A multi-scale comparison of modeled and observed seasonal methane emissions in northern wetlands

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Abstract:
Wetlands are the largest global natural methane (CH$_4$) source, and emissions between 50°N and 70°N latitude contribute 10-30% to this source. Predictive capability of land models for northern wetland CH$_4$ emissions is still low due to limited site measurements, strong spatial and temporal variability in emissions, and complex hydrological and biogeochemical dynamics. To explore this issue, we compare wetland CH$_4$ emission predictions from the Community Land Model 4.5 (CLM4.5-BGC) with site to regional scale observations. A comparison of the CH$_4$ fluxes with eddy flux data highlighted needed changes to the model’s estimate of aerenchyma area, which we implemented and tested. The model modification substantially reduced biases in CH$_4$ emissions when compared with CarbonTracker CH$_4$ predictions. CLM4.5 CH$_4$ emission predictions agree well with growing season (May-September) CarbonTracker Alaskan regional-level CH$_4$ predictions and site-level observations. However, CLM4.5 underestimated CH$_4$ emissions in the cold season (October-April). The monthly atmospheric CH$_4$ mole fraction enhancements due to wetland emissions are also assessed using the WRF-STILT Lagrangian transport model coupled with daily emissions from CLM4.5 and compared with aircraft CH$_4$ mole fraction measurements from the Carbon in Arctic Reservoirs Vulnerability Experiment (CARVE) campaign. Both the tower and aircraft analyses confirm the underestimate of cold season CH$_4$ emissions by CLM4.5. The greatest uncertainties in predicting the seasonal CH$_4$ cycle are from the wetland extent, cold season CH$_4$ production and CH$_4$ transport processes. We recommend more cold-season experimental studies in high latitude systems, which could improve understanding and parameterization of ecosystem structure and function during this period. Predicted CH$_4$ emissions remain uncertain, but we show here that benchmarking against observations across spatial scales can inform model structural and parameter improvements.
1 Introduction

Natural wetlands are the largest natural methane (CH$_4$) source, contributing up to 34% of global CH$_4$ emissions (Kirschke et al., 2013). Between 1980 and 2009, estimated global annual CH$_4$ emissions from wetlands varied from 115 to 231 Tg CH$_4$ in top-down atmospheric inversion models and 169 to 284 Tg CH$_4$ in bottom-up process-based land models (Kirschke et al., 2013). Peat-rich bogs and fens lying between 50°N and 70°N constitute about half of the global wetland area, and release 10-30% of the total wetland CH$_4$ (Wania et al., 2010; Zhuang et al., 2004; Bergamaschi et al., 2009; Riley et al., 2011). Much of the northern wetland area is in the permafrost zone, which stores 1035±150 Pg soil organic carbon for the 0-3m soil depth (Hugelius et al., 2014). When permafrost soils thaw, CH$_4$ is produced under anaerobic conditions by methanogenic archaea. Once CH$_4$ is produced, it can be oxidized by methanotrophic archaea. CH$_4$ surface emissions occur through several transport pathways: aqueous and gaseous diffusion, ebullition, and aerenchyma diffusion and advection. At any point in the soil, the CH$_4$ concentration is governed by the balance between CH$_4$ production in anoxic zones, CH$_4$ consumption in oxic zones, transport, and atmospheric CH$_4$ diffusion at the soil-atmosphere interface.

Many interacting factors (e.g., temperature, thaw depth, soil moisture, depth of the water table, vegetation type) affect CH$_4$ production and emission. CH$_4$ production has a positive response to temperature increase (Van Hulzen et al., 1999; van Winden et al., 2012; Hommeltenberg et al., 2014) and laboratory incubations of soil samples from the active layer show that large variability of $Q_{10}$ values for CH$_4$ production (1.5 to 28, Segers et al., 1998) is related to site-specific peatland type and organic matter quality (Lupascu et al., 2012). CH$_4$ emissions also show positive temperature dependence above freezing. The temperature dependence of surface CH$_4$ emission is much stronger than that of respiration and photosynthesis, which indicates increases in both CH$_4$ emissions and the ratio of CH$_4$ to CO$_2$ emissions with seasonal increases in temperature (Yvon-Durocher et al., 2014). The positive temperature dependence of CH$_4$ emissions may only be valid when CH$_4$ oxidation is less sensitive to temperature (van Winden et al., 2012). The $Q_{10}$ value for CH$_4$ oxidation was reported to be 1.4 to 2.1 in northern peat soils (Dunfield et al., 1993). Strong oxidation temperature sensitivity can lead to decreased CH$_4$ surface emissions with rising temperature (Wang et al., 2014). The positive dependence of CH$_4$ emissions on soil temperature can be most significant in areas with sufficient soil moisture or a shallow water table (Roulet et al., 1992; Moosavi et al., 1996; Wickland et al., 1999). The dependency of CH$_4$ emissions on temperature can vanish at high temperature and low water table (Hommeltenberg et al., 2014). At low water table levels, large CH$_4$ oxidation can mask the CH$_4$ production temperature sensitivity in the net emissions. CH$_4$ production under sub-zero temperatures was reported in incubation experiments (Clein and Schimel, 1995; Brouchkov et al., 2003), however, the mechanisms that regulate CH$_4$ production under cold temperatures have not been clarified.

Soil water content exerts strong control on CH$_4$ emissions by affecting belowground carbon decomposition and root growth (Iversen et al., 2015). A lowered water table typically reduces CH$_4$ production and emission, because of a higher aerobic to anaerobic respiration ratio in the soil column and CH$_4$ oxidation during diffusive
transport through the oxygen-rich surface layer (Whalen and Reeburgh, 1990). If CH$_4$
produced in anoxic zones (e.g., below the water table) is transported to the atmosphere
through aerenchyma, the impact of methanotrophy on net CH$_4$ emissions is diminished
(Bartlett et al., 1992; Torn and Chapin, 1993; King et al., 1998; Juutinen et al., 2003;
McEwing et al., 2015). The reduced methanotrophic impacts vary with vascular species
cover and root density and are more common in tall vegetation, because taller plants have
more extensive root systems that enable more methanogenesis and pore water CH$_4$ to
escape to the atmosphere (van Fischer et al., 2010). The correlation between water table
depth and CH$_4$ emission can be very weak if the water table drops in an already oxic
surface layer (Sturtevant et al., 2012).

The seasonal cycle of CH$_4$ emissions and their physical controls are strongly
controlled by the freeze-thaw cycle in northern wetlands, and its regulation of wetland
extent. The northern wetland area retrieved from the 19- and 37-GHz passive microwave
Special Sensor Microwave/Image (SSM/I) brightness temperature database shows that
maximum inundation is usually observed during July, August, and September in north
America (48°N-68°N) and between June and September in northern Eurasia (Mialon et
al., 2005). The inundation dynamics retrieved from SSM/I and ISCCP observations, ERS
scatterometer responses, and AVHRR visible and near-infrared reflectance also show that
maximum inundation occurs in July and August in northern boreal regions (55°N-70°N)
(Prigent et al., 2007). The inferred wetland extent increases rapidly during the spring
thaw period and shrinks again during the fall freeze period; though it is unclear at large
scales how much of this seasonal cycle is due to changes in the areal fraction of land in
which water ponds at the surface versus changes in the phase of that water. The
interannual variability of high-latitude summer wetland extent is very small. Larger
interannual variability during the intermediate seasons arises from the large variability of
the timing and extent of snowmelt and accumulation (Mialon et al., 2005). For boreal
bogs north to 50°N, the variation in wetland area contributed about 30% to the annual
emissions and can explain the interannual variation in regional CH$_4$ emissions (Ringeval
et al., 2010).

Site measurements have shown great variability in seasonal CH$_4$ emissions
(Wilson et al., 1989; Mastepanov et al., 2008; 2013; Zona et al., 2016). In the late fall to
winter, the surface water or shallow peat zone are frozen, and CH$_4$ produced below the
frozen layer can be trapped. Only a small portion of the trapped CH$_4$ is oxidized because
of low oxygen concentrations below the frozen layer (Mastepanov et al., 2008). Observed
CH$_4$ emissions during spring thaw are highly variable and contribute substantially to total
annual emissions. CH$_4$ fluxes during the spring thaw period contributed 11% to the
annual budget over an aapa mire in Finnish Lapland (Hargreaves et al., 2001). The
emission amounts can be 24% of the total annual emissions during the spring period after
snowmelt next to an open pool in Caribou Bog, Maine, while the proportion can be as
high as 77% in the adjacent upland area (Comas et al., 2008). In the non-inundated
upland tundra, the cold season (September to May) emissions account for more than 50% of
the annual CH$_4$ emissions (Zona et al., 2016). Although wetlands can contribute a
large proportion of annual CH$_4$ emissions during the cold season, the seasonal peak of
CH$_4$ emissions is usually observed in the summer (Pickett-Heaps et al., 2011; Zona et al.,
2016). A transport model combined with flight measurements showed the peak CH$_4$
emission to be in July-August in the Hudson Bay Lowlands (Pickett-Heaps et al., 2011).
Although the recorded emission pulses during spring thaw and late fall (Song et al., 2012; Tokida et al., 2007; Rinne et al., 2007; Mastepanov et al., 2008; 2013) may be more localized and of minor importance to annual emissions (Chang et al., 2014; Rinne et al., 2007), the pulses indicate the complexity and heterogeneity in the seasonal CH$_4$ cycle.

Many modeling studies have shown that there is large uncertainty in predictions of spatial patterns of CH$_4$ emissions from natural wetlands at the regional and global scales (Melton et al., 2013; Bohn et al., 2015). This uncertainty can be roughly split into poor knowledge of water table and soil moisture dynamics versus poor knowledge of CH$_4$ fluxes per unit area of land with a given water table depth or soil moisture state; both contribute substantially to the overall uncertainty. One approach to reducing this overall uncertainty is to focus on the seasonal cycles of CH$_4$ emissions at the site scale (where inundation dynamics can be more easily constrained) versus at larger scales to ask whether model predictions and errors are consistent across these scales. The temporal dynamics of CH$_4$ emissions over the season cannot be ignored when calculating long-term CH$_4$ budgets (Morin et al., 2014). To investigate the seasonal cycle of CH$_4$ emissions in northern wetlands and the underlying processes in a climate model context, we evaluated and modified the CH$_4$ biogeochemistry module in the Community Land Model (CLM 4.5). Seasonal cycles of CH$_4$ emissions in Alaskan wetlands are analyzed based on the modified model predictions, CH$_4$ emission measurements at high-latitude sites, CarbonTracker CH$_4$ emission estimates, and atmospheric inversion estimates of surface CH$_4$ emissions from data collected in the Carbon in Arctic Reservoirs Vulnerability Experiment (CARVE). The models and data are described in section 2. Multi-scale comparison results and discussions are given in section 3, and concluding remarks in section 4.

2 Data and Methods

2.1 Models description

2.1.1 CH$_4$ model in CLM4.5-BGC

The CH$_4$ biogeochemistry model used here (CLM4Me; Riley et al. (2011)) has been coupled to the revised land model CLM4.5, which includes numerous changes to vegetation, soil biogeochemistry, and hydrology from the CLM4.0 in which CLM4Me was originally developed. CLM4Me includes representation of CH$_4$ production, oxidation, and transport through the soil column. Transport includes multiple pathways: aerenchyma transport, ebullition, and aqueous and gaseous diffusion. Aerenchyma is the most efficient pathway for gas exchange between the soil and atmosphere in wetlands or aquatic environments, through which atmosphere O$_2$ is supplied to roots and the rhizosphere while CH$_4$ is removed from the soil to shoots and the atmosphere. In CLM4Me, aerenchyma transport ($A$) is parameterized as gaseous diffusion in response to a concentration gradient between the soil layer ($z$) and the atmosphere ($a$) as:

$$A = \frac{C(z) - C_a}{\frac{\partial C}{\partial z} + \frac{r_a}{r_l^2}}$$

(1)
where $D\ (m^2\ s^{-1})$ is the free-air gas diffusion coefficient, $C(z)\ (mol\ m^{-3})$ is the gaseous concentration at depth $z$, dimensionless $r_L$ is the ratio of total root length to root depth, $p$ (-) is tiller porosity; $T\ (m^2\ m^{-2})$ is specific aerenchyma area, $r_a\ (s\ m^{-1})$ is the aerodynamic resistance between the surface and the atmospheric reference height, and $r_r\ (-)$ is the root mass fraction in the soil layer. The aerenchyma area $T$ is seasonally varying with phenology $S$ (described below):

$$T = \frac{f_N N_a S}{0.22} \pi R^2,$$

(2)

where $N_a\ (gC\ m^{-2})$ is annual net primary production (NPP), $R\ (2.9 \times 10^{-3}\ m)$ is the aerenchyma radius, $f_N$ is the belowground fraction of current NPP, and the factor 0.22 (gC) is the mass of C per tiller. The dimensionless term $S$ is included in CLM4Me to capture seasonal cycles of aerenchymous tissues. In the absence of data on phenology of aerenchyma, $S$ was originally taken as the leaf area index (LAI).

The default method for calculating inundation fraction ($F_{def}$) remains the same as described in Riley et al. (2011), which applied a simple inversion model to represent the spatial inundation:

$$F_{def} = p_1 e^{-z_w/p_2} + p_3 Q_r,$$

(3)

The three parameters ($p_1, p_2, p_3$) are optimized with the inundation map by Prigent et al. (2007). $z_w$ is simulated water table depth (m) and $Q_r$ is surface runoff (mm s$^{-1}$). We also applied an estimate of inundation fraction $F_{S+G}$ (Poulter et al., In Review) derived from seasonal cycle of inundation fraction from the Surface WAter Microwave Product Series Version 2.0 (SWAMPS, Schroeder et al., 2015) developed at the NASA Jet Propulsion Laboratory with the Global Lakes and Wetlands Dataset (GLWD, Lehner and Doll, 2004) to discuss the potential uncertainties in CH$_4$ emissions caused by wetland area.

Our model is driven by half-degree CRUNCEP V5 6-Hourly Atmospheric Forcing dataset (1901-2013) (http://dods.extra.cea.fr/data/p529vio/cruncep/readme.htm). Monthly wetland CH$_4$ emissions are simulated between the year 2000 and 2012 during which $F_{S+G}$ is available. The monthly CH$_4$ emissions in half-degree resolution are regridded to 1$^\circ$×1$^\circ$ and averaged longitudinally to compare with CarbonTracker predicted CH$_4$ fluxes. Daily wetland CH$_4$ emissions are simulated for year 2012 and 2013 to calculate the atmospheric enhancements of CH$_4$ due to modeled surface emissions.

### 2.1.2 WRF-STILT modeling of CH$_4$ transport
We simulate the atmospheric CH$_4$ mole fraction enhancements due to wetland emissions by combining the CLM4.5 predicted daily surface emissions with the land surface influences (“footprint”) calculated by the Weather Research and Forecasting-Stochastic Time-Inverted Lagrangian Transport (WRF-STILT) model (Henderson et al.; 2015). WRF-STILT estimates the upwind surface influence along the flight track of the CARVE aircraft by releasing 500 particles at the point of flight measurement and allowing them to stochastically disperse in reverse time over 10 days (Henderson et al., 2015). The resolution of the resulting footprint sensitivity used in this study is 0.5°×0.5°, covering 30-90°N, circumpolar. However, we assume that CH$_4$ transported from areas outside of Alaska are most likely mixed thoroughly in the atmosphere before they reach Alaska, and therefore only contribute to the background abundance of CH$_4$.

2.2 Measurements of CH$_4$

2.2.1 Site-Scale Observations

We compare CLM4.5 CH$_4$ emission predictions with data obtained from published studies and recent measurements of northern hemisphere static chamber (SC) measurements at 10 sites and eddy covariance (EC) measurements at 10 sites, of which 8 are in Alaska (Supplement Table S1). The eddy covariance measurements in Alaska (Fig. S2) are obtained at the Barrow Environmental Observatory (BEO1) tower operated by the Next Generation Ecosystem Experiment (NGEE)-Arctic group; Barrow Environmental Observatory tower (BEO2), Biocomplexity Experiment South (BES) tower, Climate Monitoring and Diagnostics Laboratory (CMDL) tower, Atqasuk (ATQ) tower and Ivotuk (IVO) tower operated by Global Change Research Group at San Diego State University (Zona et al., 2016); tower in Fairbanks (FAI, Iwata et al., 2015) operated by International Arctic Research Center, the University of Alaska Fairbanks; and tower at the Imnavait Creek watershed (IMN, Euskirchen et al., 2012). Monthly means are calculated across each observational record to compare to predicted mean seasonal CH$_4$ cycle. We discarded the monthly mean if the number of valid measurement days is less than half a month.

2.2.2 Comparisons to Airborne Measurements

The regionally integrated CH$_4$ mole fraction enhancements over Alaska were calculated from the CH$_4$ mole fractions measured by NOAA and Harvard Picarro spectrometers aboard a NASA C-23B aircraft (N430NA) during CARVE aircraft flights (Chang et al., 2014). The Harvard CH$_4$ measurements were gap filled with the NOAA CH$_4$ measurements to create a continuous 5-s time series. The flight measurements were conducted on selected days from May to September in 2012 and April to October in 2013 during the Carbon in Arctic Reservoirs Vulnerability Experiment (CARVE) campaign, for a total of 31 flight days in 2012 and 43 flight days in 2013 (Fig. S1 and Table S2). The measurements of CH$_4$ with concurrent CO mole fractions above 150 ppb are excluded to remove possible CH$_4$ production from biomass burning. In Alaska, atmospheric boundary layer depth is in the range of 1100-1600 m above ground level (agl) during April and October according to COSMIC satellite and Radiosonde data.
We assume that the observed concentration fluctuations below 500 m agl can be used to infer the variation of surface CH$_4$ fluxes; the measurements above 1600 m agl are used to infer background mole fraction of CH$_4$. The monthly mean enhancements in observed atmospheric CH$_4$ mole fraction is compared to that estimated from the CLM4.5 CH$_4$ enhancements.

### 2.2.3 Comparisons to Global-Scale Inversions

To compare our methane emissions with global and regional scale inversions, we use monthly regional CH$_4$ emissions predicted by CarbonTracker (Peters et al., 2007; Bruhwiler et al., 2014) at 1° × 1° resolution. In CarbonTracker estimates, the natural CH$_4$ emissions correspond to wetlands, soils, oceans, insects, and wild animals. To examine the land CH$_4$ emissions only, we apply the CLM land mask to exclude the inferred CarbonTracker CH$_4$ emission from the ocean surface. CarbonTracker CH$_4$ estimates are available from January 2000 through December 2010; we therefore limit comparisons against the CLM4.5 predictions to this period.

### 3 Results and Discussion

#### 3.1 Model constraints and comparison with observations

We performed sensitivity analyses of all the parameters affecting seasonal CH$_4$ production, oxidation, and emission pathways and found that the parameterization of aerenchyma transport has the greatest impact on the seasonal CH$_4$ emissions in saturated areas. The CH$_4$ surface flux sensitivity to aerenchyma is most sensitive to aerenchyma area in saturated conditions, and decreases with increasing aerenchyma area, because increased O$_2$ fluxes through aerenchyma cause more CH$_4$ oxidation in the rhizosphere (Riley et al., 2011). Meng et al. (2012) tested plant functional type (pft)-specific fine root carbon (C$_{FR}$) as a proxy of aerenchyma area and found that aerenchyma area dependence on C$_{FR}$ leads to about 39% increases in global annual CH$_4$ emissions. In that study, an early spring spike in CH$_4$ emission through aerenchyma transport was shown at a Michigan site in both LAI and C$_{FR}$ based aerenchyma area. Our analysis shows that the simulated CH$_4$ burst through aerenchyma transport during spring thaw is very common in areas experiencing winter dormancy. In CLM4.5, CH$_4$ production in a given volume of soil is proportional to heterotrophic respiration (HR) in that soil volume, adjusted by soil temperature, pH, redox potential, and variation of seasonal inundation fraction. In the model, CH$_4$ production starts when the soil temperature is above the freezing point. However, CLM4.5 LAI lags behind the primary thaw day, which, because the original representation of aerenchyma in CLM4.5 is tied directly to LAI, results in a very low aerenchyma area and thus low aerenchyma transport of O$_2$ into the soil during spring thaw period. Only a very small portion of the CH$_4$ produced in the soil column is oxidized, allowing a large fraction of CH$_4$ to be transported to the surface by aerenchyma. The low oxidation rate also occurs when aerenchyma area is calculated with C$_{FR}$.

The uncertainty in representing the seasonality of aerenchyma area is due to (1) poor current understanding of root dynamics and their control on aerenchyma area and (2) scant relevant observations. In tundra, the aboveground production is often not a good
proxy for belowground production, because the soil temperature peaks later in the
growing season than solar irradiance (Sullivan and Welker, 2005; Sloan, 2011). Further,
root dynamics are strongly species dependent. Root growth of *Eriophorum angustifolium*
may not be delayed when soil temperature is near 0°C (Chapin, 1974; Billing et al., 1977),
while *Dupontia Fischeri* produces many fewer root tips at these low temperatures. In
*Eriophorum vaginatum*, fine root growth is lagged significantly behind the aboveground
spring growth flush (Kummerow and Russell, 1980).

To eliminate the possible bias in the seasonal variation of roots and the extremely
low oxidation rate which caused CLM4.5 to predict a large CH₄ burst from inundated
areas during the spring thaw, we modified the model parameter $S$ to be constant, which is
used in the aerenchyma area estimation. We constrained $S$ using global total CH₄
emissions estimated by top-down and bottom-up simulations during 2000-2009 (Kirschke
et al., 2013) and site-level measurements. We exclude the CH₄ emission from non-
inundated areas for the analysis of seasonal dynamics because the model shows very
small seasonal contribution of CH₄ emissions from non-inundated areas globally (Fig. 1).
This CH₄ emission pulse from non-inundated areas, which may be related to soil moisture
anomalies during spring thaw, has not been experimentally validated, but can lead to
large biases in simulated CH₄ emissions from northern high latitudes (>50°N) in May and
June (Fig. 1a and 1b). This simplification of the model produced seasonal cycles that did
not contain the large springtime CH₄ emission bursts, and we therefore used this modified
version for all experiments here.

We assessed the sensitivity of the modeled CH₄ fluxes to parametric uncertainty
in the constant dimensionless factor $S$, as described above. $S$ has a direct effect on the
magnitude of modeled CH₄ emissions via its control of oxygen diffusion through the soil
column and thus CH₄ oxidation. When $S = LAI$, the very low LAI in the spring thaw
period leads to low oxidation and consequently overestimated CH₄ net emissions
compared to CarbonTracker predictions. During the growing season, the model
overestimates LAI at high latitude (Tian et al., 2004) leading to high oxidation and
consequently underestimated net CH₄ emissions (Fig. 1e and f). However, few
observations of aerenchymous tissue biomass are available to provide an a priori
constraint to this value. Our goal here is to use a reasonable value of this parameter, not
to fully characterize the uncertainty of the parameter choice on CH₄ emissions.

Based on a comparison of the globally integrated CH₄ flux with other global
estimates, we choose $S=4$, which resulted in an estimated annual total CH₄ emission of
228 [Inter-annual Variability (IAV): 221- 239] Tg CH₄ yr⁻¹ with $F_{def}$ and 206 [IAV: 200-
217] Tg CH₄ yr⁻¹ with $F_{s+G}$ during the period 2000 - 2009. The top-down and bottom-up
models provide estimates of CH₄ emissions from natural wetlands of 175 [IAV: 142-208]
Tg CH₄ yr⁻¹ and 217 [IAV: 177-284] Tg CH₄ yr⁻¹, respectively, during the same period
(Kirschke et al., 2013). The mean CH₄ emission predicted by CLM4.5 is about 42 Tg
CH₄ yr⁻¹ lower than the original CLM4Me prediction (annual mean of 270 Tg CH₄ yr⁻¹
from 1948 to 1972), but slightly larger than the mean value from other bottom-up and
top-down models. The disagreement between studies with different models is as large as
66% (Kirschke et al., 2013), hence our estimate is well within the range of values from
top-down constraints and underscores the uncertainty involved in using such a constraint
in inferring model parameters.
Compared with CarbonTracker predictions, CLM’s biases of underestimated growing-season CH$_4$ emissions north of 56°N and biases of overestimated CH$_4$ emissions in 2-53°N and 34-56°S are reduced when using $S = 4$ compared to the default parameterization (Fig. 1d and f). For the global zonal mean, the CLM CH$_4$ prediction biases are reduced with $F_{S+G}$ (RMSE=2.5 mg CH$_4$ m$^{-2}$ day$^{-1}$) compared with $F_{def}$ (RMSE = 3.1 mg CH$_4$ m$^{-2}$ day$^{-1}$). With $F_{S+G}$, the biases are much reduced in 2-50°N and 30-58°S. However, negative CH$_4$ emission biases in the tropics remain (Fig. 1c and 1e). The differences in CH$_4$ emissions using SWAMPS-GLWD and CLM4.5 predicted inundation fraction implies that the prediction uncertainties are not only from the biogeochemical parameterization but also from the wetland extent, consistent with several recent model inter-comparison analyses (Melton et al., 2013; Bohn et al., 2015). In Alaska, the predicted annual CH$_4$ emissions between 2000 and 2010 are 1.47±0.20, 1.58±0.07, and 1.12±0.05 Tg CH$_4$ yr$^{-1}$ for CarbonTracker, CLM4.5 with $F_{S+G}$, and CLM4.5 with $F_{def}$, respectively. Although our predicted annual emissions are reasonable compared with most land surface model predictions, the May to September predictions are about 50-70% of the emissions estimated using an atmospheric inversion based on CARVE observations of 2.1±0.5 Tg CH$_4$ yr$^{-1}$ (Chang et al., 2014).

3.2 Seasonal CH$_4$ emissions

3.2.1 Site level comparison

The mean seasonal cycle of predicted CH$_4$ emissions is calculated from the 2000-2012 monthly mean in a 0.5°×0.5° grid cell where site measurements exist, while the seasonal cycle of site measurements is calculated for the measurement years. If multiple measurement sites and multiple measurement years with the same measurement method (SC or EC) exist within a given grid cell, the observations are averaged to create a grid cell mean value that can be directly compared with the modeled value for that grid cell. In the 10 site-level static chamber measurements at saturated sites (Fig. 2a-l), the seasonality is well predicted by the revised CLM4.5 CH$_4$ model at most sites. Measurements and predictions show the peak emission month to be July or August at most sites, except the site in Michigan, USA (Fig. 2f) where the model successfully predicted the peak emissions in May. However, the model misrepresents the seasonality at the Stordalen (Sweden) (Fig. 2a and k) and the Boreas NSA (Canada) (Fig. 2i) site. At the Ruoergai (China) (Fig. 2j), the model does not show a strong seasonal variation from April to September, and notably underestimates the growing season CH$_4$ emissions. The underestimation of growing season emissions is also found in the Minnesota (USA), Michigan (USA), and Boreas NSA (Canada) sites (Fig. 2d, 2e, 2f and 2h). The sites experiencing soil frost with valid measurements in the cold season demonstrate the CLM4.5 underestimation of CH$_4$ emissions during this period (Fig. 2a, 2d, 2e and 2i).

The eddy covariance measurements from four sites, the BEO1, BEO2, BES, and CMDL sites are in the same model grid cell, therefore, the measurements in these four sites are aggregated to the same grid cell as that of Alaska (Fig. 2m). As the footprints of the measurement towers were not estimated, all the modeled CH$_4$ emissions at eddy covariance sites are weighted with an observationally estimated seasonal-invariant range of inundation faction: Stordalen: 80-100%; Boreas SSA: 50-90%; Barrow: 60-100%;
Atqasuk: 10-30%; Ivotuk: 5-25%; Fairbanks: 0.5-2.5% and IMN: 5-25%. Measurements at the Stordalen site (Fig. 2a and k) show very different CH₄ emission patterns in seasonality and magnitude for different years and measurement methods. The model significantly underestimates CH₄ emissions even with the maximum fraction of inundation in Stordalen (Fig. 2k). In comparison with the static chamber measurements at Alaska (Fig. 2h), the model predicts a much shorter CH₄ emission season at the non-inundated sites (Fig. 2m-q). The estimated CH₄ emissions begin in April at Ivotuk, Fairbank, and Imnavait. At the northern sites, Barrow and Atqasuk, the estimated CH₄ emissions begin in May. In the short emission season, the model underestimates CH₄ emissions in June and July at Barrow and Atqasuk and in July at Imnavait, even with the maximum inundation estimation. While the cold-season measurements at Barrow, Atqasuk, and Ivotuk show large CH₄ emissions from October to April in agreement with the static chamber measurements at the sites with cold season soil frost, predicted CH₄ emissions end in October at all the Alaskan sites. The largest monthly mean emissions in Alaska cold season are 24.8±9.0 mg CH₄ m⁻² day⁻¹ measured in October at Ivotuk.

A number of factors affect the correspondence between site-level CH₄ emission observations and CLM4.5 predictions (Fig. 2), including: (1) we used reanalysis climate forcing data which may lead to some of the differences with the site observations; (2) we used the model’s default surface characterization, which is unlikely to exactly match the actual vegetation and soil properties; (3) the spatial and temporal coverage of the site data are sparse; (4) the inter-annual variation of wetland CH₄ emission can be significant; (5) the method of measuring CH₄ fluxes varied from site to site and (6) the seasonal fraction of inundation in eddy covariance tower footprint is unknown. We also expect differences between our CLM4.5 predictions and those reported in Riley et al., (2011) at the site-level comparison, because: (1) simulations in this study were done at higher resolution (0.5°x0.5°) than those in Riley et al. (2011) (1.9° x2.5°); (2) the current simulations are forced by CRUNCEP climate, while Riley et al., (2011) simulations were forced with Qian et al., (2006) climate; (3) the S parameter is changed, as discussed above; and (4) the overall water and carbon cycles of CLM changed substantially between CLM4.0 and CLM4.5 (Koven et al., 2013). The site-level discrepancies occur because of the uncertainties discussed above and those arising from other parameters (Riley et al., 2011), including: Q₁₀ of CH₄ production and oxidation, CH₄ half-saturation oxidation coefficient, O₂ half-saturation oxidation coefficient, maximum oxidation rate of CH₄ oxidation, and impact of pH and redox potential on CH₄ production.

### 3.2.2 Regional CH₄ emissions comparison

The biases between CLM4.5 and CarbonTracker CH₄ emissions vary with latitude (Fig. 3). The aggregated $F_{S<0}$ led to larger CH₄ emission biases in Alaska (RMSE = 4 mg CH₄ m⁻² day⁻¹) compared to the CH₄ prediction with $F_{def}$ (RMSE = 3 mg CH₄ m⁻² day⁻¹), although it led to smaller global CH₄ emission biases. In Alaska between 58-66°N during the growing season, CLM4.5 using $F_{def}$ has good agreement with CarbonTracker predictions. In this region, CH₄ emissions begin in May, peak in July and August, and end in October (Fig. 4). In May and June, CarbonTracker shows a weak CH₄ sink (~O[10⁻²-10⁻¹] mg CH₄ m⁻² day⁻¹) in contrast to a CLM4.5 predicted weak CH₄ source (~O[10⁻¹] mg CH₄ m⁻² day⁻¹) with $F_{def}$ and stronger CH₄ source (~O[1] mg CH₄ m⁻² day⁻¹) with
$F_{S+G}$ in the interior region of Alaska (Interior Alaska) between 63°N-66°N. We hypothesize that this discrepancy occurs because of the difference in the two wetland datasets and the accounting of CH$_4$ emissions from the non-inundated areas in CarbonTracker. Net CH$_4$ consumption occurs at dry sites where oxygen is available in the top soil layers (Wickland et al., 1999); however, CH$_4$ fluxes from the non-inundated areas which could be substantial (Zona et al., 2016) are excluded in CLM4.5 predictions shown in Fig. 3, as described in Methods. Interior Alaska has a highly continental climate with warm and relatively dry summers and extremely cold winters. The weak CH$_4$ source in the dry summer is thus caused by a reduced wetland extent in Interior Alaska. Interior Alaska experiences the most rain events in autumn, mainly in August and September (Hinzman et al., 2006), which restores some of the extent of wetlands and leads to increases in CH$_4$ emissions in August and early September. CarbonTracker successfully represented the restored wetland in August and September but not CLM4.5 (Fig. 3 and 4). The autumn emission period is very short and ends with the onset of winter, resulting in a strong drop in CH$_4$ emissions in October.

The CLM4.5 underestimation of northern (> 68°N) Alaska site-level CH$_4$ emissions during the growing season at some sites is confirmed with comparison to CarbonTracker inversions (Fig. 3b). In southern and northern coastal Alaska, CLM4.5 predicts a much shorter CH$_4$ emission season and a smaller magnitude of CH$_4$ emissions than CarbonTracker. The period of the largest underestimation by CLM4.5 is from May to July with the maximum underestimation of about 9.2 mg CH$_4$ m$^{-2}$ day$^{-1}$ in June. The underestimated CH$_4$ emissions occur with both $F_{S+G}$ and $F_{def}$ in the north of 68°N. During the cold season from October to April, CLM4.5 predictions with $F_{S+G}$ or $F_{def}$ are consistently smaller than CarbonTracker estimates across all the latitudes. The mean underestimation of cold season CH$_4$ emission is less than 1 mg CH$_4$ m$^{-2}$ day$^{-1}$, which is much smaller than the underestimation we found compared to site level measurements. In comparison with CarbonTracker, CLM4.5 predicted 0.46±0.07Tg and 0.39±0.08Tg less Alaska wide CH$_4$ emissions in cold season (October to April) with $F_{S+G}$ and $F_{def}$, respectively.

The CarbonTracker inversions suggest 21.9±3.2% of the annual Alaska CH$_4$ emissions occur during the cold season, while CLM4.5 predicts only 3.5±1.3% and 8.3±3.0% (with $F_{def}$ and $F_{S+G}$, respectively) occur during the cold season. When September and April are included in the “cold season”, the contribution is increased to 45.3±4.5% by CarbonTracker, which is slightly smaller than the cold season contribution (50±9%) inferred from site-level (BEO2, BES, CMDL, ATQ and IVO) measurements (Zona et al., 2016). The September-April contributions to annual emissions predicted by CLM4.5 are 32.1±8.1% and 40.1±14.7% of the predicted annual emissions with $F_{S+G}$ and $F_{def}$ respectively. Although CH$_4$ fluxes from the ocean surface are excluded, we cannot exclude some influence of coastal grid cells on the CarbonTracker estimates.

The atmospheric CH$_4$ mole fraction enhancements calculated from CLM4.5 predicted CH$_4$ emissions are lower than the CARVE measured CH$_4$ mole fraction enhancements (Fig. 5). However, in contrast to the emission underestimations that only occur from May to July, the monthly atmospheric CH$_4$ mole fraction enhancements are underestimated throughout the year, with a maximum underestimation in August (Fig. 5a). The CARVE measured peak mole fraction enhancement due to surface CH$_4$
emissions is in August for both 2012 and 2013. Although CLM4.5 predicted the peak
CH₄ mole fraction enhancement in August, 2012, predicted seasonal CH₄ mole fraction
enhancements are much smaller in 2013 and peaks in September. The underestimation of
cold season mole fraction CH₄ enhancements by CLM4.5 leads to 24.0±9.2 ppb and
18.9±17.3 ppb lower CH₄ mole fraction enhancements in April and October 2013,
respectively. From April to October, the two-year mean monthly atmospheric CH₄ mole
fraction enhancements are underestimated by 15 ppb in WRF-STILT-CLM model
predictions. The underestimation may not be attributed to anthropogenic CH₄ source and
agricultural waste because: (1) we excluded both observed and modeled CH₄ mole
fraction enhancements when [CO]>150 ppb, given that anthropogenic CH₄ mole fraction
enhancements are consistently correlated to CO mole fraction enhancements (Zona et al.,
2016) and (2) The CH₄ emissions from agricultural waste does not show strong seasonal
variation according to CarbonTracker estimates. The large standard deviation of CARVE
observed CH₄ mole fraction enhancements implies that the CH₄ emissions have large
spatial and temporal variability. The CLM4.5 predictions are generally within the
observed range of variation except in April and May in 2013.

The very low cold season CH₄ emission predictions at site and regional scales
occurs because of the assumed temperature sensitivity for CH₄ production when the soil
temperature of a given layer is at or below freezing (i.e., no CH₄ production occurs in that
soil layer). The multi-layer structure of CLM4.5 can in principle generate CH₄ emissions
deeper in the soil after the surface has frozen, though even then, modeled diffusion rates
through frozen surface layers are low. Although the measurements show winter CH₄
emissions, it remains uncertain whether these emissions are from production at low
temperature or residual CH₄ from the end of the growing season. Understanding which of
these is occurring is important for diagnosing how to improve model representation of the
processes responsible for the wintertime fluxes. The cold season underestimation by
CLM4.5 is also partly attributed to the low wetland area during this period at high
latitudes (currently, F_{def} is set to zero when snow is present). Given the current
observations of CH₄ emissions during the cold season, we believe these two factors need
to be re-evaluated in CLM4.5.

3.3 Interannual variation of CH₄ cycle

The CLM4.5 simulated Alaska CH₄ emissions using F_{def} are in very good
agreement with CarbonTracker-CH₄ emission in the growing season but biased in the
cold season (Fig. 6). The largest growing season discrepancies occur in 2006 and 2007.
Bruhwiler et al. (2014) attributed the CarbonTracker 2007 CH₄ emission anomaly to
warmer temperatures and higher than normal precipitation. However, the CRUNCEP
reanalysis data we used to force CLM4.5 do not have a positive precipitation anomaly in
either 2006 or 2007 (Fig. 7a). In contrast, there is a strong negative precipitation
CRUNCEP reanalysis data are not directly related to the predicted and measured wetland
area anomaly or CH₄ emission anomaly. The mean air temperature in 2007 is only
slightly higher than 2000-2012 mean air temperature (Fig. 7b). The correlation analysis
implies that the model predicted interannual CH₄ variation is mainly explained by
temperature variation (Fig. 8a, r=0.86, P=0.0007), followed by the default wetland extent
(F_{def}) variation (Fig. 8b, r=0.65, P=0.03), but weakly explained by SWAMPS-GLWD
wetland extent ($F_{S+G}$) variation ($r=0.44$, $P=0.17$) and precipitation variation ($r=0.18$, $P=0.58$). When the CH$_4$ predictions are calculated with $F_{S+G}$, correlation between the interannual variation of CH$_4$ and variation in $F_{S+G}$ ($r=0.18$, $P=0.59$), precipitation ($r=0.36$, $P=0.29$), and temperature ($r=0.32$, $P=0.33$) are substantially reduced. Interannual variation of CH$_4$ emissions by CarbonTracker are not well correlated to SWAMPS-GLWD wetland extent variation ($r=0.33$, $P=0.32$), variations in CRUNCEP temperature ($r=-0.23$, $P=0.49$), or precipitation ($r=-0.06$, $P=0.86$).

4 Concluding remarks

We implemented and tested needed changes to the estimate of aerenchyma area in CLM4.5. The modeled and measured CH$_4$ emissions and enhancements in atmospheric mole fractions of CH$_4$ are used to analyze the seasonal wetland CH$_4$ emission cycle in Alaska. Both the measurements and model predictions show large latitudinal variability of CH$_4$ seasonal cycles. At the site level, CLM4.5 generally captures the seasonality in growing season CH$_4$ emissions. However, comparing eddy covariance CH$_4$ observations with the model predictions is complicated by the unknown fraction of inundation in the footprint of the measurement tower, which may cause large variations in CH$_4$ emission predictions. Measurements from the sites experiencing wintertime soil frost imply that CH$_4$ emissions continue in the cold season (October to April). The likely incorrect treatment of CH$_4$ production under soil frost in CLM4.5 leads to underestimates of the wintertime emissions. This conclusion is confirmed by the discrepancies between CLM4.5 and CarbonTracker predictions, although the cold season discrepancies between CLM4.5 and CarbonTracker are much smaller than the discrepancies between CLM4.5 and site-level measurements. The differences between the seasonality predicted by CLM4.5 and CarbonTracker vary with time and latitude, although the Alaska area-integrated CH$_4$ emissions agree well. Besides the strength of wintertime CH$_4$ emissions, the main discrepancies between CLM4.5 and CarbonTracker estimates are northern and southern coastal area CH$_4$ emissions. The inundation area leads to uncertainties in predictions of seasonal and interannual variability of CH$_4$ emissions. Compared with the CLM4.5 predicted inundation area, the aggregated $F_{S+G}$ inundation led to smaller global CH$_4$ emission biases than $F_{def}$ (RMSE dropped from 3.1 mg CH$_4$ m$^{-2}$ day$^{-1}$ to 2.5 mg CH$_4$ m$^{-2}$ day$^{-1}$) between CLM4.5 and CarbonTracker. In contrast, the $F_{S+G}$ inundation area increased seasonal emission biases in Alaska by increasing RMSE from 3 to 4 mg CH$_4$ m$^{-2}$ day$^{-1}$ compared with the CLM4.5 predicted inundation. The larger SWAMPS-GLWD inundation area leads to much stronger Alaska wide annual CH$_4$ emissions compared to those calculated from the default predicted inundation area. CLM4.5 predictions show that the interannual variations of CH$_4$ emissions are correlated with the reanalysis air temperature and wetland extent variation. In contrast, interannual variation in CarbonTracker CH$_4$ emissions is weakly related to interannual variation in SWAMPS-GLWD wetland area and reanalysis precipitation and temperature.

The CLM4.5 CH$_4$ module constrained from global total annual CH$_4$ emissions does not accurately represent the seasonal cycles at the regional and site scale seasonal cycles due to large temporal and spatial heterogeneity in surface CH$_4$ emissions and wetland extent. Further improving the CH$_4$ biogeochemical model at the seasonal and annual time scales requires further extensive experiments to better understand climate controls on above- and below-ground physiological processes and how vegetation...
controls gaseous transport (e.g. CH₄ production under low temperatures). Although cold
season site-level measurements are rare, the large discrepancies in winter emissions
between CLM4.5 and CarbonTracker predictions and site measurements indicate that
studies on winter ecosystem activities and wetland evolution in high latitude would be
valuable.

Acknowledgements: Funding for this study was provided by the US Department of
Energy, BER, under the RGCM program and NGEE-Arctic project under contract # DE-
AC02-05CH11231. We thank the CARVE flight group for efforts on CARVE science
flights. CarbonTracker CH₄ results provided by NOAA ESRL, Boulder, Colorado, USA
from the website at http://www.esrl.noaa.gov. The eddy covariance tower data used in
this study were supported by the Division of Polar Programs of the National Science
Foundation (NSF) (Award 1204263); Carbon in Arctic Reservoirs Vulnerability
Experiment (CARVE), an Earth Ventures (EV-1) investigation, under contract with the
National Aeronautics and Space Administration; and Department of Energy (DOE) Grant
DE-SC005160. Logistical support was funded by the NSF Division of Polar Programs.
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Fig. 1. Zonal mean biases of CH$_4$ emissions between CLM4.5 predictions and CarbonTracker (CH$_4$ CLM4.5-CH$_4$ CarbonTracker) with SWAMPS-GLWD ($F_{S+G}$) and CLM4.5 predicted ($F_{def}$) inundation fraction: CLM4.5 predictions of both inundated and noninundated emissions with $F_{S+G}$ (a) and $F_{def}$ (b), while aerechyma area is corrected with $S=4$; CLM4.5 predictions of inundated emissions only with $F_{S+G}$ (c) and $F_{def}$ (d), while aerechyma area is corrected with $S=4$; CLM4.5 predictions of inundated emissions only with $F_{S+G}$ (e) and $F_{def}$ (f), while aerechyma area is parameterized by default $S=LAI$. 
Fig. 2. Comparison of monthly mean simulated net CH$_4$ flux between 2000 and 2012 and observed monthly mean net CH$_4$ emissions in measurement year(s). The site measurements with static chamber are shown in (a-j) and measurements with eddy covariance (EC) towers are shown in (k-q). The error bars are standard deviation of monthly mean. The measurements with EC tower are weighted with a range of Inundation Fraction (IF) based on best estimates available: Stordalen: 80-100%; Boreas SSA: 50-90%; Alaska-Barrow: 60-100%, Alaska-Atqasuk: 10-30%; Alaska-Ivotuk: 5-25%; Alaska-Fairbanks: 0.5-2.5%, Alaska-IMN: 5-25%. Detailed description of the sites and measurements are shown in Table S1.
Fig. 3. The 2000-2010 zonal mean annual cycle of CH$_4$ emission (mg CH$_4$ m$^{-2}$ day$^{-1}$) across Alaska predicted by CarbonTracker (a), and biases of CLM4.5 with CLM4.5 predicted inundation fraction ($F_{def}$) (b) and SWAMPS-GLWD inundation fraction ($F_{S+G}$) (c). The 0.5°×0.5° CLM4.5 is regridded to 1°×1° to be consistent with CarbonTracker.
Fig. 4. CLM4.5 simulated mean monthly CH₄ emissions with $F_{def}$ across years 2000-2012.
Fig. 5. The monthly mean atmospheric mole fraction enhancements in CH$_4$ estimated by WRF-STILT-CLM4.5 and CARVE measurements. (a) Observed and simulated monthly CH$_4$ mole fraction enhancements in 2012 and 2013; (b) Linear regression of measured versus modeled CH$_4$ mole fraction enhancements. The error bars are standard deviation of monthly mean.
Fig. 6. Time variation of integrated CH₄ (Tg CH₄ yr⁻¹) emissions from Alaska by CarbonTracker (brown), CLM4.5 with internally-predicted fraction of inundation $F_{\text{def}}$ (blue) and CLM4.5 SWAMPS-GLWD fraction of inundation $F_{S+G}$ (green).
Fig. 7. The anomalies of annual precipitation and inundated area in Alaska (a) and the anomalies of annual mean temperature (b). The anomalies are calculated by subtracting the average between 2000-2012.
Fig. 8. The correlation between CLM-predicted annual CH$_4$ emission anomalies and mean annual temperature anomalies (a) and correlation between annual CH$_4$ emission anomalies and predicted inundated area anomalies during 2000-2010. The anomalies are calculated by subtracting the average between 2000-2010.