Chapter 2

Uncertainties in modelling CH$_4$ emissions from northern wetlands in glacial climates: effect of hydrological model and CH$_4$ model structure

C. Berrittella and J. Van Huissteden

2.1 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 modelling 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

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1The contents of this chapter have been published as: Berrittella, C., and J. Van Huissteden. "Uncertainties in modelling CH$_4$ emissions from northern wetlands in glacial climates: effect of hydrological model and CH$_4$ model structure." Climate of the Past 5, no. 3 (2009).
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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.

2.2 Introduction

Due to its large Global Warming Potential (GWP), CH$_4$ plays an important role in the positive feedback mechanisms that amplify global warming [75]. Most preindustrial CH$_4$ emissions arose from wetlands which are situated in broad latitudinal belts in the humid tropics and boreal-arctic zones [75]. The atmospheric CH$_4$ concentration (AMC) appears to be closely linked to climate change during the last 800 000 years [165]. 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 [47, 87]. 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 [139, 101];

2. reactions of wetland CH$_4$ emissions to changes in precipitation and soil temperature [46, 276];

3. release of CH$_4$ from receding ice caps [293] and

4. release of CH$_4$ from seafloor methane-hydrates [144, 145].

Modelling has shown that fluctuations in the OH sink in the atmosphere can be considerable [265, 139, 101], 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. [101] 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. [46] concluded that wetlands north of 30° degrees north are likely to have been a major source. Dällembach et al. [71] 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 [276] 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 CH$_4$ derived from subglacial methanogenesis, is very uncertain due to poorly quantified data about the originating microbial metabolism [293]. A marine hydrate source is less likely to be a cause of the pre-LGM AMC peaks, based on isotope evidence of glacially preserved $CH_4$ [174, 232, 249, 86]. 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 [244, 102]. 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\textsubscript{4} and (c) the conversion of old soil carbon to CH\textsubscript{4} and CO\textsubscript{2} \cite{320,305}. In addition new CH\textsubscript{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 \cite{276}. To understand the role of the CH\textsubscript{4} feedback mechanism within climate change more completely, improved global scale models of the interaction between climate and wetland CH\textsubscript{4} emissions are necessary. Various approaches modelling emissions at global or continental scale have been attempted. These models tend to focus on only some of the processes that influence CH\textsubscript{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 modelling approach is most accurate, due to the lack of data regarding CH\textsubscript{4} emissions for past climates.

The goal of this study is to test different modelling 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, to allow the model to be refined against available paleogeographic and paleoclimate information \cite{276}. 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\textsubscript{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.

2.3 Models

2.3.1 Previous modelling experiments

Several attempts have been made to model global CH\textsubscript{4} fluxes from wetlands using a bottom-up approach based on modelling the process of CH\textsubscript{4} emission \cite{64,60,94,265}. Christensen et al. \cite{64} modelled CH\textsubscript{4} emission as a small (\sim3\%) percentage of heterotrophic soil respiration derived from the BIOME 3.5 predictive vegetation model \cite{103} and an empirical equation \cite{164}. The model of Cao et al. \cite{60} is process based and includes both soil organic matter decomposition and hydrology. Gedney et al. \cite{94} used a simple equation based on water table depth, soil carbon and temperature, coupled to a land surface hydrology model. However, the CH\textsubscript{4} flux equation includes a global constant that needs to be calibrated to known CH\textsubscript{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 \cite{138} (for the LGM, based on the approach of Christensen et al. \cite{64}); Van Huissteden (LGM and MIS 3 stadials/interstadials
for Europe) [276]; and Valdes et al. [265] — (LGM, stadials and interstadials, based on Cao et al. [60]. The models of Van Huissteden [276] and Valdes et al. [265] 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 model [60] and implicitly by Christensen et al. [64]. Van Huissteden [276] used a modified version of an existing model [302] 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 [97, 302, 242, 241]. Their use for large-scale modelling 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 et al. [302], the one of Cao [60] includes a number of process components, in particular modelling 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.

2.3.2 Modelling experiments in this study

In this study two contrasting modelling methodologies are compared. First, the process-based plot-scale model of Walter-Heimann [302] as implemented in the PEATLAND-VU model [284] is applied to grid cells of a regional climate model over Europe. 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 (Figure 2.2 on page 24).

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. [303] and Walter-Heimann [302] model soil profile scale CH$_4$ flux model [284]. 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 submodel [284]. 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. [242, 241]). As such, the Walter-Heimann model [302] 
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 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 [284]. 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 [284]. According to Walter-Heimann [302] 
the production factor for CH$_4$ from labile organic compounds in the soil (R$_0$ in Walter- 
Heimann 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$_{ox}$) [302, 284]. NPP influences substrate availability for CH$_4$ production. 
It is modelled using an optimum function of soil temperature [284]. 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 
[32]. Water table simulation

The groundwater table strongly influences CH$_4$ fluxes [54, 191]. Realistic modelling of 
hydrological processes, in particular water table position and active layer depth is therefore 
crucial. Van Huissteden [276] 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. [60], 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. [60]. 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.
**Simplified CH₄ 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 [64] modelled CH₄ 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 CH₄ flux is assumed to be a fixed percentage of NPP, provided by BIOME 3.5 itself. This assumption is justified by δ¹⁴C pulse labelling experiments on tundra vegetation by King [147], indicating that approximately 2 to 3% of assimilated carbon is emitted as CH₄. We modelled CH₄ 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 CH₄ fluxes. The model of Christensen et al. [64] 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 [201]. Such emission hotspots may be river plains [282] or thermokarst lakes [1, 305].

**2.4 Modelled climate changes**

This study demonstrates not only modelled wetland CH₄ 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.

**2.4.1 Paleogeography: climate and environment**

The climate model simulations used here have been derived from the Stage 3 project [266], 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. The model experiments [19] 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;
2.4. MODELLED CLIMATE CHANGES

Figure 2.1: Paleogeographic maps used for the "Stage 3 Project" climate model simulations and for this study. For references, see the text.

- MODERN, being a control experiment simulating the modern climate.

The paleogeography (ice distribution, sea level and coastlines) of the MIS 3 and LGM climates (see Figure 2.1 on page 21) in the climate model simulations is derived from paleogeographical reconstruction and modeling of sea level and isostasy [15][19]. 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. [276]). Basin fill successions in the Northwest European plain have been described in many studies (e.g. [152][216][140][186][280] and references therein, [45]). Valley fills with gravel-bed rivers in areas with more pronounced relief also contain intercalated fine-grained beds with organic deposits [186][280][45].

The organic deposits in these successions represent sedge mires dominated by Cyperaceae spp. and mosses (e.g. [214][45]). Water level was at, or above, the surface for much of the growing season, and soil pH was around neutral [214][45] 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 [275]. Reports of sphagnum peat in Middle Weichselian deposits are rare [26]. 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 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. [123][11]). 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 [124]. Organic beds were not only restricted to warm interstadials, but were also deposited also during stadials [216]. Summer temperatures were generally low (average July temperatures between 7$^\circ$ to 10$^\circ$C in the Netherlands), but warmer periods did occur [152][214][215][67] with
temperatures even close to modern temperatures in Northern Finland [107]. 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 [275, 140, 280].

2.4.2 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 (Figure 2.2 on page 24). 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 [290]. 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 (Figure 2.2 on page 24) has been checked with the distribution of valleys and basins in The Netherlands and northwestern 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 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.

2.4.3 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. An important effect of *Sphagnum* sp. is a reduction of the CH$_4$ emissions to the atmosphere by means of symbiosis with methanotrophic bacteria [212]. 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 [32].
Figure 2.2: Example of model output. The upper map displays fluxes of CH$_4$ as modelled by the PEATLAND-VU model for each climate grid cell (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.
2.5 Results

2.5.1 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 (Figure 2.3 on page 26 and Figure 2.4 on page 27). 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.

2.5.2 Sensitivity to CH$_4$ production parameters in PEATLAND

Figure 2.2 on page 24 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 ice-covered and do not contribute to CH$_4$ sources. Figure 2.5 on page 28 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 Q$_{10}$ factor is defined as the relative increment in bacterial metabolism after an increase in temperature of 10°C [287]. It is included in the Walter-Heimann model [302] 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 Q$_{10}$ factor for CH$_4$ formation is generally higher than the one for CH$_4$ oxidation [302] so CH$_4$ formation is expected to be strongly influenced by climate change. However, a wide range of values (2 – 16) for Q$_{10}$ related to CH$_4$ formation has been cited in the literature [302]. Therefore we conducted a series of experiments with different Q$_{10}$ 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. In Figure 2.5 the modelled yearly emission over the study area is shown for a CH$_4$ production Q$_{10}$ of 3, a value that performs well for validations of PEATLAND-VU [284]. Figure 2.6 shows a simulation with different Q$_{10}$ values for the MIS 3 Warm climate. The contribution of land areas rises with higher Q$_{10}$; while the exposed seafloor areas do not display a strong increase. The R$_0$ factor ($\mu$M/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 [302]. In practice, it does not differ significantly when the model is calibrated with data from various wetland sites [284] [281]. To test the influence of this parameter, runs have been performed with a fixed water table (cf.
Figure 2.3: 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 [159]; (2) Loch More, Scotland from [167]; (3) Mt. Broken, Germany from [260]; (4) ASA Exp. Forest, Sweden from [14]; (5) Stor-Åmyran, Sweden from [255]; (6) Vesijako, Finland from [183].

The result (Figure 2.7 on page 29) 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.
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Figure 2.4: Overview of mires measured fluxes versus modelled values. The hummocky mires include submerged Sphagnum vegetation in pools. Site reference are: (1) Glencar, Ireland from [159]; (2) Loch More, Scotland from [167]; (5) Stor-Åmyran, Sweden from [255]; (7) Vindeln, Sweden from [97].
Methane fluxes in periglacial wetlands are highly sensitive to the level of the water table (e.g. [282, 54, 191]). On the other hand, the water table position is difficult to model accurately for paleoclimate simulations [60]. The results of the two different approaches to water table modeling outlined in previous sections (Simple Hydrology after Van Huissteden [276] and Modelled water table after Cao et al. [60]) are displayed in Figure 2.8 on page 31. For all climates, the total fluxes are very similar, although the simple water table model results in lower emissions, 6 to 18% less, than those of the Cao [60] model water table. The effects of the structure of the CH$_4$ emissions model were investigated by comparing the simple CH$_4$ emission model outlined in the section about PEATLAND-VU. Results for the same climate (Figure 2.8 on page 31) 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, (Figure 2.9 on page 31) 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 2.1 on page 32) compared to PEATLAND-VU.
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Figure 2.6: "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 $Q_{10}$.

Figure 2.7: Model runs indicating the influence of the $\text{CH}_4$ production rate factor $R_0$. The runs have been performed with a $Q_{10} = 3.0$, for the warm MIS 3 climate.
2.6 Discussion

It has been assumed that one of the causes of low CH\textsubscript{4} emission during glacial stadials was the extent of large ice sheets (e.g. [101]). 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 ([275][5]). The two most important parameters through which climate change is expected to influence wetland CH\textsubscript{4} emission are temperature and water table changes. In our model setup temperature effects are governed by the CH\textsubscript{4} production Q\textsubscript{10} 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 Q\textsubscript{10} 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\textsubscript{4} fluxes. Fluxes from areas with a colder climate will be more closely affected by a higher Q\textsubscript{10}. 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 [276], and water table model of Cao et al.[60]). With the water table simulated by the Cao model [60], the fluxes of all glacial climates are slightly higher, with the ST3WARM CH\textsubscript{4} fluxes moderately (11%) larger than those of the modern climate (Figure 2.8 on page 31). 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 [276], although there is a general increase in the land fluxes and a decrease in the seafloor fluxes.

2.6.1 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 Figure 2.9 and Table 2.1 on page 32. 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
2.6. DISCUSSION

Figure 2.8: Effects of water table model. Simple hydrology as applied by Van Huissteden [276] and water table model cf. Cao [60]. Values refer to the total study area.

Figure 2.9: Comparison between a simple BIOME NPP-based model of CH₄ fluxes and fluxes modelled using PEATLAND-VU and modelled water table [60]. Corresponding values are reported in the Table 2.1 on page 32.

climate the Scandinavian ice cap is very small, as confirmed by paleodata. Helmens et al. [107] indicate the existence of ice-free conditions in Arctic Finland during an OIS3 interstadial. Furthermore, the simulated water tables in the lowlands of Southeastern Europe are somewhat higher during the glacial climates than those for the modern climate, which causes larger fluxes in these areas (Figure 2.10 on page 32).
**Table 2.1:** 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. 2.1 on page 21.

<table>
<thead>
<tr>
<th>MODEL</th>
<th>Land flux</th>
<th>Seafloor flux</th>
<th>Land flux PEATLAND</th>
<th>Seafloor flux</th>
</tr>
</thead>
<tbody>
<tr>
<td>LGM</td>
<td>1.55</td>
<td>0.61</td>
<td>LGM 2.46</td>
<td>1.55</td>
</tr>
<tr>
<td>ST3 ADHOC</td>
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<td>0.80</td>
<td>ST3 ADHOC 3.29</td>
<td>1.23</td>
</tr>
<tr>
<td>ST3 COLD</td>
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<td>0.64</td>
<td>ST3 COLD 3.42</td>
<td>1.45</td>
</tr>
<tr>
<td>ST3 WARM</td>
<td>1.72</td>
<td>0.86</td>
<td>ST3 WARM 5.15</td>
<td>1.72</td>
</tr>
<tr>
<td>MODERN</td>
<td>6.09</td>
<td>0</td>
<td>MODERN 4.43</td>
<td>0</td>
</tr>
</tbody>
</table>

**Figure 2.10:** Simulated water table for the climate scenarios based on the Cao model [60]. Units are meters below soil surface.
2.7 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 modelling 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 $Q_{\text{CH}_4}$ is relatively small; there is more uncertainty in the CH$_4$ production rate itself. So far, past experience with modelling fluxes from different wetland sites do not indicate large between-site differences [284]. Despite these uncertainties of large scale CH$_4$ flux modelling, 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 modelled values with ice core data (e.g. [46, 101]), 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.

Acknowledgements This study was conducted with a research grant from the Dutch organization for scientific research NWO (grant no. 815.01007). We acknowledge the three reviewers for their insight, helpful comments on the manuscript, with particular regard to R. Sphani valuable and constructive remarks. We are grateful to Han Dolman, James Weedon and William Critchley for their helpful review of the text.