Appendix A

A1. Parameterisation PEATLAND-VU model

The PEATLAND-VU model requires parameters on microbial population activity of methanogenic and methanotrophic bacteria, vegetation parameters related to gas transport through plants and soil parameters (horizon thickness, organic matter content, dry bulk density and pH). There is insufficient information available to specify these parameters for each grid cell separately. Model sensitivity analysis using the GLUE (Generalized Likelihood Uncertainty Estimation) has shown that the model is not strongly sensitive to soil parameters (Van Huissteden et al., 2009). This sensitivity analysis indicated that the model was more sensitive to microbial population and vegetation parameters, in particular the CH$_4$ production rate $R_0$, its temperature sensitivity $Q_{10}$, and the model parameter specifying oxidation of CH$_4$ during transport in plants, $P_{ox}$. For single site CH$_4$ flux measurement data, good model-data fits can be obtained by optimizing these parameters (Van Huissteden et al., 2006a; Petrescu et al., 2008; Van Huissteden et al., 2009).

The GLUE analysis showed that there is a high amount of equifinality in the model solutions, a good model-data fit can be realized with a quite large range of parameters. Therefore we selected parameter values that have shown previously to perform well for data sets from various sites (Petrescu et al., 2008; Van Huissteden et al., 2006a). The selection of the CH$_4$ microbial population model input parameters (CH$_4$ production rate $R_0$, temperature correction $Q_{10}$) was based on previous optimization by Petrescu et al. (2008). Different parameters were set for bogs and floodplains. For both bogs and floodplains the oxidation factor was set to a value of 0.7. For both bogs and floodplain simulations a $Q_{10}$ value of 4 was set. The $R_0$ was set for bogs to 0.075 $\mu$Mh$^{-1}$ and for floodplains to 0.05 $\mu$Mh$^{-1}$ (Table A2). The soil physical parameters per soil horizon used in the PEATLAND-VU Model were also kept similar to the parameters used in Petrescu et al. (2008) (A3). The selection of uniform soil profiles and soil parameters introduces some uncertainty in the model results. The NPP values used were the same for all types of wetlands being set to 0.0015 kg C m$^{-2}$ d$^{-1}$ after (Van Huissteden et al., 2006a).

A2. Table with parameters used by PEATLAND-VU model

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Wetland</th>
<th>Floodplain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production rate ($R_0$)</td>
<td>0.07</td>
<td>0.05</td>
</tr>
<tr>
<td>Value for temperature correction CH$<em>4$ production ($Q</em>{10}$)</td>
<td>4.0</td>
<td>4.0</td>
</tr>
<tr>
<td>Plant oxidation ($P_{ox}$)</td>
<td>0.7</td>
<td>0.7</td>
</tr>
</tbody>
</table>
A3. Soil physical parameters used by PEATLAND-VU model

<table>
<thead>
<tr>
<th>Soil physical parameters per soil horizon</th>
<th>Floodplains (estimated data)</th>
<th>Wetlands (estimated data)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of horizons</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Horizons depths with respect to surface</td>
<td>(0.1 0.2 2.0)</td>
<td>(0.1 0.2 0.3 2.0)</td>
</tr>
<tr>
<td>C/N ratios for each soil layer</td>
<td>(15 15 15)</td>
<td>(48 38 31 15)</td>
</tr>
<tr>
<td>Dry bulk density for each horizon</td>
<td>(100 130 975)</td>
<td>(88 102 519 808)</td>
</tr>
<tr>
<td>Percentage organic matter for each horizon</td>
<td>(95.0 80.0 5.0)</td>
<td>(90.0 80.0 70.0 5.0)</td>
</tr>
<tr>
<td>pH</td>
<td>(6.0 6.0 7.0)</td>
<td>(4.0 4.0 4.1 4.0)</td>
</tr>
</tbody>
</table>

A4. Description of calculation of wetland and floodplain submerged areas as done by PCR-GLOBWB model

The extent of saturated area of the improved Arno Scheme is not directly equivalent to the wetland extent as the parameterisation of PCR-GLOBWB includes other sources of shallow soils (e.g., urbanized areas or rocky soils and an estimate based on the orography as suggested by Hageman and Gates (2003) and does not consider the poor drainage conditions that characterize northern wetlands. In order to include poor vertical drainage conditions due to permafrost, the parameterisation of the improved Arno Scheme was updated with the circumpolar permafrost and ground ice data set of Brown et al. (1998) that provides a unified representation of the distribution and properties of permafrost and ground ice in the Northern Hemisphere (20°N to 90°N). We regridded the data set to 0.5° and neglected sporadic or isolated permafrost, thus including only discontinuous and continuous permafrost in our parameterisation. The minimum soil depth was for both classes reset to 0 whereas the fraction of the maximum soil depth over the average soil depth was left unchanged (Figure A6). The average soil depths were scaled relative to the maximum soil depth of 1.5 m of PCR-GLOBWB. For continuous area, the maximum was reset to 0.6 m, for the discontinuous permafrost to 1.2 m. Percolation to the groundwater reservoir was further restricted by the extent of ground ice (95% for continuous, 70% for discontinuous permafrost as given by Brown et al., 1998). Additional pre-processing was required to obtain the depth of the snow pack and the volumetric moisture content for the soil layers prescribed to PEATLAND-VU.
A5. Delineation of the potential wetland areas as present in the five approaches

To delineate potential wetland areas for PCR-GLOBWB approach, we used a selection of potential wetlands of the Food and Agriculture Organization (FAO/ISRIC) delineated by the 5° C limit as shown by the Figure A7 (grey area) we define as boreal/arctic area all regions which have the annual maximum temperature < 5 °C. FAO soil maps provide information about soil properties in various regions of the world. Data from FAO soil maps were incorporated in a gridded digital data set (Zobler, 1986). The wetland extent from the FAO map (Figure A6) can be considered as an upper limit to the occurrence of bogs and mires. Thus, it can be used together with the saturated fraction of the improved Arno Scheme to estimate CH4 fluxes for wetlands. The same database including the digitized information from the FAO soil maps was used by Matthews and Fung (1987) in order to evaluate the global distribution, area, and characteristics of natural wetlands and to estimate global CH4 emissions from wetlands.

The dataset of Matthews and Fung (1987) delineates different wetlands and floodplains with a spatial resolution of 1° and constant in time as five, mutually exclusive classes that are associated with a fractional inundation value. To apply our approach, we grouped forested and non-forested bogs into the class of wetlands and lumped forested swamps, non-forested swamps and alluvial plains as floodplains with their corresponding fraction of inundation (Figure A7). This information was used to derive the fractional wetland cover of Equation (5-5) and to calculate the CH4 fluxes using the average emissions from PEATLAND-VU at 1° weighed by saturated fraction.

The Prigent et al. (2007) database specifies fractional inundation at 0.25° for the entire globe for the period 1993-2000 with a monthly resolution as observed with remote sensing. It does, however, not distinguish between wetlands and floodplains and the fraction is zero whenever an area is covered with snow, thus returning fractional inundation fractions for the Arctic for part of the year only. Overall, the fractional inundation ranges between 0 and 0.78.

The period covered by the dataset of Prigent et al. (2007) covers a different period and has a finer spatial resolution. In order to use it in the comparison, a monthly climatology was derived at the degraded resolution of 0.5°. The climatology corresponds to the monthly averages of fractional inundation over the period 1993-2000 (Figure A8) where the average of the minimum fraction not equal to zero has been substituted for the snow period. This climatology then provides the maximum, potential wetland extent.

As Prigent’s dataset does not distinguish between floodplains and bogs, information from PCR-GLOBWB may be used, such as wetland and floodplain areas calculated with the use of the FAO soil map, wetland extent (Figure A6).

This information was used to calculate the CH4 fluxes per m2 for the floodplain and wetland area within a cell which can be scaled on the basis of the saturated fractions of wetlands and floodplains. These were multiplied with the monthly averaged inundation to constrain the flux to the area observed by Prigent et al. (2007).

The Lehner and Döll (2004) dataset, GLWD-3, comprises lakes, reservoirs, rivers and different wetland types in the form of a global raster map at 30 arc second resolution. It serves as an estimate of wetland extents for global hydrology and climatology models, or to identify large-scale wetland distributions and important wetland complexes (Lehner and Döll, 2004). For this study, the following fractional areas of floodplain/wetland types were extracted: floodplains contain classes 4 and 5 ("Freshwater Marsh, Floodplain", "Swamp Forest, Flooded Forest"), while the
wetlands contains class 8 ("Bog, Fen, Mire (Peatland)") as well as classes 10 and 11 ("50-100% Wetland", "25-50% Wetland"), each set to fractional covers of 75% and 37.5% respectively. The wetland/floodplain extent from the Lehner and Döll (2004) GLWD-3 is presented by Figure A9.

Kaplan (2002) empirically defines as being a wetland any area with threshold values for slope angle (< 0.3%) and volumetric soil wetness (>65%). In this way, the grid cells are sufficiently flat and with enough soil moisture on a monthly basis to sustain a wetland. He does not define floodplains.

Based on this hypothesis, PCR-GLOBWB calculated the maximum wetland extent and replaced his implicit assumption of saturated area (degree of saturation of the soil column > 65%) by the explicit fraction of saturation, excluding built-up (urban areas). 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. The maximum wetland extend defined by Kaplan (2002) is found in Figure A10.

A6. The wetland maximum extent and fractional inundation used by PCR-GLOBWB/FAO (ISRIC).

A9. GLWD3 wetland and floodplain extent after Lehner and Döll (2004).

A11. CH$_4$ arctic-boreal distribution maps as calculated with PCR-GLOBWB parameterisation using as input the FAO/ISRIC soil map. Each map represents the CH$_4$ average flux for each of the six years, 2001-2006 in g m$^{-2}$ d$^{-1}$.
A12. CH₄ arctic-boreal distribution maps as calculated with Matthews and Fung (1987) parameterisation. Each map represents the CH₄ average flux for each of the six years, 2001-2006 in g m⁻² d⁻¹.
A13. \( \text{CH}_4 \) arctic-boreal distribution maps as calculated with Prigent et al. (2007) parameterisation. Each map represents the \( \text{CH}_4 \) average flux for each of the six years, 2001-2006 in g m\(^{-2}\) d\(^{-1}\).
A14. CH$_4$ arctic-boreal distribution maps as calculated with Lehner and Döll (2004) GLWD3 parameterisation. Each map represents the CH$_4$ average flux for each of the six years, 2001-2006 in g m$^{-2}$ d$^{-1}$.
A15. CH$_4$ arctic-boreal distribution maps as calculated with Kaplan (2002) parameterisation. Each map represents the CH$_4$ average flux for each of the six years, 2001-2006 in g m$^{-2}$ d$^{-1}$. 
A16. CH$_4$ distribution maps calculated with: a) PCR-GLOBWB using as input the FAO/ISRIC soil map; b) Matthews and Fung (1987); c) Prigent et al. (2007); d) Lehner and Döll (2004); e) Kaplan (2002) parameterisations. Each map represents the monthly maximum CH$_4$ flux in g CH$_4$ m$^{-2}$ d$^{-1}$.
Appendix A

A17. Global budgets in Tg yr\(^{-1}\) for the three approaches calculated as yearly averages for each of the six years in study.

<table>
<thead>
<tr>
<th></th>
<th>2001</th>
<th>2002</th>
<th>2003</th>
<th>2004</th>
<th>2005</th>
<th>2006</th>
<th>Wetland extent area</th>
</tr>
</thead>
<tbody>
<tr>
<td>PCR-GLOBWB/FAO(ISRIC)</td>
<td>79.8</td>
<td>73.5</td>
<td>76.6</td>
<td>75.4</td>
<td>81.5</td>
<td>81.5</td>
<td>2.97 x 10(^{12}) m(^{2})</td>
</tr>
<tr>
<td>Matthews and Fung (1987)</td>
<td>38.7</td>
<td>34.8</td>
<td>38</td>
<td>34.5</td>
<td>40.5</td>
<td>40</td>
<td>2.44 x 10(^{12}) m(^{2})</td>
</tr>
<tr>
<td>Prigent et al. (2007)</td>
<td>84</td>
<td>85.9</td>
<td>88.1</td>
<td>83.4</td>
<td>96.3</td>
<td>99.1</td>
<td>4.37 x 10(^{12}) m(^{2})</td>
</tr>
<tr>
<td>Lehner and Döll (2004)</td>
<td>128.5</td>
<td>138</td>
<td>144</td>
<td>135.5</td>
<td>164.2</td>
<td>163.5</td>
<td>3.42 x 10(^{12}) m(^{2})</td>
</tr>
<tr>
<td>Kaplan (2002)</td>
<td>163.3</td>
<td>149.8</td>
<td>155.5</td>
<td>148.5</td>
<td>161.3</td>
<td>165.7</td>
<td>2.16 x 10(^{12}) m(^{2})</td>
</tr>
</tbody>
</table>

A18. Cumulative sums

We plotted, as an example, the cumulative sums of CH\(_4\) emissions for 2006 as calculated with our coupled models, PCR-GLOBWB FAO and PEATLAND-VU, because this is the year with the highest CH\(_4\) fluxes out of all the 6 years in study. Cumulative sums of the CH\(_4\) emissions over longitude bands plotted against latitude show the areas that contribute most to the CH\(_4\) emissions. Each plot represents the cumulative sum of the CH\(_4\) flux from the entire Northern Hemisphere broken down into 20\(^\circ\) x 20\(^\circ\) large boxes (Figure A18).

For most longitude bands the areas which contribute the most to the global CH\(_4\) emissions are to be found between 60\(^\circ\)-80\(^\circ\)N. For the western Siberian peatlands and north Canadian bands (-140\(^\circ\)W to -80\(^\circ\)W) high emissions start from 50\(^\circ\)N. The Russian-Siberian tundra band of 60\(^\circ\)E to 140\(^\circ\)E also accounts for pronounced emissions at higher latitudes.

A19. Figure representing the cumulative sum of CH\(_4\) emissions
A20. Site-by-site description

A) In our study, Cherskii is parameterised as a floodplain cell. Data from the Cherskii site have been compared to the flux over the anoxic part of the wetland profile (Corradi et al., 2005). The comparison spans the years 2002 - 2004, the period of measurements. The agreement between measurements and simulations is good (Table A22). However, there are some exceptions where the simulations deviate from the observations. Petrescu et al. (2008) showed that the model cannot simulate the large fluxes that occur when the groundwater table varies widely within the modelling time step, for instance as a result of rain showers. Similarly, some peaks may be caused by the ebullition of CH₄, which cannot be exactly predicted by the model. Notwithstanding, the observed variability is large and the error band comprises all simulated values.

B) Kytalyk is in our study a floodplain parameterised cell. The measurements were done from 2004 until 2006. As described in Petrescu et al. (2008), the data used for this comparison belongs to the flooded area of the site. Measurements at Kytalyk pertain to an area that is frequently flooded (Petrescu et al., 2008) and have been compared to the flux over the anoxic part of the floodplain profile. The results are averaged values over the few days when the measurements were performed. The PEATLAND-VU model also has been tested with the GLUE method (Van Huisteden et al., 2009) on a longer data set that includes data from the summer of 2007 and 2008, and for these years based on longer (1 month) field campaigns. To generate water table time series from precipitation data a different hydrological model was used (MMWH model, see Granberg et al., 1999; Yurova et al., 2007; Petrescu et al., 2008). Calibration was done for both floodplain and tundra mire sites, using the Nash-Sutcliffe objective function, and calibrating microbial population, vegetation and soil parameters. The R₀, Q₁₀ and Pox parameters proved to be the most sensitive parameters. The model provides reasonably stable results over a series of years for both types of wetlands. Flux peaks and pronounced minima in the longer measurement periods were simulated correctly. Other flux peaks generated by the model, in particular at the start of the season at snowmelt, unfortunately cannot be confirmed by data but have been reported from other sites (e.g. Hargreaves et al., 2001; Tokida et al., 2007). During 2004 to 2006, the CH₄ fluxes were measured in Kytalyk in short (few days) field campaigns during the summer period (July-August) (Petrescu et al., 2008). See Table A22 for measured values and comparison with the simulated results.

C) Lena Delta is the northern-most site with wetland cell characteristics. The full description of the site and measurement campaigns is in Sachs et al. (2008) and Wille et al. (2008). For the year 2006 CH₄ measurements were done using the closed chamber technique (Sachs et al., 2008). The values of the measured CH₄ are lower than the simulated CH₄ but the trends are similar showing more or less the same variation in time. The CH₄ measured flux represent the average of 3 chambers per micro-site (polygon) measured twice a day usually (average of 6 measurements per polygon). For simulating the CH₄ fluxes we used the PEATLAND-VU Model with the simulated water table from the PCR-GLOBWB Model as input. The comparisons between measured and simulated results are shown in Table A22.

D) Stordalen cell is parameterised as in the wetland category. We used a similar comparison approach as in Petrescu et al. (2008). This showed that the CH₄ model simulates the fluxes in good agreement with the observations. The comparison was done for the years 2004-2006 due to the availability of the observed data. Using the simulated water table depth produced by PCR-GLOBWB Model from the fen part of the Stordalen Mire, the CH₄ flux trend is similar to the
simulated one. The site specific parameters are not available for all the pixels but parameterised as in Petrescu et al. (2008). The Stordalen site shows also a good agreement between the measurements and simulations (see Table A22).

A21. Site by site characteristics

<table>
<thead>
<tr>
<th>Site name</th>
<th>Cherskii</th>
<th>Kytalyk</th>
<th>Lena Delta</th>
<th>Stordalen</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site type</td>
<td>Floodplain</td>
<td>Floodplain</td>
<td>Wetland (bog)</td>
<td>Wetland (bog)</td>
</tr>
<tr>
<td>Coordinates</td>
<td>68°36’ N, 161°20’ E</td>
<td>70°48’ N, 147°26’ E</td>
<td>72°22’ N, 126°30’ E</td>
<td>68°21’ N, 19°02’ E</td>
</tr>
<tr>
<td>Mean annual temperature</td>
<td>-12.5°C</td>
<td>-14.3°C</td>
<td>-14.7°C</td>
<td>-0.7°C</td>
</tr>
<tr>
<td>Mean annual precipitation</td>
<td>200–215 mm</td>
<td>232 mm</td>
<td>137 mm</td>
<td>300 mm</td>
</tr>
<tr>
<td>Vegetation</td>
<td>Carex appendiculata, Eriophorum angustifolium, Potentilla palustris</td>
<td>Carex/Eriophorum, Sphagnum</td>
<td>Carex aquatilis, Carex chordorrhiza, Carex rariflora, Drepanocladus revolvens, Meesia triquetra, Dryas octopetala, Salix glauca</td>
<td>Eriophorum angustifolium</td>
</tr>
<tr>
<td>Active layer thickness</td>
<td>6-51 cm</td>
<td>18-53 cm</td>
<td>30-50 cm</td>
<td>29-69 cm</td>
</tr>
</tbody>
</table>

A22. Comparison between observed CH₄ fluxes and simulated CH₄ fluxes from the four sites.

<table>
<thead>
<tr>
<th>Total averaged CH₄ flux (mg m⁻² day⁻¹)</th>
<th>Cherskii</th>
<th>Kytalyk</th>
<th>Lena Delta</th>
<th>Stordalen</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed flux</td>
<td>205.38 ± 128.95</td>
<td>268.8 ± 77</td>
<td>86.37 ± 43.67</td>
<td>179 ± 104.71</td>
</tr>
<tr>
<td>PCR-GLOBWB estimate</td>
<td>166.13 ± 99.23</td>
<td>109.29 ± 38</td>
<td>142 ± 81.9</td>
<td>137.48 ± 94.62</td>
</tr>
<tr>
<td>Matthews estimate</td>
<td>98.45</td>
<td>126.8</td>
<td>273.6</td>
<td>134.16</td>
</tr>
<tr>
<td>Lehner and Döll estimate</td>
<td>185.5</td>
<td>11.8</td>
<td>44.6</td>
<td>66</td>
</tr>
<tr>
<td>Prigent estimate</td>
<td>129.61</td>
<td>38.3</td>
<td>129.3</td>
<td>64.83</td>
</tr>
<tr>
<td>Kaplan estimate</td>
<td>58.8</td>
<td>63.3</td>
<td>43.3</td>
<td>69.16</td>
</tr>
</tbody>
</table>
A23. Explanation SCIAMACHY approach

Another approach to compare our results with available data sets would be the use of the SCIAMACHY products. The data is available for the years 2002-2004 and it shows the atmospheric CH$_4$ concentrations over the globe. These satellite observations enabled for the first time the global mapping of column-averaged atmospheric CH$_4$ mixing ratios with sensitivity down to the surface Meirink et al. (2008a). Frankenberg et al. (2006) presented a longer, two-year, SCIAMACHY CH$_4$ data set, showing that the most pronounced tropical CH$_4$ enhancements compared to model simulations occur in the months September to November. Bergamaschi et al. (2007) conducted synthesis inversions, constraining continental-scale emissions by these SCIAMACHY observations. To compare these data with our results requires separation of natural fluxes and man-made emissions. The only way is to incorporate an atmospheric transport model as done in Meirink et al. (2008a). He made a study on inverse modelling of CH$_4$ concentrations and compared the SCIAMACHY observations with output results of TM5 model (Krol et al., 2005). The introduction of another model introduces extra model uncertainty in the data-model comparisons; therefore we rely on comparison with site investigations. However, in future work such an extended model validation, next to inclusion of more site data, will help to constrain the model results more precisely.
References


References


References


References


HYDRO 1K Elevation Derivative Database and GCIP/EOP Land Characterization is available at: http://data.eol.ucar.edu/codiac/dss/id=21.078

HYDRO 1K data set is available at: http://edc.usgs.gov/products/elevation/gtopo30/hydro/index.html


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