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Evaluation of $CH4MOD_{wetland}$ and Terrestrial Ecosystem Model (TEM) used to estimate global CH_4 emissions from natural wetlands

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Supplementary material S1 Model calibration of CH4MOD$_{\text{wetland}}$

We used the independent datasets from the literature and the field measurements for model calibration. The vascular plants provide an effective mechanism by which CH_4 can be transported to the atmosphere (Chanton et al., 1992; Schimel, 1995; Shannon et al., 1996). According to previous study (Walter et al., 1996; Zhang et al., 2002), grasses and sedges are good gas transporters, but shrubs and trees are poor ones. T_{veg} ranges from 0 (plants without aerenchyma) to 1 (plants with well-developed aerenchyma). For herbaceous plants and woody plants, f_r was the average value of several observed proportion of BNPP to the total NPP derived from the data sets compiled from the amount of literatures (Gill and Jackson, 2000; White et al., 2002). F_N was calculated by the initial concentrations of nitrogen and lignin (g kg^{-1}) in the plant litter (Li et al., 2010). The nitrogen and lignin concentration of the above-ground and below-ground litter for grass and forest were from the global data set developed by the Oak Ridge National Laboratory Distributed Active Archive Center (ORNL-DAAC) (White et al., 2002; Gordon and Jackson., 2003). VI and P_{ox} are calibrated using the CH_4 measurements from three wetland sites (Table 1). CH_4 measurements from the Sanjiang Plain, China in year 2002 (Hao, 2006; Song et al., 2009; Yang et al., 2006) and from the Wuliangsu lake, China in year 2003 (Duan et al., 2005) were used to make calibration for the wetland dominated by the herbaceous plants. CH_4 measurements from Sarawak, Malaysia (Table 1) (Melling et al., 2005) in year 2002 were used to make calibration for the wetland dominated by the woody plants. The calibration was done by running CH4MOD$_{\text{wetland}}$ for the observation period driven with the local climate, soil and vegetation data at each site. By setting the increment of 0.1 for VI and P_{ox}, the model was run for all combinations of VI within the range of 0.5-3.0 and P_{ox} within the range of 0.1-1 until the root-mean-square error (RMSE) between the daily simulated and observed CH_4 fluxes was minimized. After setting VI and P_{ox}, the empirical constant of the salinity influence (a) is calibrated as -0.025 by minimizing the RMSE between observed fluxes and simulated fluxes at the coastal wetland in Chongming island, China in year 1997 (Li et al., 2016) . Table 2 shows the main parameter values for different wetland types. Site-level parameters were extrapolated to the 0.5°×0.5° pixel of the global natural wetland map.

Supplementary material S2 Model calibration of TEM

Supplementary material S2 Model calibration of TEM

In this study, the vegetation and soil data sets were used to assign vegetation- and soil-specific parameters to each grid cell globally. The methane emission in wetland simulated in TEM was mainly controlled by the following parameters, which include the ecosystem-specific maximum potential CH_4 production rate (M_{GO}), the dynamic Q_{10} coefficient indicating the dependency of CH_4 production to soil temperature (D_{Q10}), the reference temperature used in the Q_{10} function for simulating the effects of soil temperature on methanogenesis (T_{REF}), and maximum daily NPP for a particular ecosystem (MaxFresh). These parameters are calibrated using the CH_4 measurements from 5 sites (Table 1). CH_4 measurements from Toolik Lake, USA in year of 1992 and 1993 (Schimel et al., 1994; 1995), from Saskatchewan, Canada, in year of 1995 (Sellers et al., 1997), from the Sanjiang Plain, China in year 2002 (Hao, 2006; Song et al., 2009; Yang et al., 2006), from Sarawak, Malaysia (Melling et al., 2005) in year 2002, from the coastal wetland in Chongming island, China in year 1997 (Li et al., 2016) was used to calibrate parameters for tundra, peatland, marsh, swamp and coastal wetland. We used the Monte-carlo approach to calibrate parameters for each wetland type (Zhuang et al., 2004). Specifically, the intervals of each parameter were firstly determined according to the former studies (Lu and Zhuang, 2012; Zhu et al., 2013; Zhuang et al., 2004). Then, the parameters were randomly sampled within the intervals based on uniform distribution. Consequently, the CH_4 emission simulated by TEM with these parameters was compared with the observed by using the coefficient of determination and RMSE. These steps were repeated 5000 times to obtain the set of optimized parameters which made the model simulation closest to the observation. (Table S2 described the main parameter values of TEM model)

Supplementary material S3: Equations used to calculate the statistics

The RMSE was used to measure the coincidence between the measured and the modeled values. The RMD was calculated to evaluate the model for any systematic bias (Brisson et al., 2002). A positive EF value indicates that the simulated values describe the trend in the measured data better than the mean of the observations, while a negative value indicates that the simulated values describe the data less well than the mean of the observations (Smith et al., 1997) The CD is a measure of the proportion of the total variance in the observed data that is explained by the predicted data (Smith et al., 1997).

We first calculated RMSE as follows:

$$\mathrm{RMSE} = \frac{100}{\bar{O}} \sqrt{\frac{\sum_{i=1}^{n} (P_i - O_i)^2}{n}} \tag{1}$$

where $\bar{O}$ represents the average value of the observations. P_i and O_i represent the simulated and observed values, respectively. n represents the number of observations.

We then decomposed the RMSE into three components:

$$\frac{1}{n}\sum_{i=1}^{n}(P_i - O_i)^2 = (\bar{P} - \bar{O})^2 + (S_P - rS_O)^2 + (1 - r^2){S_O}^2 \tag{2}$$

where $\bar{P}$ is the mean modeled value, and

$${S_P}^2 = \frac{1}{n}\sum_{i=1}^{n}(P_i - \bar{P})^2 \tag{3}$$

$${S_O}^2 = \frac{1}{n}\sum_{i=1}^{n}(O_i - \bar{O})^2 \tag{4}$$

$$\mathrm{r} = \frac{\sum_{i=1}^{n}(P_i - \bar{P})(O_i - \bar{O})}{\{\sum(P_i - \bar{P})^2 \sum(O_i - \bar{O})^2\}^{1/2}} \tag{5}$$

The first component, $(\bar{P} - \bar{O})^2$, measures the bias in the simulation procedure. In this study, if the simulation consistently overestimates or underestimates the CH_4 fluxes, this component will have a large value. If the value of the second component, $(S_P - rS_O)^2$, is zero, the regression between the simulated and observed CH_4 fluxes has a slope of 1. This component often occurs in subjective forms of simulation where the simulations are biased upward if the observed CH_4 fluxes are low but are biased downward when the observed CH_4 fluxes are high. The third component, $(1 - r^2){S_O}^2$, can be considered to be a measure of the error due to random disturbances.

Finally, we normalized the above components by dividing each component by $\frac{1}{n}\sum_{i=1}^{n}(P_i - O_i)^2$. The ultimate proportions of the errors were thus defined as:

$$U_M = \frac{(\bar{P} - \bar{O})^2}{\frac{1}{n}\sum_{i=1}^{n}(P_i - O_i)^2} \tag{6}$$

$$U_R = \frac{(S_P - rS_O)^2}{\frac{1}{n}\sum_{i=1}^{n}(P_i - O_i)^2} \tag{7}$$

$$U_E = \frac{(1 - r^2){S_O}^2}{\frac{1}{n}\sum_{i=1}^{n}(P_i - O_i)^2} \tag{8}$$

And hence

$$U_M + U_R + U_E = 1 \tag{9}$$

RMD, *EF* and *CD* were calculated as follows:

$$RMD = \frac{100}{\bar{O}}\sum_{i=1}^{n}\frac{P_i - O_i}{n} \quad (10)$$

$$EF = 1 - \frac{\sum_{i=1}^{n}(P_i - O_i)^2}{\sum_{i=1}^{n}(\bar{O} - O_i)^2} \quad (11)$$

$$CD = \frac{\sum_{i=1}^{n}(O_i - \bar{O})^2}{\sum_{i=1}^{n}(P_i - \bar{O})^2} \quad (12)$$

Supplementary material S4 Spatial pattern of annual mean CH_4 fluxes

The simulated latitudinal contributions of CH_4 fluxes were consistent between the two models (Fig. 5a and 5b). Large fluxes were modeled in tropical regions. $CH4MOD_{wetland}$ simulated a peak flux of 30.18 g m^{-2} yr^{-1} in the 10°S–0° latitudinal band, followed by fluxes over 20 g m^{-2} yr^{-1} in the 20°–10°S latitudinal band and 0°–20°N latitudinal band (Fig. 5a). A peak flux of 30.61 g m^{-2} yr^{-1} was simulated in the 0°–10°N latitudinal band, followed by fluxes over 20 g m^{-2} yr^{-1} in the 20°S–0° latitudinal band and 10°–20°N latitudinal band (Fig. 5b). Lower fluxes under 15 g m^{-2} yr^{-1} were modeled in the 40°–80°N latitudinal band by $CH4MOD_{wetland}$ and in the 50°N–80°N latitudinal band by the TEM (Fig. 5a and 5b). The simulation of meridional annual mean CH_4 fluxes showed the largest peak at approximately 60°–80°W and a secondary large peak at approximately 20°–30°E (Fig. 5a and 5b).

Table S1 Environmental conditions of wetland sites

ID	Annual mean temperature (℃)	Annual Precipitation (mm)	Water table depth (cm)	Salinity	CH_4 emissions ($g\ m^{-2}\ yr^{-1}$)	Measurement method	Reference
1	-13.6	319	-10.0	--	2.64, 3.15	Chamber & EC	Wille et al., 2008; Wagner et al., 2003
2	-13.4	200	No data	--	1.26	Chamber	Nakano et al., 2000
3	-12.4	200	11.8	--	8.40	Chamber	Nakano et al., 2000
4	-10.5	220	2.0–15.0		2.63, 2.27, 1.42	EC	Parmentier et al., 2011
5	-10.3	223	-45.0–4.0	--	9.55, 6.70, 9.07	Chamber	Christensen et al., 2000; Joabsson and Christensen, 2001
6	-0.2	263	-35.0–3.0	--	0.45	Chamber	Svensson et al., 1999
7	-2.2	397	-3.6–7.0	--	5.50	EC	Aurela et al., 2002
8	2.3	600	5.3	--	28.10, 53.20, 55.00	Chamber	Song et al., 2008; Song et al., 2009
9	7.3	650	0.9	--	11.65	Chamber	Wang et al., 2002
10	17.7	188	46.0	--	63.30	Chamber	Kang et al., 2016; Duan et al., 2005
11	12.3	490	14.3	--	15.20	Chamber	Song et al., 2015; Hirota et al., 2004
12	12.7	625	27.0	--	30.20	Chamber	Huang et al., 2011
13	10.9	625	18.0	7.2	3.81	Chamber	Huang et al., 2005
14	18.1	1004	7.0	6.9	6.52, 8.29, 5.05	Chamber	Gao et al., 2010; Li et al., 2014
15	22.8	1582	15.7	12.5	25.37	Chamber	Kang et al., 2008
16	24.5	1670	0.0	15.2	0.91	Chamber	Ye et al., 2000
17	27.4	2015	-44.0	--	0.01	Chamber	Melling et al., 2005
18	25.5	2528	-80.0 – 20.0	--	1.36	Chamber	Jauhiainen et al., 2005
19	20	1500	-20.0 – 40.0	--	32.00	Chamber	Coynel et al., 2005; Tathy et al., 1992
20	20	1500	-20.0 – 40.0	--	16.00	Chamber	Tathy et al., 1992; Coynel et al., 2005
21	No data	No data	No data	--	49.00	Chamber	Alvalá and Kirchhoff, 2000; Melack et al., 2004
22	No data	No data	No data	--	69.00	Chamber	Crill et al., 1988
23	No data	No data	No data	--	40.00	Chamber	Devol et al., 1988
24	No data	No data	0.0 – 130.0	--	29.20	Chamber	Belger et al., 2011
25	-1.4	406	No data	--	3.70	Chamber	Bartlett et al., 1992
26	-1.4	406	No data	--	0.49	EC	Fan et al., 1992

27	No data	No data	No data	--	11.20	Chamber	Sebacher et al., 1986
28	No data	No data	-10.0 – 15.0	--	3.50, 5.10, 4.80	Chamber	Whalen and Reeburgh, 1992
29	12.8[*]	3240[*]	No data	--	21.70	EC	Suyker et al., 1996; Sellers et al., 1997
30	No data	No data	No data	--	37.00, 37.00, 55.00	Chamber	Shannon et al., 1996
31	15.1[^]	126[^]	No data	--	3.35	Chamber	Christensen, 1993; Schimel et al., 1994; 1995
32	10.8[&]	479[&]	-35.0 – 100.0	--	4.57	Chamber	Moore et al., 1994
33	No data	No data	-80.0 – 20.0	--	7.18	Chamber	Moore et al., 1990
34	No data	No data	4.0 – 25.0	--	47.7, 38.8	Chamber	Koh et al., 2009
35	15.1	335	-80.0 – -50.0	--	4.4	EC	Hatala et al., 2012
36	3.7	584	-14.0 – 24.0	--	15.73, 16.00	EC	Olson et al., 2013
37	6.0 ± 0.8	943	-65.0 – -28.0	--	8.00	EC	Moore et al., 2011
38	No data	No data	15.0 – 20.0	--	3.24	EC	Harazono et al., 2006
39	No data	No data	No data	--	8.10	EC	Harazono et al., 2006
40	3.0	344	-15.0 – 20.0	--	13.04, 9.26, 12.13	EC	Hanis et al., 2013
41	No data	No data	-13.0 – 10.0	--	1.48	EC	Zona et al., 2009
42	2.1	504	-62.0 – -38.0	--	3.20	EC	Long et al., 2010
43	16.6	1330	-50 – 60.0	--	3.47	EC	Morse et al., 2012

[*] May to October

[^] Summer period

[&] June to October

Table S2 Parameters of CH4MOD$_{wetland}$ for global simulation

Parameter	Description	A	B	C	References
VI	Vegetation index	2.4	1	1	This study
T_{veg}	The fraction of plant mediated transport was available	1	1	0.1	Walter and Heimann, 2000
P_{ox}	The fraction of CH_4 oxidized during plant mediated transport	0.5	0.9	0.9	This study
f_r	Proportion of below-ground NPP to the total NPP	0.5	0.5	0.45	Gill and Jackson, 2000;White et al., 2002
F_{N_shoot}	Fraction of nonstructural component in above-ground litter	0.8	0.8	0.3	White et al., 2002;Gordon and Jackson., 2003
F_{N_root}	Fraction of nonstructural component in below-ground litter	0.5	0.5	0.2	White et al., 2002

A for the wetland dominated by herbaceous plant calibrated by CH_4 measurements from the Sanjiang plain, China, year 2002.

B for the wetland dominated by herbaceous plant with high productivity (annual aboveground biomass >1000 g m^{-2} yr^{-1}), calibrated by CH_4 measurements from the Wuliangsu lake, China.

C for the wetland dominated by woody plant, calibrated by CH_4 measurements from Sarawak, Malaysia.

Table S3 Parameters of TEM for global simulation

Parameter	Description	Prior interval	Optimized value					Unit
			Tundra	Marsh	Swamp	Coastal wetland	Peatland	
M_{GO}	Maximum potential CH_4 production rate	[0, 2]	1.45	1.03	0.8	0.10	0.48	$\mu mol\ L^{-1}\ h^{-1}$
D_{Q10}	Dependency of CH_4 production on soil temperature	[1, 6]	1.11	1.07	2.82	1.60	1.45	unitless
T_{REF}	Reference temperature in Q_{10} function	[-6, 2]	-3.13	1.98	1.55	0.72	-3.41	°C
MaxFresh	Maximum daily NPP for a particular ecosystem	[2, 20]	12.03	8.70	8.83	4.97	11.73	$g\ C\ m^{-2}\ day^{-1}$

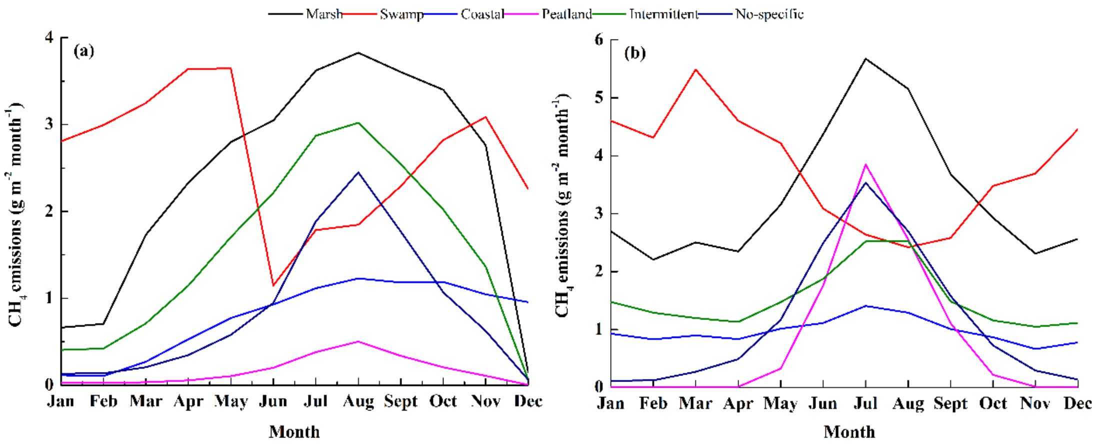

Fig. S1 Simulated seasonal patterns of CH$_4$ emissions by CH4MOD$_{\text{wetland}}$ (a) and TEM (b) based on the average monthly CH$_4$ emissions from 2000–2010.

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