Modelling regional to hemispheric CH$_4$ emissions of boreal, subarctic and arctic wetlands

5.1. Introduction

Northern latitudes above 50° N contain 53% of the global wetland area (Aselmann and Crutzen, 1989). Wetlands are thought to be the largest natural source of methane (CH$_4$) second to natural CH$_4$ seeps/geologic emissions (Etiope et al., 2002) although the total anthropogenic source, primarily from rice agriculture, ruminants, and energy production, is the largest (IPCC, 2001). In relatively cold non-aerated waterlogged soils, anaerobic conditions drastically reduce microbial respiration rates, leading to accumulation of soil organic matter and CH$_4$ emission. CH$_4$ is a much stronger greenhouse gas than carbon dioxide (CO$_2$) on a molecular basis and has the second larger radiative forcing after CO$_2$ (IPCC AR4, 2007). The total global CH$_4$ source is relatively well known but the strength of each source component and their trends are not (IPCC AR4, 2007).

During the last decades several attempts were made to estimate the global budget of CH$_4$ from wetlands. Khalil and Rasmussen (1983) estimated an annual CH$_4$ emission rate from wetlands of 150±50 Tg yr$^{-1}$. Seiler (1984) estimated that northern wetlands produce annually 11 to 57 Tg CH$_4$. In all these studies, the total area of northern wetlands varies between $2.6 \times 10^{12}$ m$^2$ (Twenhofel, 1926, 1951) and a maximum of $9.0 \times 10^{12}$ m$^2$ (Sebacher et al., 1986). Other measurements from boreal and sub-arctic wetland regions reveal an annual emission rate, ranging between 0.5 and 10 g CH$_4$ m$^{-2}$ yr$^{-1}$ (Crill et al., 1988; Moore and Knowles, 1987, 1990; Moore et al., 1990; Sebacher et al., 1986; Whalen and Reeburgh, 1988). Fung et al. (1991) and Bartlett and Harris (1993) estimated a flux of 35 Tg yr$^{-1}$ from the northern wetlands. The total range of estimates present in previous studies places the CH$_4$ emissions rates between 11 and 300 Tg yr$^{-1}$ (Matthews and Fung, 1987).

More recently models have been developed to estimate CH$_4$ emissions from northern wetlands. One of the first studies to apply a process-based CH$_4$ model was Cao et al. (1996). They calculated present-day global CH$_4$ emissions from wetlands using a process-based model to simulate CH$_4$ emissions based on the amount of decomposed organic carbon, water table, and temperature. In 1996 Cao et al. (1996) derived an estimate of global CH$_4$ emission of 145 Tg yr$^{-1}$, of which 92 Tg yr$^{-1}$ came from natural wetlands. Northern wetlands contributed 24 Tg yr$^{-1}$.
Table 5-1. Estimates of global northern hemisphere CH$_4$ emissions from natural wetlands as present in the literature.

<table>
<thead>
<tr>
<th>Literature source</th>
<th>CH$_4$ estimate (Tg yr$^{-1}$)</th>
<th>Extent</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Khalil and Rasmussen, 1983</td>
<td>150 ± 50</td>
<td>natural global wetlands</td>
<td>Model simulations</td>
</tr>
<tr>
<td>Seiler et al., 1984</td>
<td>13-57</td>
<td>natural global wetlands</td>
<td>Measurements</td>
</tr>
<tr>
<td>Sebacher et al., 1986</td>
<td>45-106</td>
<td>natural global wetlands</td>
<td>Global wetland database from digital sources</td>
</tr>
<tr>
<td>Matthews et al., 1987</td>
<td>–60% of −110 = −66</td>
<td>peat-rich bogs 50-60°N</td>
<td>Global wetland database from digital sources</td>
</tr>
<tr>
<td>Fung et al., 1991</td>
<td>35</td>
<td>wetlands and tundra poleward of 50°N</td>
<td>Compilation of CH$_4$ flux measurements</td>
</tr>
<tr>
<td>Christensen, 1993</td>
<td>18-30</td>
<td>sub-arctic tundra</td>
<td>CH$_4$ flux measurements</td>
</tr>
<tr>
<td>Bartlett et al., 1993</td>
<td>38</td>
<td>northern wetlands north of 45°N</td>
<td>From extensive flux data base and the wetland areas compiled by Matthews and Fung (1987)</td>
</tr>
<tr>
<td>IPCC, 1994</td>
<td>115 (55-150)</td>
<td>northern wetlands</td>
<td>Model estimates</td>
</tr>
<tr>
<td>Cao et al., 1996</td>
<td>23.3</td>
<td>northern wetlands</td>
<td>Process-based ecosystem model</td>
</tr>
<tr>
<td>Walter et al., 2001b</td>
<td>25% of 290 = 72.5</td>
<td>wetlands above 30°N</td>
<td>Process based CH$_4$ model</td>
</tr>
<tr>
<td>Mikaloff Fletcher et al., 2004a,b</td>
<td>54</td>
<td>bogs and tundra</td>
<td>inverse modeling approach based on isotopic rations of CH$_4$</td>
</tr>
<tr>
<td>Zhuang et al., 2004</td>
<td>31-106</td>
<td>high-latitude soils of the Northern Hemisphere</td>
<td>Terrestrial Ecosystem Model (TEM)</td>
</tr>
<tr>
<td>Chen and Prinn, 2006</td>
<td>−30% of 143–148 = 42.9-44.4</td>
<td>northern wetlands</td>
<td>Atmospheric inversion approach (3-D global chemical transport model)</td>
</tr>
<tr>
<td>IPCC, 2001</td>
<td>115-237</td>
<td>(global wetlands) and 1/3 to 1/2 of it from northern wetlands, north of 50°N</td>
<td>Model estimates</td>
</tr>
<tr>
<td>IPCC, 2007</td>
<td>−60% of 200 = −120</td>
<td>northern wetlands</td>
<td>Model estimates</td>
</tr>
<tr>
<td>Wania, 2008</td>
<td>43.1±2.2 to 46.5±2.3</td>
<td>45-90°N</td>
<td>Coupled vegetation model and CH$_4$ model</td>
</tr>
<tr>
<td>PCR-GLOBWB, 2009 (based on FAO/ISRIC approach)</td>
<td>78 ± 3.3</td>
<td>wetlands and floodplains above 30°N</td>
<td>Coupling between a CH$_4$ model and a global hydrological model</td>
</tr>
<tr>
<td>PCR-GLOBWB, 2009 (based on Lehner and Döll, 2004 approach)</td>
<td>145.6 ± 14.9</td>
<td>wetlands and floodplains above 30°N</td>
<td>Coupling between a CH$_4$ model and a global hydrological model</td>
</tr>
<tr>
<td>PCR-GLOBWB, 2009 (based on Matthews and Fung, 1987 approach)</td>
<td>37.7 ± 2.5</td>
<td>wetlands and floodplains above 30°N</td>
<td>Coupling between a CH$_4$ model and a global hydrological model</td>
</tr>
<tr>
<td>PCR-GLOBWB, 2009 (based on Prigent et al., 2007 approach)</td>
<td>89.4 ± 6.6</td>
<td>wetlands and floodplains above 30°N</td>
<td>Coupling between a CH$_4$ model and a global hydrological model</td>
</tr>
<tr>
<td>PCR-GLOBWB, 2009 (based on Kaplan, 2002 approach)</td>
<td>157.3 ± 7</td>
<td>wetlands and floodplains above 30°N</td>
<td>Coupling between a CH$_4$ model and a global hydrological model</td>
</tr>
</tbody>
</table>

In 1996, Christensen et al. (1996) used a process-oriented ecosystem source model to calculate present day CH$_4$ emissions from northern wetlands (>50° N) based on heterotrophic respiration and they estimated a CH$_4$ flux from the northern wetlands of 20 Tg yr$^{-1}$.

To simulate interannual variations in CH$_4$ emissions from natural wetlands, Walter et al. (2001) developed a process-based model that derives CH$_4$ emissions from natural wetlands as a function of soil temperature, water table, and net primary production (NPP). In addition, a simple hydrologic model (bucket type) was developed in order to simulate the position of the water table in wetlands and was validated against data from different wetland sites. The model was applied to the global wetland distribution map of Matthews and Fung (1987). Their main result was that global annual methane emissions from wetlands was 260 Tg yr$^{-1}$ of which 25% originated from wetlands north of 30°N.

One of the largest uncertainties in the global CH$_4$ budget remains seasonal and interannual variations in wetland areas, especially the ~60% of wetlands that are inundated only at some time.
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in the year. Characterising global inundated wetlands and their dynamics is extremely difficult because they comprise a broad range of environments. Existing global datasets of natural wetlands and rice cultivation (e.g. Matthews et al., 1987, 1991; Cogley, 1991) represent wetland distributions based on vegetation and soils but rely on incomparable wetland definitions (Prigent et al., 2001). Lehner and Döll (2004) developed and validated a global database of lakes, reservoirs and wetlands (GLWD) based on different available cartographic sources. Kaplan (2002) used the BIOME4-TG model, an equilibrium-state terrestrial biosphere model that couples biogeography and biogeochemistry, which is able to calculate the vegetation distribution at any time in the past or future in response to both changing climate and atmospheric CO2 concentrations. To define wetlands, it uses simple empirical algorithms based on topography and soil moisture, selecting grid cells sufficiently flat (slope <0.3%) and sufficiently wet on a monthly basis (relative degree of saturation > 65%) (Kaplan, 2002). He calculated the CH4 as a fraction of heterotrophic respiration, Rh (Christensen et al., 1996).

Gedney et al. (2004) studied the potential for wetland emissions to feedback on climate change by including an interactive wetlands scheme that was radiatively coupled to an integrated climate change effects model. The scheme predicts wetland area and CH4 emissions from soil temperature and water table depth, and was optimized to reproduce the observed inter-annual variability in atmospheric CH4. Gedney et al. (2004) created a simple CH4 emission scheme coupled to the land surface scheme MOSES-LSH which parameterizes the CH4 flux from wetlands including basic control of temperature, water table and soil carbon. Their results predict a considerable increase in the CH4 emission and it suggests ~500–600 Tg CH4 yr⁻¹ by 2100. The total wetland area decreases only slightly by 2100, suggesting that it is the response to increased wetland temperature and not an increase in wetlands extent that dominates the change in natural CH4 emissions. Bergamanschi et al. (2007) developed a new wetland map by assembling the best available source of large-scale wetland cover information for each continent or region. In this way they created a globally consistent dataset containing presence or absence of wetland. To calculate the CH4 emissions they used the algorithm described by Christensen et al. (1996) and Kaplan (2002).

Recently, Wania (2007) integrated the Lund-Potsdam-Jena dynamic global vegetation model to simulate permafrost dynamics, peatland hydrology and peatland vegetation and was used to study the dynamics of the active layer depth, water table regimes and vegetation in northern peatlands. A CH4 model was also developed and coupled with the LPJ hydrology-vegetation model and resulted in LPJ-Why model. The results were tested against five sites and the calculated CH4 fluxes for 45° N - 90° N varied between 29 and 46 Tg CH4 yr⁻¹.

Clearly, hydrology is a crucial factor in the production of CH4 released from northern wetland (e.g. Petrescu et al., 2008). However, actual data on water table dynamics are not generally available and the hydrological regimes have to be modelled from climatic data. By coupling a processed based CH4 model with a global hydrological model, this study aims to create maps of the pan-arctic CH4 emission from floodplains and wetlands, consisting of bogs, fens and mires, for the Northern Hemisphere with emphasis on seasonal and inter-annual variability. For the coupling, we used the macro-scale hydrological model PCR-GLOBWB (Van Beek, 2007) and the CH4 emission model PEATLAND-VU (Van Huissteden et al., 2006a). These models were applied on a spatial resolution of 0.5° and a temporal resolution of days for the period 2001-2006. The resulting output of daily CH4 emissions was then aggregated to monthly values for each 0.5° cell, thus revealing the spatial-temporal distribution of CH4 emissions from the northern circum-arctic hemispheric domain.
To establish the robustness of the approach, we applied it to different estimates of the distribution of global wetlands. For a static comparison we processed the emissions with the datasets of Matthews and Fung (1987), the GLWD-3 dataset of Lehner and Döll (2004) and Kaplan et al. (2002). For a dynamic comparison we used the fractional monthly inundation dataset of Prigent et al. (2007). As part of the comparison with other datasets, the simulated CH$_4$ fluxes were compared with measurements of CH$_4$ fluxes from four existing sites while at a larger spatial scale they were compared to the regional values of Roulet et al. (1994), who calculated the CH$_4$ budgets for the Hudson Bay Lowlands.

5.2. Methodology

Our assessment of spatial-temporal variations in CH$_4$ fluxes from boreal wetlands concerns the Northern Hemisphere land mass with a mean annual temperature of less than 5°C, corresponding to an area of $32 \times 10^{12} \text{ m}^2$. To estimate CH$_4$ fluxes we performed a coupling between PEAFLAND-VU and PCR-GLOBWB (Figure 5-1). PEAFLAND-VU is a process-based model of CO$_2$ and CH$_4$ emission from peat soils under various management scenarios (Van Huissteden et al., 2006a). It includes, among others, a modified version of the Walter and Heimann (2000) soil profile scale CH$_4$ flux model and a simplified soil physical model to simulate soil temperatures and soil freezing/thawing. Since wetlands vary widely in hydrologic, soil and vegetation conditions, a distinction was made between bogs, mires and fens (wetlands) on the one hand and floodplains on the other. The first group, although quite diverse in itself, experiences flooding as a result of local precipitation and receives a limited nutrient supply, restricting net primary production (e.g. Charman, 2002). The second group floods as a result of elevated river discharge, importing sediment and nutrients from elsewhere. Thus, floodplains tend to have mineral soils and can sustain more productive vegetation. These differences may induce higher CH$_4$ fluxes from floodplains (Van Huissteden et al., 2005; van der Molen et al., 2007). Hence, a separate parameterisation of soil and vegetation characteristics was applied in PEAFLAND-VU for wetlands and floodplains respectively (see Appendix A1).
Figure 5-1. Diagram describing the coupling of PEATLAND-VU and PCR-GLOBWB. Shown are spatial input (maps, cyan), location specific parameterisation for PEATLAND-VU (time series and tables, orange) and output (time series, green). Arrows (yellow) indicate the direction of information exchange. Output time series have subsequently been processed and aggregated to obtain maps of CH₄ fluxes for different periods. We define wetlands as bogs, fens and mires.

The hydrological conditions for PEATLAND-VU were prescribed as time series by PCR-GLOBWB using a spatial resolution of 0.5° globally and a temporal resolution of days. PCR-GLOBWB is a macro-scale hydrological model that calculates the water storage on a cell-by-cell basis in two vertically stacked soil layers and an underlying groundwater reservoir. The exchange between the soil column and the atmosphere includes rainfall, snow melt and evaporation from plants and interception while drainage from the soil column is routed along the drainage network (Van Beek, 2007). The meteorological forcing of PCR-GLOBWB consisted of daily forecast fields of precipitation, air temperature and actual evapotranspiration from the ECMWF Operational Archive for the period 2000-2006. Two hydrological situations were considered, being a fully saturated or anoxic profile and an unsaturated oxic one given the key control of oxidation on CH₄ emission. Anoxic conditions are specified by the mean height of the floodwaters, oxic conditions by the depth of the water table relative to the soil surface.

The height of the floodwaters over the floodplain and the extent of flooding were calculated using the HYDRO1k dataset (Verdin, 1997). For sub-catchments typically smaller than the 0.5° cells, the relative height above the floodplain of each 1 km cell was calculated. For each cell, the aggregated sub-grid distribution was subsequently represented by percentiles (0.01, 0.05 and 0.1 through 1.0 by increments of 0.1). This distribution was applied a posteriori to the river stages that were simulated by PCR-GLOBWB for a fixed floodplain extent based on a blended dataset of the GLWD1 and the HYDRO1k dataset (Lehner and Döll, 2004; Verdin, 1997). The consequent height of the floodwaters and the extent of the submerged area followed from intersecting the cumulative floodplain volume with the discharge in excess of channel storage.
For the wetlands, the extent of the inundated area experiencing anoxic conditions was approximated by the saturated fraction from the improved Arno Scheme of Hagemann and Gates (2003) that returns the fraction under the cumulative soil depth distribution that becomes saturated as the local storage capacity is exceeded by the cell-averaged moisture storage \( W \) (Figure 2). As the moisture storage changes, so will the storage capacity, \( w \), and the saturated fraction. Thus, the oxic and anoxic parts are given by equations (5-1) and (5-2):

\[
x_{sat} = \min(x_t, x_{t+1})
\]

\[
x_{unsat} = |x_t - x_{t+1}|
\]

where \( x_{sat} \) is the saturated, anoxic, part of the cell and \( x_{unsat} \) is the unsaturated, oxic, part; \( t \) and \( t+1 \) represent the previous and present time step respectively.

The height of the floodwaters was estimated by the average water storage, \( w \), in excess of the water holding capacity of the soil. The corresponding water heights, \( h \), or depths over these areas is respectively given by:

\[
h_{sat} = \frac{1}{2}(w_{t+1} - w_{min})
\]

which represents the ponded water level on top of the anoxic part, taken as the average between \( w \) at \( t+1 \) and the minimum water storage capacity; in case of flooding this is the depth of which an expanding wetlands floods;

\[
h_{unsat} = \frac{1}{2}(w_{t+1} - w_t)
\]

or

\[
h_{unsat} = \frac{1}{2}(w_{t+1} - w_t) \sum_i z_i (\theta_{sat} - \theta_{FC})
\]

which is the depth in case of drainage when the groundwater in the soil becomes located at a depth greater than the maximum decrease in water depth. This is achieved by dividing it by the specific yield, the difference between saturation and field capacity (\( \theta_{sat} - \theta_{FC} \)); this is weighted on basis of the respective depths of the layers (\( z_i \)); \( w \) is the water storage capacity at past, \( t \), and present time, \( t+1 \), respectively and \( \theta \) is the volumetric moisture content (\( m^3 m^{-3} \)) for each soil layer.
For both wetlands and floodplains, the area experiencing oxic conditions was defined as the area that floods or drains depending on whether the inundated area is expanding or contracting. Since the depth of the water table depends on local conditions only, the Arno Scheme was used for both floodplains and wetlands alike. To parameterize the soil physical model of PEATLAND-VU, snow depth data from PCR-GLOBWB were used in combination with the 2 m air temperature of the ECMWF Operational Archive. More details are found in the Appendix A4.

For the depth of the snow pack, water equivalent snow cover was converted by dividing it by the density of snow:

\[ Z_{\text{Snow}} = \frac{Z_{\text{Snow WE}}}{\rho_{\text{Snow}}} \]  

(5.6)

where \( Z_{\text{Snow}} \) is the depth of the snow pack in m per m\(^2\), \( Z_{\text{Snow WE}} \) is the water equivalent snow cover and \( \rho_{\text{Snow}} \) is the density of snow in kg m\(^{-3}\).

Snow density was dependent on the age of the snow, maturing from 100 kg m\(^{-3}\) for fresh snow to 350 kg m\(^{-3}\) after 120 days. The development of snow density with age was simulated as follows:

\[
\rho_{\text{Snow}} = \frac{\frac{1}{2}(\rho_{\text{Snow}(t)} + \rho_{\text{Snow}(t-1)}) \cdot Z_{\text{Snow WE}(t-1)} + \rho_{\text{Snow}(t = 0)} \cdot \Delta Z_{\text{Snow WE}(t)} + \rho_{w} \cdot Z_{\text{Snow Liq WE}(t)}}{Z_{\text{Snow WE}(t-1)} + \Delta Z_{\text{Snow WE}} + Z_{\text{Snow Liq WE}}} \]  

(5.7)

where \( Z_{\text{Snow}(t-1)}, Z_{\text{Snow}(t)} \) and \( Z_{\text{Snow}(t = 0)} \) are the density of the maturing snow for the previous and present day and for freshly fallen snow, respectively, \( \rho_{w} \) is the density of any liquid water retained by the snow pack. These densities are weighed on the basis of water equivalent depths, being the snow cover handed down from the previous time step, \( Z_{\text{Snow WE}(t-1)} \), any freshly fallen snow for the current time step, \( \Delta Z_{\text{Snow WE}(t)} \), and the retained liquid water in the snow pack, \( Z_{\text{Snow Liq WE}(t)} \). Thus, maturation and melt result in a denser snow pack whilst any fresh snow will lighten it.

To remove errors in the initial conditions (mainly temperature profiles), the year 2000 was used to spin up PEATLAND-VU, thus effectively limiting the analysis to the period 2001-2006. Coupled with PCR-GLOBWB, PEATLAND-VU returns four time series of CH\(_4\) fluxes per 0.5\(^\circ\) cell (floodplains and wetlands under respectively oxic and anoxic conditions). Dependent on site characteristics (see Appendix A2 and A3) the anoxic flux was used in calculations, as the measurements took place on almost waterlogged soil, often underlain by permafrost. To obtain the average flux per 0.5\(^\circ\) cell the respective fluxes per unit area of a particular surface condition were weighed by the fractions of potential wetland type and hydrological conditions over the total cell area and aggregated over longer periods:

\[ \bar{J}_{\text{CH4}} = \frac{1}{N} \sum_{d} \sum_{w} f_{w} \sum_{s} x_{w}^{s} J_{w}^{s} \]  

(8)

where \( \bar{J}_{\text{CH4}} \) is the average CH\(_4\) flux in g m\(^{-2}\) d\(^{-1}\), \( f \) is the fractional cover per wetland type, \( x \) the fractional cover of the wetland area experiencing oxic or anoxic conditions (\( f \) and \( x \) both in m\(^2\) m\(^{-2}\)), and \( J \) is the flux per day. The subscript \( w \) denotes the wetland type, \( d \) the daily time step adding up to \( N \) days per month or year, and the superscript \( s \) the oxic and anoxic conditions per wetland type. When appropriate, fluxes were multiplied by the cell area to obtain fluxes.

Inclusion of the potential wetland type was necessary as the parameterisation of the improved Arno Scheme in PCR-GLOBWB include other areas with shallow soils (e.g., urbanized areas or rocky soils). To delineate potential wetland areas in PCR-GLOBWB, we used the FAO Digital Soil
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Map of the World (ISRIC) and identified the soil units *gleysols*, *histosols* and those with a *gleyic* phase as areas with poor drainage (cf. Matthews and Fung, 1987) and converted their frequency to fractional extent. Since PCR-GLOBWB considers the distribution of the floodplain elevations in detail, potential floodplains were not constrained beforehand. If the sum of both the fractional floodplain cover and that of the wetland exceed unity, the floodplain encroaches onto the wetland area and that cell is parameterized as being a floodplain.

To establish the robustness of the outcome based on the parameterisation of PCR-GLOBWB, we applied a static approach to the datasets of wetland extent of Matthews and Fung (1987), Lehner and Döll (2004) and Kaplan (2002) and a dynamic approach to the datasets of Prigent et al. (2007). The detailed description of all datasets are to be found in the Appendix A5 and the wetland extent maps in A6, A7, A8, A9 and A10.

5.3. Results

5.3.1. Potential wetland extents and \( \text{CH}_4 \) distribution maps

We were running the \( \text{CH}_4 \) model for the maximum extent of global northern wetland area consisting of 23564 0.5° cells and covering 32 x \( 10^{12} \) m\(^2\) (see Appendix A7, grey area). This area is further restricted by each of the five parameterisations for which we calculated the extent of the wetlands and floodplains. Using the wetland distribution based on the FAO (ISRIC) map and PCR-GLOBWB, the average boreal wetland area contributing to \( \text{CH}_4 \) emissions was 2.97 x \( 10^{12} \) m\(^2\).

Using the wetland extent of Lehner and Döll (2004) the area was 3.42 x \( 10^{13} \) m\(^2\), while using Matthews and Fung (1987) this area became 2.44 x \( 10^{12} \) m\(^2\). Using the mean monthly inundated area of Prigent et al. (2007), the mean area was 4.37 x \( 10^{12} \) m\(^2\) while Kaplan (2002) wetland area was 2.16 x \( 10^{12} \) m\(^2\). In addition to the variations in the fraction inundated area as obtained from PCR-GLOBWB, the Prigent et al. (2007) dataset includes the monthly variations in wetland area.

Figure 5-3a to 5-3e shows the averaged \( \text{CH}_4 \) flux over the six years for all approaches. In the Appendix A11, A12, A13, A14 and A15, we present detailed maps showing the spatial-temporal variation of the annual \( \text{CH}_4 \) fluxes and monthly maximum \( \text{CH}_4 \) fluxes for all approaches. For PCR-GLOBWB/FAO(ISRIC), the total averaged \( \text{CH}_4 \) flux over the six years was 78 Tg yr\(^{-1}\). For Matthews and Fung the total average \( \text{CH}_4 \) flux over the six years was 37.7 Tg yr\(^{-1}\). For Lehner and Döll the total average \( \text{CH}_4 \) flux over the six years was 145.6 Tg yr\(^{-1}\). For Prigent parameterisation the total average \( \text{CH}_4 \) flux over the six years was 89.4 Tg yr\(^{-1}\), while for Kaplan the total average \( \text{CH}_4 \) flux over the six years was 157.3 Tg yr\(^{-1}\). The total monthly maximum \( \text{CH}_4 \) fluxes over the corresponding areas were: PCR-GLOBWB/FAO July 2005: 569.4 g m\(^{-2}\) d\(^{-1}\), Matthews and Fung (1987) July 2005: 229.8 g m\(^{-2}\) d\(^{-1}\), Prigent et al. (2007) July 2006: 877.8 g m\(^{-2}\) d\(^{-1}\), Lehner and Döll (2004) July 2006: 1066 g m\(^{-2}\) d\(^{-1}\) and Kaplan (2002) July 2005: 968.4 g m\(^{-2}\) d\(^{-1}\).
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Figure 5-3a-b. Six year average CH₄ flux a) PCR-GLOBWB/FAO (ISRIC) approach; b) Matthews and Fung (1987) approach.
Figure 5-3c-e. Six year average CH₄ flux c) Prigent et al. (2007) approach; d) Lehner and Döll (2004) approach and e) Kaplan (2002) approach. The grey area represents maximum extent of global boreal wetland area as defined by the 5 °C limit.

Figure 5-4 shows the total CH₄ estimates in Tg yr⁻¹. We can observe a similar trend between the five approaches. In most cases, the maximum years are 2001 and 2006 while 2004 has the lowest fluxes for three out of all approaches (see also Appendix Table A16).
To show the areas that contribute most to the CH$_4$ emissions, we plotted as an example the cumulative sums of CH$_4$ emissions over longitude bands for 2006 as calculated with our coupled models, PCR-GLOBWB/FAO(ISRIC) and PEATLAND-VU (Appendix Table A17 and Figure A18).

5.3.2. Validation

We validated the simulations performed with PCR-GLOBWB/FAO(ISRIC) parameterisation against the results presented by Roulet et al. (1994). They performed measurement campaigns in the Hudson Bay Lowlands (HBL) with 320,000 km$^2$, the second biggest wetland in the Northern Hemisphere, after the Western Siberian Lowlands (540,000 km$^2$). They measured during the snow free months of 1990. Measurements were done by aircraft using airborne eddy correlation technique (Roulet et al., 1994). The total HBL annual emissions were estimated to $0.538 \pm 0.187$ Tg CH$_4$ yr$^{-1}$. We extracted from our area of interest the corresponding area ($77^\circ$-94$^\circ$ W, 50$^\circ$-58$^\circ$ N) covering 405330 km$^2$. Our estimate, 2.09 Tg CH$_4$ yr$^{-1}$ averaged over 2001-2006, is higher than Roulet et al. (1994) estimates from 1990. In 2000, Worthy et al. (2000) concluded, after calculating the CH$_4$ fluxes for the same HBL that the measured fluxes were much lower than fluxes derived empirically by different models and were more sensitive to temperature. They also state that the global CH$_4$ budgets need a substantial revision. Therefore, taking into account that during the last years the CH$_4$ emissions registered a slight increase (Table 5-1) we believe that our results show a valid estimate.
We also compared the simulations against observed CH$_4$ fluxes (four sites). Results are shown in mg m$^{-2}$ d$^{-1}$, the original unit of measurement (Appendix, A22). Dependent on site description and characteristics (A20, A21), and their soil physical properties, the flux over the anoxic profile of the floodplain or wetland parameterisation was used (Appendix A2 and A3).

### 5.4. General discussion

This study maps and quantifies CH$_4$ emissions from the Northern Hemisphere by coupling a global hydrological model, PCR-GLOBWB, with a wetland CH$_4$ emission model, PEATLAND-VU. Moreover, by aggregating the calculated fluxes for other existing datasets of circum-arctic wetland extent (Matthews and Fung, 1987; Lehner and Döll, 2004; Prigent et al., 2007 and Kaplan, 2002) we have been able to identify the uncertainty in variations in CH$_4$ emissions under given hydrological conditions.

Our main approach was based on simulating the CH$_4$ emissions using the water table and snow cover output from PCR-GLOBWB as input into the PEATLAND-VU Model. Because the PEATLAND-VU model was developed from the model of Walter and Heimann (2000), which was designed to be a plot scale process based model, the site-specific soil parameters are very hard to obtain for the entire simulated area. Therefore, we used the same soil parameters as published in Petrescu et al. (2008) and slightly changed R$_0$ (CH$_4$ production rate) values. R$_0$ is controlled by the amount of substrate present in the soil and a measure of the substrate availability. As Walter and Heimann (2000) state, R$_0$ is a tuning parameter which has to be adapted to obtain the right amplitude of the methane emissions.

The difficulty to calibrate the PEATLAND-VU model and set all the optimum parameters to run the model on a global scale remains a major challenge. For instance, the simplification of introducing a globally uniform parameter set, instead of one calibrated on particular sites is unknown. Van Huissteden et al. (2009) tested the PEATLAND-VU model using the GLUE methodology (Lamb et al., 1998; Beven, 2001) and references therein) with validation data from different sites, including temperate and permafrost wetlands. In this method, the model is
evaluated against a validation dataset using a large number of runs with randomly selected parameters. The results showed that the model has more predictive power than a simple emission factor approach, based on averages of measurement data only. However, there is considerable interaction between parameters and equifinality of model solutions, implying that different parameter sets may yield similar model results. Behavioural model runs are usually well within the error margin of the data. This indicates that with a well-chosen globally uniform parameter set the number of cases where the model is unable to model the fluxes correctly, should be limited. Deviations of single data points are consistent among the Monte Carlo model runs. These points may represent data errors or events for which the model is not designed for, e.g. ebullition events induced by weather conditions. Errors may be larger for the floodplains than for the other wetlands, because the GLUE analysis resulted in larger uncertainty for eutrophic, high-flux sites.

CH$_4$ fluxes are known to be temporally and spatially highly variable. Although observed magnitudes are generally related to water table, soil temperature and vegetation, the variability of fluxes between measurement points with similar soil type, vegetation and water table position is usually high (e.g. Van Huissteden et al., 2005; Hendriks et al., submitted 2009). This small-scale spatial variation is probably related to small-scale differences in vegetation characteristics and soil. Therefore it can be argued that the model should reproduce the average flux of a group of similar points, rather than the measurements at single points. Also, small-scale (sub-daily) temporal variation in CH$_4$ fluxes exists that currently cannot be modelled. In particular short-lived ebullition events are difficult to reproduce exactly with the right magnitude and time. In 2007, Walter et al. (2007) measured the CH$_4$ bubbles from 16 northern thermokarst lakes and by extrapolating the results came up with a northern (>45°N) global budget estimate of approximately 24.2±10.5 Tg CH$_4$ yr$^{-1}$.

If we compare our yearly trends of CH$_4$ emissions for all approaches (Figure 5-4) we see that the spatial variation is not very pronounced between the years as the main CH$_4$ contribution comes from same areas. Each approach identifies the hotspots but these are not present in all. The most variations are observed in the maps showing the maximum monthly flux (Appendix A16). We conclude that this is due to the input maps of wetland or inundation extent and their sources. Remote sensing data (Prigent et al., 2007) differ from cartographic sources (as in Matthews and Fung (1987) or Lehner and Döll (2004)). As shown in Appendix A, Table A17, the values are different between the approaches and it is mainly due to differences in extent and nature of wetland areas delineated by these approaches. For instance, in the PCR-GLOBWB - PEATLAND-VU simulations, the fluxes tend to be higher in the southern part of the boreal zone, as a result of higher soil temperatures (see also Appendix A, Figure A19 for cumulative sums), such as for the Kaplan (2002) approach. PCR-GLOBWB uses much spatial detail (e.g., HYDRO 1K for floodplain flooding) and recent (2001-2006) climate data (ECMWF Operational Archive) with fine temporal detail. Compared to other estimates our results are matching with literature-based information (see Table 5-1). In the simulations based on the Matthews and Fung (1987) wetland distribution, the Western Siberian lowlands and the Baltic Shields with their widespread ombrotrophic wetlands stand out as a major CH$_4$ emission area. For the Lehner and Döll (2004) dataset the main emissions come from the Western Siberian lowlands and the Canadian lowlands. The same holds to a smaller extent for the Prigent et al. (2007) dataset. We can notice that, some of the high emissions from more southern wetlands are predicted by some approaches but not all datasets report those areas as being a wetland. This might be due to a different vegetation type which dominates those areas and are not included in models.

We base our results on the other approaches used to validate the CH$_4$ emissions. Using the dataset of Matthews and Fung (1987), which used three different cartographic sources to yield the
wetland type and corresponding fractional inundation map for the globe, our results (37.7 Tg CH₄ yr⁻¹, averaged over 2001-2006) are half of the estimates made 20 years ago (~60% of the total of ~110 Tg CH₄ yr⁻¹ = ~66 Tg yr⁻¹ come from peat rich bogs concentrated from 50-70°N). They are lower due to the difference in calculated area. The area used by Matthews et al. (1987) was ~3.7 x 10¹² m² while PCR-GLOBWB’s estimated area for this approach was 2.44 x 10¹² m². According to Matthews and Fung (1987), the area of wet tundra between 70-80°N is about 0.1 x 10¹² m². This area was estimated by Fung et al. (1991) to contribute with 3% of the total of 30 CH₄ Tg yr⁻¹ which is ~1 Tg yr⁻¹. If we apply this hypothesis to our calculation we get an estimate of 2.4 Tg yr⁻¹ over the same area. This difference may relate to estimation methods or means that, compared to the 1990s, the CH₄ emissions may be increasing. This may be caused by changes in hydrological conditions and temperature as incorporated in our models. The same result we obtained from the comparison performed on the Hudson Bay Lowlands where we obtained a doubled CH₄ value compared to the one from 1990. This is in line with the study made by Bousquet et al. (2006). They quantified the processes that controlled variations in methane emissions between 1984 and 2003 using an inversion model of atmospheric transport and chemistry. The main conclusion was that the wetland emissions dominated the inter-annual variability of methane sources and that on longer timescales the decrease in atmospheric methane growth during the 1990s was caused by a decline in anthropogenic emissions. Thus, atmospheric methane levels may increase in the near future if wetland emissions return to their mean 1990s levels (Bousquet et al., 2006).

The dataset of Lehner and Döll (2004) used the wetland information from a large variety of existing maps (eighteen), generalizing the global information at three different resolutions (GLWD 1-3). For this study we used the wetland information from the map with the finest spatial detail (GLWD-3 at 30 arc seconds) which contains twelve different classes (see dataset description in Appendix A5). Similar as in the PCR-GLOBWB approach based on the FAO-derived wetland extent, the main areas emitting the most CH₄ are the south of the Western Siberian lowland and the south of the HBL. The averaged CH₄ over the six years was 145.6 Tg yr⁻¹, the highest estimate out of all approaches. This is mainly caused by the large area with floodplains, defined in the database as classes 4 and 5, which, compared to the other datasets, cover a very large area in North Canada and Western Russia (Appendix A9).

The approach of Prigent et al. (2007) used the information from multiple satellites to derive the monthly averages of fractional inundation over the years 1993-2000. We processed our emissions with this information and calculated the emissions for 2001-2006. This might be one of the reasons why our calculation of the CH₄ budget (89.4 Tg CH₄ yr⁻¹ averaged over 2001-2006) is one of the highest estimates. There is still uncertainty in estimating the inundation extent for a single pixel which may be highly variable (inundated and non-inundated) in the northern wetlands. The timing and the duration of the flooding conditions is still unclear. This dataset gives an explanation on the maximum inundation extent and not on how long the flooded areas persist. This is also valid for the other approaches. More observations need to be done with reference to the vegetation changes and estimation of the inundated area (Prigent et al., 2001). The inundated area reported by Prigent et al. (2007) was 1.6 x 10¹² m² for 55°-70°N. We calculated a possible mean wetland area for the northern hemisphere of 4.37 x 10¹² m² for Tavg < 5°C. Unlike Matthews and Fung (1987) in which inundated area comes from cartographical charts and which probably accounts for the warm season of maximum flooding, the Prigent (2007) dataset does not distinguish among standing water in natural wetlands, rice paddies nor lakes/rivers.

Using Kaplan’s (2002) empirical approach, PCR-GLOBWLB calculated the maximum wetland extent where Kaplan’s implicit assumption on saturation was replaced by the explicit fraction of saturation (excluding other impervious surfaces, i.e. urban areas). With these assumptions, our
results are very high compared to the other approaches, but close to Lehner and Döll (2004) approach. As he states in his paper, by applying this calculations, his model failed to predict the known Alaskan wetlands and discontinuous Scandinavian wetlands (Kaplan, 2002). For the CH₄ emissions, he calculated a total global budget of 140 Tg yr⁻¹, while our total estimate averaged over the six years was 157.3 Tg yr⁻¹ for the area >30°. On the other hand, if we compare this estimate with the literature information used by the IPCC (2007) report on CH₄ fluxes from wetlands which states a value of 120 Tg yr⁻¹ for the northern wetlands, our result probably overestimate the budget. We believe that this is due to the initial definition of the wetlands regarding the slope percentage and by applying the detailed saturated fractions of bogs and floodplain as calculated by PCR-GLOBWB. As we can observe from Figure 5-3e, almost every cell gives a very small CH₄ flux. This is due to the application of the detailed PCR-GLOBWB/FAO maximum extent of saturation and fractional inundation definition (Appendix, Figure A6). All cells having flat slopes and some saturation will result in a flux that is larger than zero and thus shows in the map. This is partly due to unresolved detail in other datasets or processes not captured by Kaplan’s approach that prevents the formation of wetlands. The differences also show that a correct determination of wetland extent is crucial for determining wetland CH₄ fluxes.

For future research it will be very interesting to couple our models with a vegetation model (Wania, 2007), because of the importance of vegetation parameters in the model results (Van Huissteden et al., 2009). With regards to Wania (2007) estimates we observe that our estimates are higher to those obtained by coupling a methane model with a vegetation model. She obtained for 45°-90° N a CH₄ budget of 43.1 ± 2.2 to 46.5 ± 2.3 Tg yr⁻¹ for 1991-2000 for an area 2.99 x 10¹² to 3.21 x 10¹² m² (comparable to the area we calculated for Matthews parameterisation, 2.44 x 10¹² m²) while PCR-GLOBWB/FAO – PEATLAND-VU estimate was 78 Tg yr⁻¹ averaged over 2001-2006. Further research will also include validation against atmospheric CH₄ concentrations. Appendix A23 gives an explanation about why we have not used SCIAMACHY products as a validating procedure for our results in this particular study.

Our modeling study did not include emissions related to permafrost thaw (Walter et al., 2006; Zimov et al., 2006). The modeling of permafrost thaw effects would require modeling of geomorphic effects of permafrost thaw such as thaw lake formation (Khvorostyanov et al., 2008; Walter et al., 2006). However, with our approach, year-to-year variability of wetland CH₄ emissions related to changes in precipitation and temperature can be quantified and mapped. For instance, the high CH₄ emission of floodplains may be highly sensitive to precipitation and discharge variations (Van Huissteden et al., 2005); this effect is fully included in our model.

5.5. Conclusions

The overall estimated CH₄ flux for the northern hemisphere was calculated using five different parameterisations. Our results varied between a minimum average estimate of 37.7 Tg CH₄ yr⁻¹ (Matthews and Fung, 1987 approach) and a maximum of 157.3 Tg CH₄ yr⁻¹ (Kaplan, 2002 approach) and showed considerable year-to-year variation. Very high emissions were found above the 65°N in the Siberian Wetlands, Northern Europe and South Canadian lowlands. Validation on existing estimates from South Canada proved to be successful. The attempt in comparing the PCR-GLOBWB simulated results with measurements from different sites showed similar high averaged values for two out of four sites, Cherskii and Stordalen (see Appendix A, Table A22).

Uncertainties are still present and are mainly due to 1) the high variability in reported wetland extent; 2) site-specific parameters which influence the CH₄ emissions that are very hard to measure (e.g. R₀, plant oxidation, soil physical parameters) and 3) emission processes that are not
included in the model (ebullition events). A good estimation of the wetland areas, together with temperature records are an important driver for calculating CH$_4$ emissions from high latitude wetlands.

Our attempt in calculating the CH$_4$ budgets from the most important natural CH$_4$ source is a step forward in improving calculations of global estimates and wetlands extents. The coupling between a process based CH$_4$ model and a global hydrological model and the obtained results makes us believe that it is possible, based on simple approaches, to give a plausible bottom-up estimate of CH$_4$ budget and its spatial and annual/monthly variation. The calculations based on the Lehner and Döll (2004) and Kaplan (2002) parameterisations are on the high side of the literature values but PCR-GLOBWB/FAO coupled with PEATLAND-VU produced a more plausible estimate. We are aware that an even better estimate requires further studies. Further improvements of the model will be a spatially variable parameterisation of wetland vegetation characteristics in the PEATLAND-VU model. Vegetation characteristics related to plant transport and oxidation of CH$_4$ vary widely on smaller and larger scales. In particular differences between vascular (e.g. sedge and reed-type vegetation) and nonvascular (e.g. peat mosses) may be important (Raghoebarsing et al., 2006; Van Huissteden et al., 2005).