulergue et al., 2008). During glacials the AMC is low, while conversely it increases during interglacials, and rises even more sharply during phases of rapid climate warming. Next to the glacial-interglacial change, strong variation exists also on a shorter (millennial) timescale, the stadial-interstadial cycles of which the interstadials produce 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, mainly CH_4 oxidation by the OH radical in the upper atmosphere (Harder et al., 2007),

2. Reactions of wetland CH_4 emission to changes in precipitation and soil temperature (Brook et al., 2000; Van Huissteden, 2004) and

3. Release of CH_4 from seafloor methane-hydrates (Kennet et al., 2000, 2003).

Modeling has shown that fluctuations in the OH sink in the atmosphere can be considerable (Valdes et al., 2005; Harder et al., 2007), in particular at episodes of rapid climate change. This may be at least partly responsible for the observed AMC differences, beside variations in wetland sources. However, Harder et al. (2007) note that more constraints are needed on the glacial wetland CH_4 source. The wetland source consists of both tropical and temperate/high latitude wetlands. Brook et al. (2000) concluded that wetlands north of 30° degrees north should have been a major source. Dällenbach et al. (2000) indicate both tropical and northern wetlands as sources, the latter being responsible for the AMC increases at interstadials preceding the Last Glacial Maximum (LGM). Van Huissteden (2004) showed that middle/high latitude wetlands during glacial times should have been able to increase their source strength by temperature change alone. A marine hydrate source is less likely for the pre-LGM AMC peaks, based on isotope evidence of glacially preserved CH_4 (Maslin and Thomas, 2003; Schaefer et al., 2006; Sowers, 2006).

Present global warming is expected to increase the CH_4 emission 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 now, due to the melting of permafrost rich in organic carbon, due to the release of old CH_4 and conversion of old soil carbon to CH_4 and CO_2 (Zimov et al., 2006; Walter et al., 2007). In addition new CH_4 may be produced by hydrological shifts wetlands and changes in vegetation. In that respect, processes during glacial warming phases may act as an analogue for future warming. The geological record contains abundant evidence for 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 to climate change more completely, improved models of the interaction between climate and wetland CH_4 emission on global scale are necessary. To date, various approaches at global or continental scale modeling of emissions have been attempted (see below). Almost necessarily, these models tend to focus on only part of the processes that influence CH_4 emission (e.g. hydrology, primary production), using assumptions on other parts of the process chain. The results are depending on the approach that has been used, and only for the modern climate it is possible to assess which modeling approach is most accurate, due to the lack of observations on CH_4 emission for the other climates. The goal of this study is to test different modeling approaches, for both modern and past climate on a continental scale, 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 Last Glacial – Oxygen Isotope Stage (OIS) 3 and 2, including the LGM and the present-day climate. Specific attention has been paid to the differences between stadials and interstadials climate.

Our model results are based on a regional climate model simulation over Europe (see below), 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 modeling 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) have 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) use a simple equation based on water table, soil carbon and temperature, coupled to a land surface hydrology model. However, the CH_4 flux equation contains a global constant which has to be calibrated to known CH_4 emission and is therefore not independent from top-down emission 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 OIS3 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. Most 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 more

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extensive process model (Walter, 2000).

Process models for modeling CH_4 fluxes are generally plot-scale models (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 have 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 trough arenchymous tissues. The model by Van Huissteden (2004) is based on the Walter (2000) model; also the model of Cao et al. (1996) includes a number of process components, in particular modeling of the hydrology. Necessarily, (untested) assumptions have been made of essential process parameters and vegetation and soil characteristics in upscaling of these models.

2.2 Modeling experiments in this study

In this study two contrasting modeling approaches are compared. 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 below), representing an approach which allows to test the effects of different parameterizations of the detailed CH_4 emission processes. For comparison, a simplified approach is being used by assuming that wetland CH_4 emission is a fraction of wetland net primary production (NPP). 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 overlain in GIS with a paleo-wetland map (see below).

2.2.1 PEATLAND-VU

PEATLAND-VU is a process-based model of CO_2 and CH_4 emission from peat soils at various climate scenarios. It includes a modified version of the 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 is based on Walter et al. (1996) and Walter (2000). The model of Walter (2000) 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 large 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 being a full-scale process model.

The model requires as input a soil profile description with organic matter content, dry bulk density and pF curves (soil moisture retention curve) for each soil horizon and time series for soil surface or air temperature, water table depth and snow cover for each model time step of 1–10 days. To diminish 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

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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 PEATLAND-VU Model can be obtained from generic data, e.g. soil profiles and weather station data or climate model output (Van Huissteden et al., 2006a). The model has shown to be most sensitive to water table and soil temperature input, while sensitivity to variations in soil profile is comparatively small (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 NPP, the rate of transport of CH_4 through plants and the fraction of CH_4 oxidized during plant transport (P_{ox}) (Walter, 2000; Van Huissteden et al., 2006a). NPP influences substrate availability for CH_4 production. It is modelled using a simple function of soil temperature, (Van Huissteden et al., 2006a). Next, the fraction of NPP transferred to labile organic compounds 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 seperate 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 and also to explore the effect that these factors may have on global-scale model simulations.

2.2.2 Water table simulation models

The groundwater table strongly influences CH_4 fluxes (Bubier, 1995; Moore et al., 1993). Realistic modeling of hydrologic processes, in particular water table position and active layer depth is therefore crucial. Van Huissteden (2004) used a simplified

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approach, assuming a lowest water table in late summer and maximum water table depth, scaled according to summer precipitation deficit derived from the climate model. A more realistic approach is that of Cao et al. (1996), who simulated water table 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 transfers the climate model output of monthly precipitation and temperature into a water table time series used by PEATLAND-VU.

2.2.3 Simplified model

Since the Walter-Heimann model is essentially a plot-based model and requires several input parameters that cannot be specified with certainty in large scale modeling, 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 output does not contain heterotrophic respiration output; therefore CH_4 flux is assumed to be a fixed percentage of NPP, provided by BIOME itself. This assumption is justified by ^{14}C pulse labelling experiments on tundra vegetations 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. 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 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) model shows deviations between the calculated emissions and estimated emissions from an atmospheric inversion model. This is attributed to the presence of high emission hot

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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 Modeled climate changes

This study shows not only modelled wetland CH_4 emissions for Last Glacial stadial and Interstadial climates, but also for the present-day or modern climate. However, the focus is on the interstadials of OIS 3, which show the most prominent changes in AMC in the ice core record. Furthermore, also the wetland emissions during the LGM interstadial are modelled for comparison, while the Modern climate emissions serve to validate the model results against present-day 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) over Europe. Both models are coupled to the BIOME vegetation model (Haxeltine and Prentice, 1996). 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.

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The paleogeography (ice distribution, sea level and coastlines) of the OIS 3 and LGM climates (Fig. 1) in the climate model simulations is derived from paleogeographical reconstruction and modeling of sealevel 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 potential wetland distribution.

Wetlands occurred abundantly throughout Europe during the last glacial 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). Basin 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 stronger 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* and mosses (e.g. Ran, 1990; Bos et al., 2001). Water level has been at, or above the surface for much of the growing season, soil pH has been around neutral (Ran, 1990; Bos et al., 2001). 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 have been largely absent during OIS 3, although temperature should not have been a limiting factor for *Sphagnum* growth.

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

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Palynological data indicate a generally open, treeless landscape (Huntley et al., 2003). Organic beds are not only restricted to warm interstadials, but were deposited also during stadials (Ran and Van Huissteden, 1990). Summer temperatures were generally low (July temperatures between 7° to 10°C in the Netherlands), but warm spikes 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 result in a potential CH_4 flux, given the presence of wetlands. A wetland distribution map therefore is 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 occurring of glacial peat beds in these areas as discussed above.

Delineation of flat areas is based on the GTOPO30 digital elevation model (DEM) which has a 30″ resolution (Verdin and Greenlee, 1996). From this DEM, a slope map has been 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 probabilistic map indicating the likeliness of wetland presence. For the same purpose, also a sigmoid shaped membership function was used to define boundaries between 0.05% and 0.25% slope. The resulting map has been checked with the distribution of valleys and basins in The Netherlands and NW Germany, which contain OIS 3 age deposits indicating wetland presence (Fig. 2). Most of the grid cells representing wetlands are in fact located in

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valley and basin positions, while a relatively minor amount is situated in flat uplands areas. For the exposed sea floor and other areas, the seafloor bathymetry based on sea level changes over time has been used in a similar way.

3.3 Present climate and environment

A model of present-day wetland CH_4 fluxes has been included to be validated 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 actual system is no longer in a steady state because of the forcing imposed by the global climate change.

There is an important difference between present-day periglacial wetlands and the modelled paleo-periglacial wetlands (see above). At present, *Sphagnum* mosses are geographically widespread and constitute a major component of wetlands, including boreal and arctic ones. An important effect of *Sphagnum* 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* may have a strong effect on net emission, rated between 40 and 95% of the soil production. This difference has to be taken into account when modelled data are compared with present-day measured values. Sensitivity analysis of vegetation parameters is the subject of a second paper (Berritella and Van Huissteden, 2009).

4 Results

4.1 Comparison of modelled values with data for MODERN climate

The comparison between the modelled fluxes and measured ones on northwest European flux measurement sites gives a positive result. Although both set of sites for wetlands and mires are quite distant geographically, the runs performed with standard

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values for all parameters are in the same order of magnitude of the measured values and show a good approximation (Figs. 3 and 4). The model results are better in agreement with the wetland data than with the hummocky mire data, because the abovementioned effect of CH_4 oxidation in Sphagnum 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 wetlands 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 small, while in northern Europe extensive areas with flat topography exist that have supported wetlands. In the glacial climate, extensive areas of flat seafloor, exposed by the low glacial seal level, are shown in the model output, while on the other hand large land areas are 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 smallest for the cold LGM climate, with is relatively large ice cap extent. 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 Q10 factor for CH_4 formation is generally higher than the one for CH_4 formation (Walter, 2000) so CH_4 formation is expected to react much strongly to climate change. However, a wide range of values (2–16) for CH_4 formation Q10 has been cited in literature (Walter, 2000). Therefore we conducted a series of experiments with different Q10 values for

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the PEATLAND-VU/water table simulation combination for all climates. The fluxes for land areas and exposed seafloor areas have been calculated 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 in validations of PEATLAND-VU (Van Huissteden et al., 2006b). Figure 6 shows a simulation with different Q10 values for the OIS3 Warm climate. The contribution of land areas rises with higher Q10 while the exposed seafloor areas do not display a strong increase.

The R_0 factor (μM/h) relates CH_4 production rate to the labile organic matter fractions in the model (exudates, dead roots, litter). It is indicated as a tuning parameter of the model by Walter (2000). In practice, it does not differ strongly when the model is calibrated on data from various wetland sites (Van Huissteden et al., 2006a, 2009) To test the influence on this parameter, runs have been performed with 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 becomes smaller for 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

Methane (CH_4) fluxes in periglacial wetlands are highly sensitive to water table (e.g. Van Huissteden et al., 2005; Bubier, 1995; Moore et al., 1993). On the other hand water table position is difficult to model exactly in paleoclimate simulations (Cao et al., 1996). We therefore tested two different approaches to water table modeling, the approach of Van Huissteden (2004) ("Simple Hydrology" hereafter) and the model of Cao et al. (1996) ("Modeled water table"). Outputs are displayed in Fig. 8. For all climates, the total fluxes are very similar, although simple water table model results in slightly lower emissions that those of the Cao model water table.

The effects of model structure of the CH_4 emission model has been investigated by comparing the PEATLAND-VU model with a simple model outlined above. This model assumes CH_4 emission to be a small percentage of wetland NPP. A simple model is supposed to offer a faster estimation of a complex system, and will suffer less from the parameter uncertainty in the more complex model. Results for the same climate (Fig. 8) differ at least about 1 GTon with emissions for the simple model being smallest. Also the pattern of differences among the climates is changed. With the simple model, emission of the modern climate by far exceeds that of the glacial climates, while among the glacial climates the differences are considerably smaller than with PEATLAND-VU.

5 Discussion

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

The two most important parameters by 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 Walter (2000) model, the water table by the way in which the relation between water table and climate is modelled.

It is surprising that the Q10 value strongly influences the fluxes from the present-day land areas, but not the fluxes from the exposed seafloor areas for the glacial climates. The cause 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 occur considerable areas of higher elevation, with a colder climate. In particular elevated plateau areas (e.g. the Ardennes) and intramontane basins may sustain considerable wetland areas that contribute to CH_4 fluxes. Fluxes from areas with a colder climate will be more strongly affected by a higher Q10.

Two run sets have been done using the same environmental parameters and a different water table model. In one case the lowest (summer) water table is assumed to be proportional to summer precipitation deficit (Van Huissteden, 2004), in the other one it is modelled using the Cao et al. (1996) model. 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 slightly higher than those of the modern climate. 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 the amplitude and average values for the yearly water table variation are modelled correctly. The values are for both approaches compatible 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 simpler model with that of PEATLAND shows the large 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. With PEATLAND the fluxes of the glacial climates are higher, there are larger differences between the warm and cold climates, and the proportion of exposed seafloor fluxes is smaller, as reported in Fig. 9 and Table 1.

The difference is generated by the dependency of the simple model on the BIOME NPP estimates, which are considerably higher for the Modern climate than for the Glacial climates. The "OIS3 Warm" climate shows fluxes that are higher than that of the modern climate. This difference between ST3WARM and MODERN is partly caused by the considerable addition of fluxes from exposed seafloor areas; in the paleogeography of the ST3WARM climate, the Scandinavian ice cap is very small (probably a realistic estimate, see Helmens et al., 2007, who indicate the existence of ice-free conditions in Arctic Finland). Also, the simulated water tables in the lowlands of South-

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eastern Europe are somewhat higher in the glacial climates than those for the modern climate and this causes larger fluxes in these areas (Fig. 10).

6 Conclusions

In previous attempts at modeling global and continental scale of CH_4 fluxes, the effects of model structure and parametrization rarely have 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. Modeling 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 minimum and maximum and average of the water table, but smaller temporal differences apparently do not have a strong effect.

Also paleogeography has a considerable influence. Our models show 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 hand 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 CH4 production and oxidation to climate are also important. However, the effects of Q10 (relation microbial reaction rate to soil temperature) is relatively small. More uncertainty resides in the CH_4 production rate itself. However, past experience with modeling fluxes from different wetland sites do not indicate large between-site differences of the production rate (Van Huissteden, 2006).

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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 by modeling of CH_4 fluxes under different climate conditions is 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 besides the European continent. However, in that case also a larger amount of paleogeographical uncertainty arises, in particular with respect to ice sheet extent, adding up to the model uncertainty indicated in our study.

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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

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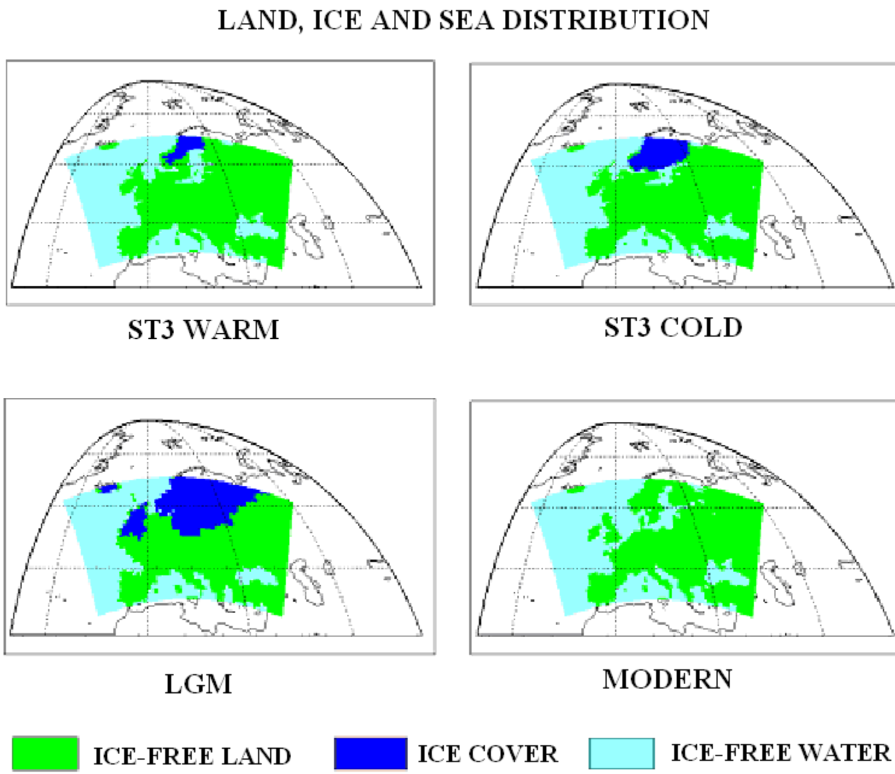

Fig. 1. Climate model paleogeography of the "Stage 3 Project" climate model simulations.

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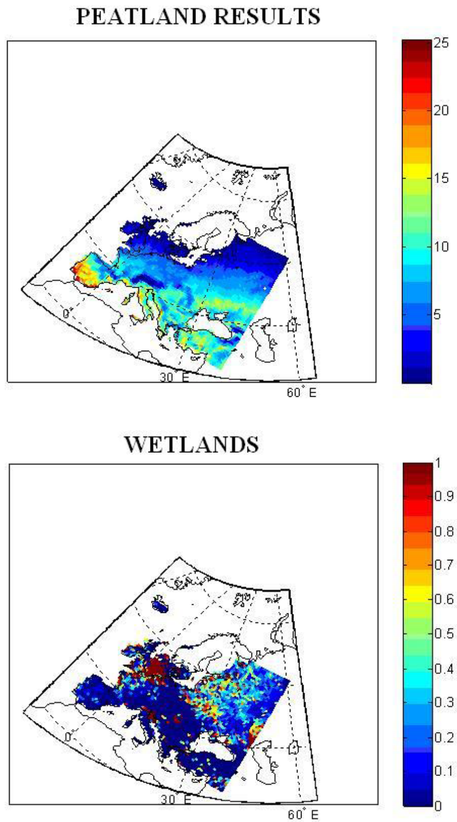
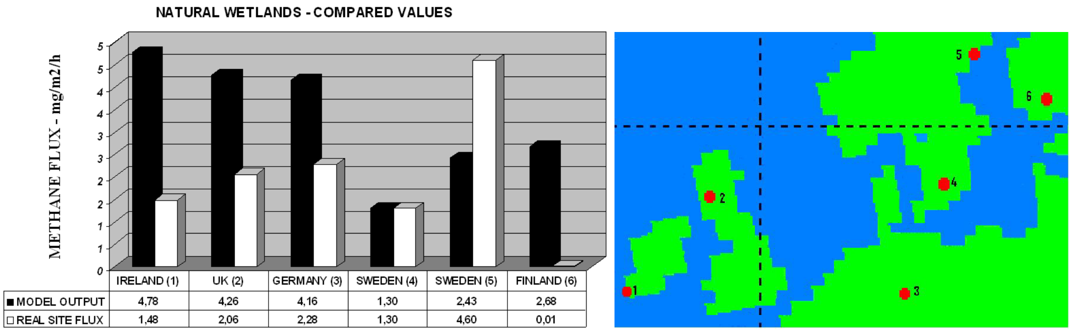


Fig. 2. Example of model output. The upper map displays simulated fluxes of peatland for each climate model gridcel (ST3ADHOC climate). The lower map shows the model results after overlay with the wetland distribution map.



	IRELAND (1)	UK (2)	GERMANY (3)	SWEDEN (4)	SWEDEN (5)	FINLAND (6)
■ MODEL OUTPUT	4,78	4,26	4,16	1,30	2,43	2,68
□ REAL SITE FLUX	1,48	2,06	2,28	1,30	4,60	0,01

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).

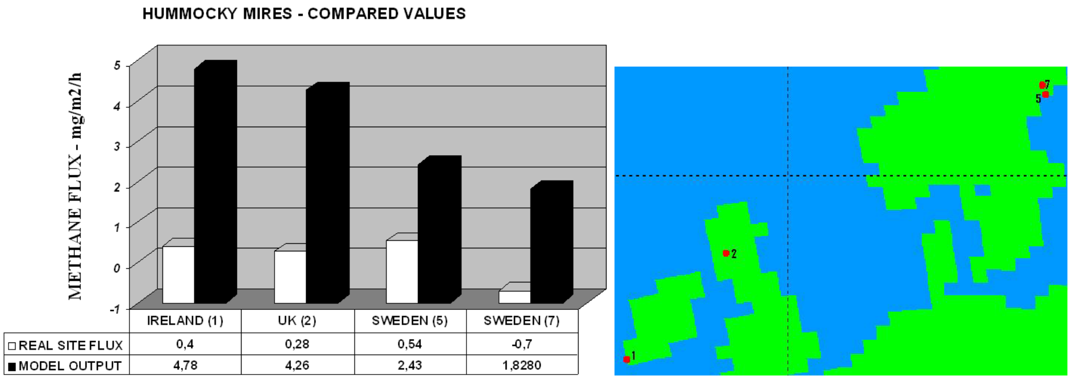


Fig. 4. Overview of mires measured fluxes versus modelled values. The hummocky mires include submerged Sphagnum vegetation in pools. Site reference are: (1) Glencar, Ireland from Laine at al. (2007); (2) Loch More, Scotland from McDonald et al. (1998), (5) Stor-Åmyran, Sweden from Sundh et al. (1995),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

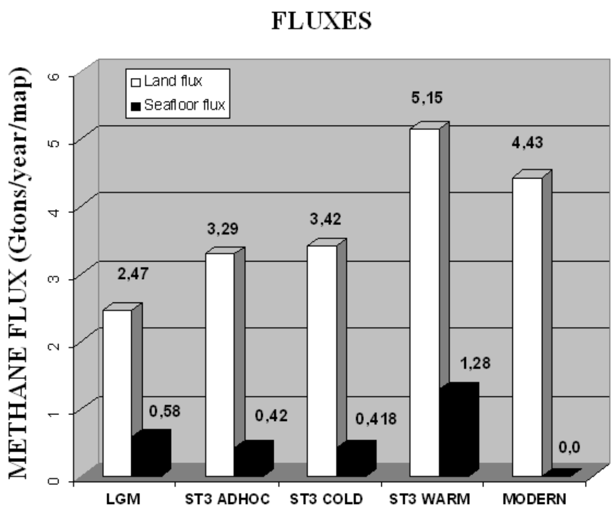


Fig. 5. Modelled fluxes using PEATLAND with modelled water table. Fluxes from present land areas and exposed seafloor areas are displayed separately.

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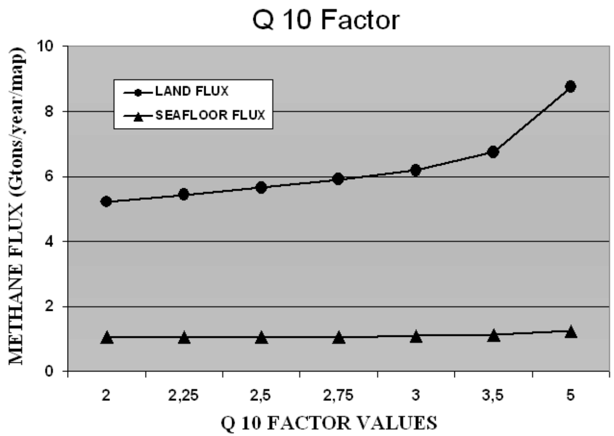

Fig. 6. OIS3 Warm Climate. The two source areas (land and seafloor) have a contrasting reaction: the land flux increases exponentially, while the exposed seafloor flux hardly rises with higher Q10. White symbols represent standard values.

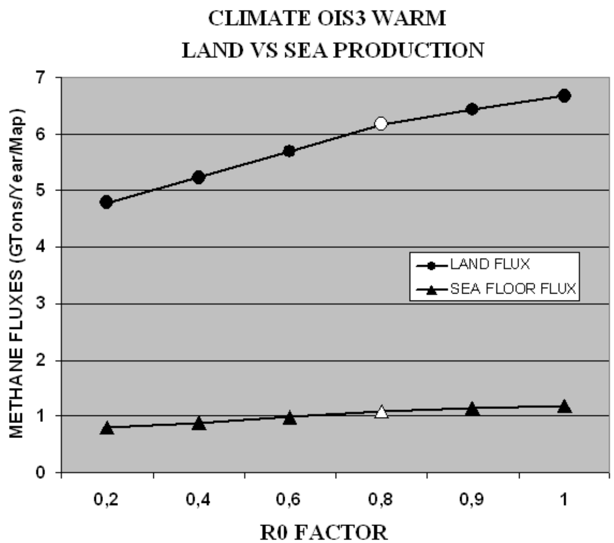

Fig. 7. Model runs indicating the influence of the CH_4 production rate factor R_0. The runs have been performed with a Q10=3.0, for the warm OIS3 climate. White symbols represent standard values.

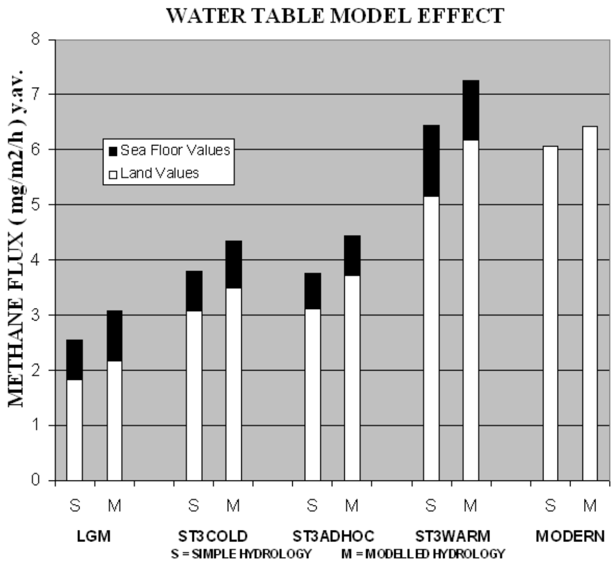

Fig. 8. Effects of water table model. Simple hydrology as applied by Van Huissteden (2004); Water table model cf Cao et al. (1996).

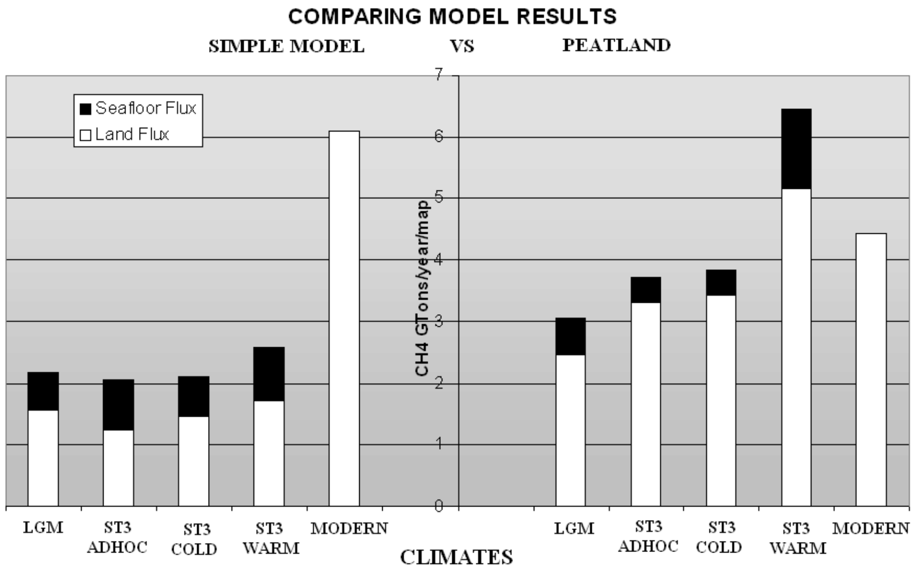

Fig. 9. Comparison between a simple BIOME NPP-based model of CH_4 fluxes and fluxes modelled using PEATLAND-VU and modelled water table (Cao et al., 1996). Corresponding values are reported in the Table 1.

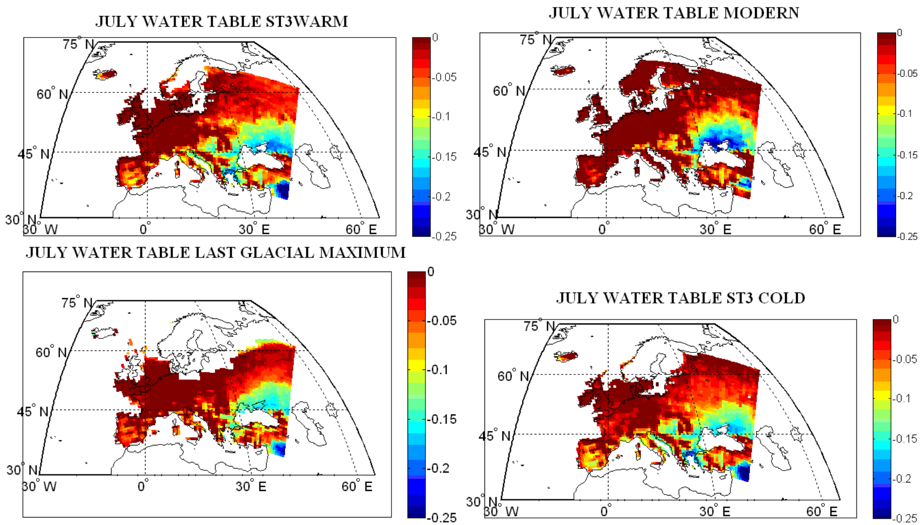

Fig. 10. Simulated water table for the climate scenarios based on the Cao et al. (1996) model.