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Seasonal variability of tropical wetland CH$_4$ emissions: the role of the methanogen-available carbon pool

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Abstract. We develop a dynamic methanogen-available carbon model (DMCM) to quantify the role of the methanogen-available carbon pool in determining the spatial and temporal variability of tropical wetland CH$_4$ emissions over seasonal timescales. We fit DMCM parameters to satellite observations of CH$_4$ columns from SCIAMACHY CH$_4$ and equivalent water height (EWH) from GRACE. Over the Amazon River basin we found substantial seasonal variability of this carbon pool (coefficient of variation = 28 ± 22 %) and a rapid decay constant ($\phi = 0.017$ day$^{-1}$), in agreement with available laboratory measurements, suggesting that plant litter is likely the prominent methanogen carbon source over this region. Using the DMCM we derived global CH$_4$ emissions for 2003–2009, and determined the resulting seasonal variability of atmospheric CH$_4$ on a global scale using the GEOS-Chem atmospheric chemistry and transport model. First, we estimated that tropical emissions amounted to 111.1 Tg CH$_4$ yr$^{-1}$, of which 24 % was emitted from Amazon wetlands. We estimated that annual tropical wetland emissions increased by 3.4 Tg CH$_4$ yr$^{-1}$ between 2003 and 2009. Second, we found that the model was able to reproduce the observed seasonal lag of CH$_4$ concentrations peaking 1–3 months before peak EWH values. We also found that our estimates of CH$_4$ emissions substantially improved the comparison between the model and observed CH$_4$ surface concentrations ($r = 0.9$). We anticipate that these new insights from the DMCM represent a fundamental step in parameterising tropical wetland CH$_4$ emissions and quantifying the seasonal variability and future trends of tropical CH$_4$ emissions.

1 Introduction

Wetlands are the single largest source of methane (CH$_4$) into the atmosphere and account for 20–40 % of the global CH$_4$ source (Denman et al., 2007; Ito and Inatomi, 2012), of which tropical wetlands account for 50–60 % of this global wetland CH$_4$ source (e.g. Cao et al., 1996; Bloom et al., 2010). Tropical wetland biogeochemistry is poorly understood compared to boreal peatlands (Mitsch et al., 2010), resulting in large inter-model discrepancies of the magnitude and distribution of tropical wetland CH$_4$ emission estimates (Riley et al., 2011). Tropical climate variability (e.g. resulting in widespread droughts, Lewis et al., 2011) can lead to large year to year variations in tropical wetland CH$_4$ emissions and subsequently the global CH$_4$ budget (Hodson et al., 2011). Moreover, Bousquet et al. (2011) found substantial disagreements between tropical wetland CH$_4$ emissions from process-based and atmospheric inversion estimates. An improved quantitative understanding of the magnitude, distribution, and variation of tropical wetland CH$_4$ emissions is therefore essential to further understanding of the global CH$_4$ cycle. Here, we parameterise tropical wetland CH$_4$ emissions, and hence introduce a predictive capability that can be used to determine future emissions and to help quantify global CH$_4$ climate feedbacks.

In wetlands and rice paddies, methanogenesis (the biogenic production of CH$_4$) occurs as the final step of anoxic organic matter decomposition (Neue et al., 1997). Factors influencing methanogenesis rates include substrate availability, soil pH, temperature, water table position and redox potential (Whalen, 2005). Wetland vegetation type and aquatic herbivore activity can also affect the transport of CH$_4$ between the soil and atmosphere (Joabsson et al., 1999; Dingemans et al.,
2011). On a global scale, seasonal variations in wetland CH$_4$ fluxes are mostly determined by temporal changes in wetland water volume and soil temperature (Walter et al., 2001; Gedney et al., 2004), and from seasonal changes in wetland extent and wetland water table depth (Ringeval et al., 2010; Bloom et al., 2010). Recent work that used SCIAMACHY lower tropospheric CH$_4$ column concentrations and Gravity Recovery And Climate Experiment (GRACE) equivalent water height (EWH) retrievals showed that the seasonality of wetland CH$_4$ emissions can be largely explained by seasonal changes in surface temperature and water volume (Bloom et al., 2010). The Amazon and Congo River basins were the only major exceptions in this study, where CH$_4$ concentrations peaked several weeks before EWH, highlighting our incomplete understanding of the processes controlling tropical wetland CH$_4$ emissions over seasonal timescales.

In this paper we focus on the seasonal lag between CH$_4$ emissions and flooding over the Amazon River basin area (Oki and Sud, 1998). We use SCIAMACHY CH$_4$ retrievals and GRACE EWH (both described in Sect. 2.2) to determine the seasonal lag between wetland CH$_4$ emissions and wetland water volume. Figure 1 shows that seasonal flooding of the Amazon basin occurs typically 1–3 months after the peak CH$_4$ concentrations, and to a lesser extent the lag persists throughout tropical wetland areas. Although typical time-lags between EWH and CH$_4$ in the Congo River basin are comparable (0–2 months), in this paper we choose to focus on the Amazon basin as it covers a larger area extent, and larger time-lags between EWH and CH$_4$ are found over this river basin. In Sect. 2, we test the hypothesis that this lag is related to the depletion of methanogen-available carbon during the onset of the tropical wet season by explicitly accounting for this carbon pool in a parameterised model of tropical wetland CH$_4$ emissions (Bloom et al., 2010). We optimise model parameters by fitting them to SCIAMACHY CH$_4$ column and GRACE EWH measurements, and use the resulting model to estimate global wetland emission estimates. In Sect. 3 we (1) compare our results to previous estimates of wetland CH$_4$ emissions and to decomposition rates of methanogen-available carbon in anaerobic environments; (2) provide an overview of additional factors which potentially influence the seasonal variability of CH$_4$ emissions in tropical wetlands; and (3) use our estimated emissions to drive the GEOS-Chem atmospheric chemistry model as an approach to test the consistency between our emission estimates and observed variations of atmospheric CH$_4$ concentration. We conclude the paper in Sect. 4.

2 Process-based model and application

Here, we introduce a methanogen-available carbon pool ($C_{\mu}$) that typically originates from labile plant litter, recalcitrant organic matter decomposition and root exudates (e.g. Wania et al., 2010). Typically, soil carbon pool decay constants are more than an order of magnitude lower than those of leaf litter (Sitch et al., 2003; Wania et al., 2010). Therefore, if $C_{\mu}$ originates mostly from the slow-decomposing recalcitrant carbon pool, then variations in $C_{\mu}$ over seasonal timescales are likely to be small. Conversely, if $C_{\mu}$ is drawn from leaf litter, then large variations in $C_{\mu}$ abundance may arise as a result of rapid litter decomposition in the tropics. Miyajima et al. (1997) measured CH$_4$ accumulation of anaerobic decomposition of incubated tropical withered tree leaves over a 200 day period. These observations showed a rapid decrease in decomposition rates over the incubation period. Bianchini Jr. et al. (2010) found similar results for anaerobic decomposition from dried and ground Oxycaryum cubense at 20°C: following a 20-day lag (where no emissions were observed) CH$_4$ produced from organic carbon decomposition peaked after a 50-day period, and then rapidly decreased. On a tropical river-basin scale, flooded areas expand at the onset of the wet season and engulf newly available plant litter; as a result, CH$_4$ emissions from plant litter may peak before the height of the water table. The occurrence of anaerobic CH$_4$ emissions from litter decomposition within sub-seasonal timescales raises the question as to whether $C_{\mu}$ significantly varies in time.

2.1 Model description

We base our model on previous work (Bloom et al., 2010) that describes the temporal variability of wetland emissions $F_{\text{CH}_4}$ (mg CH$_4$ m$^{-2}$ day$^{-1}$) as a function of EWH and surface temperature:

$$F_{\text{CH}_4} = k(T_w + D_o) Q_{10}(T_s) \frac{\Delta t}{s},$$

(1)

where at time $t$ (days), $T_w$ is the EWH, $T_s$ is the surface temperature (K), $D_o$ is the equivalent depth of the wetland soil (m), $Q_{10}(T_s)$ is the temperature dependence function implemented by Gedney et al. (2004), and $k$ is a scaling constant (mg CH$_4$ m$^{-2}$ day$^{-1}$) accounting for all temporally constant factors (e.g. Gedney et al., 2004).

Equation (1) assumes an inexhaustible source of methanogen-available carbon. Here, we account for the potential seasonal changes in $C_{\mu}$ by substituting $k$ with $\phi_0 C_{\mu}^t$, where $\phi_0$ (day$^{-1}$) is the temperature, water and carbon independent decay constant of wetland methanogenesis, and $C_{\mu}^t$ is the value of $C_{\mu}$ (mg CH$_4$ m$^{-2}$) at time $t$:

$$F_{\text{CH}_4} = \phi_0 C_{\mu}^t (T_w + D_o) Q_{10}(T_s) \frac{\Delta t}{s}.$$  

(2)

To determine temporal changes in $C_{\mu}$, we define $C_{\mu}^{t+1}$ in terms of $C_{\mu}^t$:

$$C_{\mu}^{t+1} = C_{\mu}^t + N_{\mu} \Delta t - F_{\text{CH}_4}^t \Delta t,$$

(3)

where $\Delta t$ is the time interval, $F_{\text{CH}_4}^t$ is the carbon loss due to emitted CH$_4$ (Eq. 2), and $N_{\mu}$ is the net influx of carbon.
available for methanogenesis from plant litter, root exudates, and breakdown of complex polymers from the recalcitrant carbon pool. We assume $N_\mu$ is temporally constant, and we assume wetland carbon stocks are in quasi-equilibrium on annual timescales, hence $N_\mu = F_\text{CH}_4^t$. Note that when $\phi_0$ is small, the equilibrium $C_\mu \gg N_\mu \Delta t$. In this case, $C_\mu^{t+1} \approx C_\mu^t$ and Eq. (2) converges to Eq. (1) (Bloom et al., 2010), which assumes $\phi_0 C_\mu$ is constant over seasonal timescales. In order to compare derived decay constants with observed and model values (e.g. Miyajima et al., 1997; Wania et al., 2010), we determine the annual mean decay constant of wetlands areas as ${\bar{\phi}} = F_\text{CH}_4^t / C_\mu^t$ (day$^{-1}$). Equations (2) and (3) constitute the dynamic methanogen-available carbon model (DMCM).

2.2 Data

For the sake of brevity, we only include a brief description of the datasets for our analysis and refer the reader to dedicated papers. Solar backscatter data from the Scanning Imaging Absorption Spectrometer for Atmospheric Cartography (SCIAMACHY) instrument onboard Envisat was used to retrieve the mean column concentrations of CH$_4$ in the atmosphere (Frankenberg et al., 2005). The spatial resolution of CH$_4$ retrievals is 30 km × 60 km, and the Envisat orbital geometry ensures global coverage at 6-day intervals. CH$_4$ retrievals were only achievable in daytime cloud-free conditions. The Gravity Recovery and Climate Experiment (GRACE) is a twin satellite system from which the Earth’s gravity field was retrieved at 10-day intervals. Tides, atmospheric pressure and wind are included in the applied corrections on GRACE gravity retrievals; the remaining temporal variation in GRACE gravity is dominated by terrestrial water variability (Tapley et al., 2004). We incorporated SCIAMACHY CH$_4$ concentrations, GRACE EWH and NCEP/NCAR daily 1.9° × 1.88° temperature re-analyses (Kalnay et al., 1996) into a process-based model following Bloom et al. (2010). We used the 2003–2008 SCIAMACHY column CH$_4$ retrievals (Frankenberg et al., 2008), and the CNES GRACE EWH 1° × 1° 10-day resolution product (Lemoine et al., 2007). We aggregated all three datasets to a daily 3° × 3° horizontal grid (see Bloom et al., 2010).

2.3 Global parameter optimisation

We implemented the DMCM (as shown in Eqs. (2) and (3)) on a global 3° × 3° grid for the period 2003–2009. We drove the DMCM using the aggregated daily values of $T_s^t$ and $\Gamma_w^t$. We spun up the DMCM using 2003 $T_s^t$ and $\Gamma_w^t$ values until it reached an annual equilibrium ($N_\mu = F_\text{CH}_4^t$). In contrast to Bloom et al. (2010), we supplemented the $Q_{10}(T_s)$ function with a gradual linear cut-off for temperatures for 0°C $< T_s^t < -10°C$, and when $T_s^t < -10°C$, $F_\text{CH}_4^t = 0$ as a first order approximation to wintertime CH$_4$ emission inhibition in boreal wetlands. As the $Q_{10}$ function never reached zero, this supplementary constraint effectively suppressed wintertime CH$_4$ emissions, which is broadly consistent with our current understanding of CH$_4$ emissions in boreal wetlands.

We applied the DMCM globally in order to determine (i) the magnitude of $\phi$ and $C_\mu$ in the tropics within each 3° × 3° gridcell, (ii) the potential of $C_\mu$ temporal variability on extratropical wetland environments, and (iii) CH$_4$ emissions from wetlands and rice paddies at a global scale. We determined...
the global distribution and seasonal variability of wetland CH$_4$ emissions by optimising parameters $\phi_0$ and $D_0$ at each gridcell by minimising the following cost function ($J$):

$$J = \sum_{i=1}^{n} (\kappa \times \Delta F_{CH_4}^i - \Delta S_{CH_4}^i)^2,$$

(4)

where $\Delta S_{CH_4}^i$ denotes the SCIAMACHY CH$_4$ variability, $\Delta F_{CH_4}^i$ is derived from Eqs. (2) and (3), and the conversion factor $\kappa$ (ppm kg$^{-1}$ CH$_4$ m$^{-2}$ day$^{-1}$) relates CH$_4$ emissions to the equivalent column concentration in the lower troposphere (see Bloom et al., 2010). We removed the interannual trend (represented as a second order polynomial) from $\Delta S_{CH_4}^i$ in order to minimize the influence of global atmospheric CH$_4$ trends. We then implemented the global $Q_{10}(T_s)$ optimisation approach of Bloom et al. (2010). Like other top-down parameter optimisation methods of global wetland CH$_4$ emissions (Gedney et al., 2004; Bloom et al., 2010), our method was unable to distinguish between the seasonality of CH$_4$ emissions from wetlands and rice paddies due to the concurring fluxes over seasonal timescales. However we anticipated that varying fertilisation and irrigation practices also influence the seasonality in rice paddy CH$_4$ emissions (Conen et al., 2010). We hence distinguished the sources spatially (Bloom et al., 2010), for which we had more confidence in the distribution of rice paddies. Finally, we used the IPCC global wetland and rice paddy CH$_4$ emissions median of 227.5 Tg CH$_4$ yr$^{-1}$ (Denman et al., 2007) as a base value for 2003 emissions.

We propagated the following uncertainties through our global wetland and rice paddy CH$_4$ emissions estimation (Bloom et al., 2010): (i) SCIAMACHY CH$_4$ observation errors; (ii) the uncertainty of the linear fit between $F_{CH_4}^i$ and $S_{CH_4}^i$; (iii) the uncertainty $\alpha_e = \pm 16$% associated with $\kappa$; and (iv) a global wetland and rice paddy uncertainty of $\pm 58$ Tg CH$_4$ yr$^{-1}$ (Denman et al., 2007).

We propagated SCIAMACHY CH$_4$ VMR errors to a 3°×3° resolution; compared to a global mean of $\pm 18.0$ ppb, we found mean CH$_4$ error values of $\pm 19.2$ ppb (5th–95th percentile = 6.3–37.8 ppb) over the Amazon River basin. Temporal CH$_4$ VMR error variability was dominated by the number of cloud-free CH$_4$ VMR observations within each 3°×3° gridcell for each daily timestep. We found little seasonality in the three-monthly mean propagated CH$_4$ errors (18.28–20.36 ppb). As the correlation of CH$_4$ errors within each gridcell was unknown, we chose not to weight the cost function (Eq. 4) using propagated SCIAMACHY CH$_4$ errors.

We incorporated the uncertainty of $\kappa$, $\sigma_k = \pm 16$% in our estimated CH$_4$ emissions, where $\sigma_k$ is the estimated uncertainty between surface CH$_4$ emission amplitude and CH$_4$ column VMR amplitude; this value was derived from an atmospheric chemistry transport model (GEOS-Chem) using prior emissions and SCIAMACHY averaging kernels (Bloom et al., 2010). Finally, we implemented a global wetland and rice paddy uncertainty equivalent to the variance of IPCC wetland emission estimates ($\pm 58$ Tg CH$_4$ yr$^{-1}$).

3 Results and discussion

Over the Amazon River basin, we find wetland CH$_4$ fluxes coincide with small values of $C_{\mu}$, resulting in a highly variable $C_{\mu}$ over seasonal timescales. Assuming an annual mean inundated fraction of 3.3% (Prigent et al., 2007), the median CH$_4$ flux over a flooded area is 1.06 Mg C ha$^{-1}$ yr$^{-1}$ (387 mg CH$_4$ m$^{-2}$ day$^{-1}$). The median Amazon wetland $C_{\mu} = 0.16$ Mg C ha$^{-1}$ yr$^{-1}$ with a range of 0.02–7.89 Mg C ha$^{-1}$ yr$^{-1}$ (5th–95th percentile). The large spatial variability of $C_{\mu}$ is consistent with the complexity of methanogenesis rates in wetlands (Neue et al., 1997; Whalen, 2005). Large temporal changes of $C_{\mu}$ are observed in the Amazon River basin, where the mean $C_{\mu}$ coefficient of variation ($\sigma_v$) is 28±22% over the period 2003–2009. When we allow $C_{\mu}$ to vary in extra-tropical regions, we find a median of $\sigma_v < 0.1$%, and as a result the relatively small $C_{\mu}$ variability does not influence the seasonality of CH$_4$ emissions outside the tropics. For rice paddy areas in southeast Asia we find a median of $\sigma_v = 4.8$%. We acknowledge that due to the varying rice cultivation practices around the world (Conen et al., 2010), the effects of rice paddy irrigation and the timing of fertilisation on $C_{\mu}$ cannot be captured by the DMCM approach.

To determine whether our derived values for $C_{\mu}$ and $\bar{\phi}$ are relevant to tropical ecosystems, we compared them against laboratory measurements of anaerobic decomposition of withered leaves from a wetland region in Narathiwat, Thailand (Miyajima et al., 1997). We simulated CH$_4$ production from $C_{\mu}$ at each model gridcell for a 200-day period without fresh carbon input ($N_p=0$), and we used inundated fraction observations (Prigent et al., 2007) to determine the flux magnitude over flooded areas only. Figure 2 shows the cumulative CH$_4$ production over a 200-day period for (i) simulated decomposition from derived $\bar{\phi}$ and $C_{\mu}$ values over the Amazon, (ii) simulated decomposition from derived $\bar{\phi}$ and $C_{\mu}$ values over boreal wetlands, and (iii) upscaled withered leaf mineralisation rates by Miyajima et al. (1997) using a median of 17.5 Mg C ha$^{-1}$ yr$^{-1}$ fine and coarse woody debris (Malhi et al., 2009). For boreal and tropical $C_{\mu}$ decomposition, the median cumulative CH$_4$ emissions, 68% confidence interval, and mean decay constants ($\bar{\phi}$) are shown. For the withered leaf mineralisation rates, we show the mean fitted decay constant ($\bar{\phi}$) and the range and median cumulative CH$_4$ emissions.

The top-down parameter estimation of $\bar{\phi}$ and $C_{\mu}$ suggest plant litter $C_{\mu}$ is a fundamental component of tropical CH$_4$ emission seasonality. Our top-down estimation of anaerobic decomposition rates for tropical wetland CH$_4$ emissions compare favourably with laboratory measurements of anaerobically produced CH$_4$; while the magnitude of tropical
Table 1. Model and observed decay constants for organic matter decomposition in anaerobic environments.

<table>
<thead>
<tr>
<th>Study</th>
<th>Decay Constant (yr(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amazon Wetlands ((\bar{\phi}_{\text{Amazon}}))</td>
<td>2.6—9.6(^a) (median=5.9)</td>
</tr>
<tr>
<td>This Study: Top-down wetland CH(_4) emission parameter optimisation</td>
<td></td>
</tr>
<tr>
<td>Withered Leaves (35 (^\circ)C)</td>
<td>4.0</td>
</tr>
<tr>
<td>Miyajima et al. (1997): Decay constant from anaerobic tropical leaf CH(_4) mineralisation</td>
<td></td>
</tr>
<tr>
<td>Wetland Macrophyte Decomposition</td>
<td>1.0—5.5</td>
</tr>
<tr>
<td>Longhi et al. (2008)(^b): Measured decomposition rates in Paluda di Ostiglia, Italy</td>
<td></td>
</tr>
<tr>
<td>Soil Carbon Pool (10 (^\circ)C)</td>
<td>0.001—0.03</td>
</tr>
<tr>
<td>Leaf Litter (10 (^\circ)C)</td>
<td>0.35</td>
</tr>
<tr>
<td>Root Exudates (10 (^\circ)C)</td>
<td>13</td>
</tr>
<tr>
<td>Wania et al. (2010): Bottom-up CH(_4) Emissions from Northern Peatlands</td>
<td></td>
</tr>
</tbody>
</table>

\(^a\) 68 % confidence interval  
\(^b\) Mass-loss decomposition rates

\(C_\mu\) decomposition is more than a factor of two smaller than laboratory measurements (Miyajima et al., 1997), the mean decay constant \(\overline{\phi}_{\text{Amazon}} = 0.011\) day\(^{-1}\) compares well to \(\phi_{\text{leaf}} = 0.017\) day\(^{-1}\) for withered leaf decomposition. The larger laboratory measurements (Miyajima et al., 1997) are partially explained by an incubation temperature of 35 \(^\circ\)C (cf. a mean surface temperature in the Amazon basin of 23 \(^\circ\)C), and the lack of observations for coarse woody debris decomposition. As a result of relatively high \(\overline{\phi}\) values, measured leaf decomposition and model CH\(_4\) emissions both show a significant reduction of CH\(_4\) emission rates throughout the 200-day period. In contrast, the boreal decay constant (\(\overline{\phi}_{\text{Boreal}} = 0.0003\) day\(^{-1}\)) indicates relatively constant CH\(_4\) emission rates throughout the 200-day period.

Table 1 shows a comparison between observed and model decay constants derived from a variety of methods. The range of \(\overline{\phi}_{\text{Amazon}}\) values are within the order of magnitude of leaf and wetland macrophyte decay constants (Miyajima et al., 1997; Longhi et al., 2008; Wania et al., 2010). We believe that \(\overline{\phi}_{\text{Amazon}}\) is an indicator for the cumulative decay constant of the rapid anaerobic decomposition of root exudates, plant litter decomposition, and the contribution of recalcitrant carbon pools. For a more detailed \(\overline{\phi}_{\text{Amazon}}\) comparison with observed and model decay constant values, an estimation of the overall \(\overline{\phi}\) in wetland CH\(_4\) production from bottom-up process-based models (e.g. Wania et al., 2010) is needed.

Figure 3 shows the total CH\(_4\) flux over the central branch of the Amazon River (0\(^\circ\) N–6\(^\circ\) S, 40\(^\circ\) W–80\(^\circ\) W). The temporal changes in \(C_\mu\) result in a significantly different timing for CH\(_4\) emissions over the tropics in comparison to the Bloom et al. (2010) water volume and temperature dependence.
approach. While in the dry season the minimum CH$_4$ fluxes coincide with the lowest GRACE EWH, peak CH$_4$ fluxes occur during the rising water phase. The DMCM optimisation predicts that the accumulation of carbon in the dry season results in higher $C_{\mu}$ values at the onset of the wet season. This carbon pool is then rapidly depleted during the wet season. As a result, CH$_4$ emission rates begin to decrease before the peak water phase in the wet season.

In order to determine the importance of temperature variability in estimating $\Phi$ and the $C_{\mu}$ coefficient of variation, $c_v$, we performed a temperature-driven sensitivity analysis on the DMCM. Using a range of $Q_{10}(T_s) = 1.2 - 4$ to repeat the global parameter optimisation (Sect. 2.3), we derived a corresponding ranges of $\Phi = 0.018 - 0.012$ and $c_v = 20.2 - 31.3 \%$, respectively, for the Amazon River basin. Hence, larger $C_{\mu}$ seasonality is associated with higher $Q_{10}(T_s)$. We note that the seasonal variability of $C_{\mu}$ and the relatively high turnover rates are a prominent feature in the Amazon River basin across a range of prescribed $Q_{10}(T_s)$ values.

Other hypotheses that could explain the lag between CH$_4$ and EWH include the temporal variability of (a) macrophyte biomass, (b) water column oxidation, (c) redox potential, and (d) soil pH. The presence of aquatic macrophytes plays an important role in the production of methane in wetland soils, as macrophytes produce carbon available for methanogenesis, facilitate the transport of CH$_4$ to the atmosphere, transport O$_2$ to the subsurface (e.g. Laanbroek, 2010), and can inhibit light and re-aeration in aquatic environments (Pierobon et al., 2010). Hence, an increase in macrophyte biomass during the rising water phase (e.g. Silva et al., 2009) could result in seasonal changes in CH$_4$ emissions in tropical wetland environments due to enhanced plant-mediated transport and an increase in labile carbon in aquatic environments. Conversely, seasonal macrophyte growth may result in increased methanotrophy due to increased O$_2$ transport to the subsurface. Seasonal variability in redox potential in wetland environments is controlled by microbial activity, and hence is indirectly controlled by temperature, nutrient availability, water table level and root biomass, amongst other factors (Seybold et al., 2002; Thompson et al., 2009; Schmidt et al., 2011). However, few long-term measurements of redox potential have been performed over seasonal timescales, and further research is required to determine the large-scale redox variability in wetland environments. CH$_4$ oxidation within the water column (e.g. Schubert et al., 2010) has also been proposed as a mechanism explaining reduced CH$_4$ emissions during the peak of the wet season (Mitsch et al., 2010), although this would result in a second CH$_4$ peak at the end of the wet season. The absence of this peak in our analysis suggests this process plays only a minor role in the seasonality of tropical wetland CH$_4$ emissions. Soil pH has been found to temporally vary over seasonal timescales and, in particular, has been found to increase with decreasing redox potential (e.g. Singh, 2001; Seybold et al., 2002), although pH responses to redox potential and water table can vary widely (e.g. Singh et al., 2000; Thompson et al., 2009). Although seasonal variation in wetland pH as a significant control on CH$_4$ emissions is a viable hypothesis, to our knowledge there are currently no repeat measurements of pH in response to flooding in tropical wetlands. Other mechanisms that could temporally affect CH$_4$ emissions include the subsurface sulfur and iron cycles (Laanbroek, 2010).

We also expect uncertainties in the seasonal variability of tropical wetland CH$_4$ fluxes to arise from (i) the use of GRACE EWH as a proxy for wetland water volume and (ii) the first order approximation of a temporally constant $N_{\mu}$. GRACE monthly EWH change uncertainties of 1.0–2.1 cm were reported by Wahr et al. (2004); over the Amazon River basin, EWH variability is between 0.30–0.42 m for 2003–2009. However, GRACE EWH is only a proxy for wetland water volume. Papa et al. (2008) found a strong concurrence in the seasonal cycle of GRACE EWH, inundated fraction, and modelled water storage. We also find strong seasonal covariance over the main branch of the Amazon River (Fig. 1). Although independently GRACE and inundated fraction (Prigent et al., 2007) provide proxies for wetland water volume, a better understanding of basin-scale hydrology could ultimately be achieved via a synthesis of all available hydrological parameters (e.g. Azarderakhsh et al., 2011).

We chose a constant value of $\overline{N_{\mu}} = \overline{P_{\text{CH}_4}}$ as a first order approximation of methanogen-available carbon input in wetlands. However, the likely factors influencing the temporal variability of $N_{\mu}$ are the seasonal variability of root exudates and leaf litter. While root exudates are strongly dependent on
Fig. 5. Northern Hemisphere (NH, top) and Southern Hemisphere (SH, bottom) mean observed and model methane anomalies from surface concentration measurements, 2003–2008. Surface concentration measurements (black) are from the GasLab, AGAGE and ESRL networks (Francey et al., 1996; Prinn et al., 2000; Cunnold et al., 2002; Dlugokencky et al., 2009). The GEOS-Chem global 3-D chemistry transport model (Fraser et al., 2011) is driven by wetland CH4 emission estimates from Fung et al. (1991) (blue), Bloom et al. (2010) (red), and our new top-down approach (green).

Table 2. Estimates of total annual Amazon River basin wetland CH4 emissions (Tg CH4 yr−1).

<table>
<thead>
<tr>
<th>Study</th>
<th>Amazon Wetland CH4 Emissions (Tg CH4 yr−1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melack et al. (2004)</td>
<td>22</td>
</tr>
<tr>
<td>Fung et al. (1991)</td>
<td>5.3</td>
</tr>
<tr>
<td>Riley et al. (2011)</td>
<td>58.9*</td>
</tr>
<tr>
<td>Bloom et al. (2010)</td>
<td>20.0</td>
</tr>
<tr>
<td><strong>This study</strong></td>
<td><strong>26.2 ± 9.8</strong></td>
</tr>
</tbody>
</table>

* High tropical fluxes by Riley et al. (2011) are a result of anomalously high predicted net primary productivity in the Community Land Model (CLM version 4).

By globally integrating the DMCM method, we estimated tropical wetlands emit 111.1 Tg CH4 yr−1, where Amazon wetlands account for 26.2 Tg CH4 yr−1 (24 %). Table 2 shows our estimates are within the range of other independent Amazon wetland emission CH4 estimates. Figure 4 shows the zonal profile of our top-down approach with the associated uncertainty estimates. We capture three main features of global wetland and rice paddy emissions – i.e. peaks over the tropics, subtropics and lower mid-latitudes (mainly due to rice), and boreal latitudes – in agreement with previous studies (Bloom et al., 2010; Fung et al., 1991; Riley et al., 2011). In comparison to our previous work (Bloom et al., 2010), we find a slight reduction in boreal wetland emissions (3.2 %), primarily due to the introduction of a gradual cut-off in methanogenesis rates under 0 °C (Sect. 2.3). During 2003–2008, the global change in CH4 wetland emissions amounted to an increase of 7.7 Tg CH4 yr−1, mostly as a result of boreal wetlands (3.1 Tg CH4 yr−1) and tropical wetlands (3.4 Tg CH4 yr−1), while there was also a significant increase of 1.1 Tg CH4 yr−1 from mid-latitude wetlands. The increase in Southern Hemisphere extra-tropical wetland emissions (0.13 Tg CH4 yr−1) did not significantly contribute to the CH4 wetlands emissions growth during 2003–2008. Boreal wetland emissions increased by 1.6 Tg CH4 yr−1 in between 2006–2007 and decreased by 0.1 Tg CH4 yr−1 in 2007–2008. Tropical wetland emissions increased by 1.4 Tg CH4 yr−1 in 2006–2007 and 1.2 Tg CH4 yr−1 in 2007–2008. Other work shows a larger interannual variability, a similar year-to-year trend for boreal wetlands, and a decrease in the atmospheric CH4 inversion estimates of tropical wetland emissions for 2007–2008 (Bousquet et al., 2011).

Finally, we used our wetland and rice CH4 emission estimates to drive the GEOS-Chem global 3-D atmospheric chemistry and transport model (described and evaluated by Fraser et al., 2011), allowing us to test consistency between our emissions to surface measurements of CH4 concentrations. We sampled the model at the time and geographical location of the surface CH4 measurements from the GasLab, AGAGE and ESRL networks (Francey et al., 1996; Prinn et al., 2000; Cunnold et al., 2002; Dlugokencky et al., 2009). Figure 5 shows model and observed CH4 concentration anomalies (i.e. minus the mean trend) for the Northern and Southern Hemispheres. We chose to remove the interannual trend from all CH4 concentrations to compare the seasonality of model and surface measurements of CH4. We show that the DMCM approach better describes the observed seasonality in both hemispheres ($r_{NH} = 0.9$, $r_{SH} = 0.9$), and the amplitude of the Southern Hemisphere seasonality is largely improved in comparison to the GEOS-Chem runs using Fung et al. (1991) and Bloom et al. (2010) CH4 emissions.
4 Concluding remarks

Understanding the temporal controls of temperature, water volume and carbon content of wetlands is crucial in determining the global and regional seasonal cycle of wetland CH$_4$ emissions. We showed that incorporating a temporally variable methanogen-available carbon pool, $C_\mu$, in our top-down approach results in a significant improvement in describing the temporal behaviour of tropical and global CH$_4$ emissions.

By implementing our dynamic methanogen-available carbon model (DMCM) on a global scale, we determined the effects of a seasonally variable $C_\mu$ on the seasonality of wetland CH$_4$ emissions in the Amazon River basin. We found a median decay constant of $\overline{\tau}_\text{Amazon} = 0.017$ day$^{-1}$ over the Amazon River basin. Seasonal changes in $C_\mu$ in the tropics largely explained the seasonal lag between SCIAMACHY observed CH$_4$ concentrations and GRACE equivalent water height. The relatively high seasonal variability in $C_\mu$ (mean $c_v$ = 28 %) over the Amazon River basin resulted in peak CH$_4$ emissions occurring mostly 1–3 months prior to the peak water height period; in contrast, the median boreal $C_\mu$ variability was $c_v < 0.1 \%$. We showed a substantial improvement in simulating the seasonality of surface concentrations when using the GEOS-Chem atmospheric chemistry transport model with our wetland and rice CH$_4$ emission estimates ($r = 0.9$). These improvements in the magnitude and temporal dynamics of tropical CH$_4$ emissions will ultimately help constrain global inverse modelling efforts.

We anticipate that this work will lead to further and more detailed parameterisation of tropical wetland CH$_4$ emissions, and we expect our tropical wetland CH$_4$ emission parameterisation will reduce the uncertainty in forecasting future changes in wetland CH$_4$ emissions.

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