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Evaluation of CH4MOD$_{wetland}$ and TEM models used to estimate global CH_4 emissions from natural wetlands

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Abstract

Reliable models are required to estimate global wetland CH_4 emissions. This study aimed to test two process-based models, $CH4MOD_{wetland}$ and TEM, against the CH_4 flux measurements of marsh, swamps, peatland and coastal wetland sites across the world; specifically, model accuracy and generality were evaluated for different wetland types and in different continents, and then the global CH_4 emissions from 2000 to 2010 were estimated. Both models showed similar high correlations with the observed seasonal CH_4 emissions, and the regression of the observed versus computed total seasonal CH_4 emissions resulted in R^2 values of 0.78 and 0.72 by $CH4MOD_{wetland}$ and TEM, respectively. The $CH4MOD_{wetland}$ predicted more accurately in marsh, peatland and coastal wetlands, with model efficiency (EF) values of 0.22, 0.55 and 0.72, respectively; however, the model showed poor performance in swamps (EF<0). The TEM model predicted better in peatland and swamp, with EF values of 0.77 and 0.71, respectively, but it could not accurately simulate the marsh and coastal wetland (EF<0). There was a good correlation between the simulated CH_4 fluxes and the observed values on most continents. However, $CH4MOD_{wetland}$ showed no correlation with the observed values in South America and Africa. TEM showed no correlation with the observations in Europe. The global CH_4 emissions for the period 2000–2010 were estimated to be 105.31 ± 2.72 Tg yr^{-1} by $CH4MOD_{wetland}$ and 134.31 ± 0.84 Tg yr^{-1} by TEM. Both models simulated a similar spatial distribution of CH_4 emissions across the world and among continents. Marsh contributes 36%–39% to global CH_4 emissions. Lakes and rivers and swamp are the second and third contributors, respectively. Other wetland types account for only approximately 20% of global emissions. Based on the models' generality, if we use the more accurate model to estimate each continent/wetland type, we obtain a new assessment of 116.99–124.74 Tg yr^{-1} for the global CH_4 emissions for the period 2000–2010.

1 Introduction

Atmospheric methane (CH_4) is the second most prevalent human-induced greenhouse gas (GHG) after carbon dioxide (CO_2). It has a 28-fold greater radiative forcing than CO_2 on a 100-year horizon (Myhre et al., 2013). The radiative forcing attributed to CH_4 has been re-evaluated and was reported to be almost twice as high by the Intergovernmental Panel on Climate Change (IPCC)'s 5th Assessment Report (AR5) than the value reported in the 4th Assessment Report (AR4), with values of 0.97 W m^{-2}

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versus 0.48 W m^{-2}, respectively (Myhre et al., 2013). This estimate considers that the emission of CH_4 leads to ozone production, stratospheric water vapor and CO_2, which can affect its own lifetime (Myhre et al., 2013; Shindell et al., 2012).

The growth rate of the atmospheric CH_4 concentration varied in different historical periods. There was an exponential increase from preindustrial times to the 1980s. The growth rate decreased after the 1980s and was close to zero from 1999 to 2006; then, the growth rate resumed strong growth in the period of 2007–2017 (Dlugokencky et al., 2009; Dlugokencky, 2016; Nisbet et al., 2019). However, the causes that drive the variations in growth rate remain unclear due to the uncertainties in estimating CH_4 emissions and sinks (Ghosh et al., 2015; Saunois et al., 2016; Nisbet et al., 2019; Dalsøren et al., 2016).

Integrated at the global scale, wetlands are the largest and most uncertain source of CH_4emitted to the atmosphere (Kirschke et al., 2013; Saunois et al., 2016). These emissions represent approximately 30% of the total CH_4 source (Saunois et al., 2016). Bottom-up and top-down approaches are popular methods for estimating global CH_4 emissions from natural wetlands. The top-down approach is based on inverse models (e.g., Bousquet et al., 2006; Fraser et al., 2013; Meirink et al., 2008; Tsuruta et al., 2017; Bruhwiler et al., 2014), which determine 'optimal' surface fluxes that best fit atmospheric CH_4 observations given an atmospheric transport model including chemistry, prior estimates of fluxes, and their uncertainties (Kirschke et al., 2013). The bottom-up approach uses process-based models that describe the relationship between the environmental factors and the processes of CH_4 production, oxidation and emission using mathematical equations (e.g., Li et al., 2010; Zhu et al., 2013; Zhang et al., 2002; Zhu et al., 2014; Walter and Heimann, 2000; Tian et al., 2015; Riley et al., 2011; Meng et al., 2012; Zhuang et al., 2006).

The top-down inversions show larger uncertainties regarding CH_4 sources than the bottom models (Saunois et al., 2016). Recent studies related to the bottom-up approach used an ensemble of process-based models driven by the same climate forcing to estimate the global CH_4 emissions from natural wetlands. For example, The Wetland and Wetland CH_4 Inter-comparison of Models Project (WETCHIMP) used ten land surface models and estimated a global CH_4 emissions of 190 ± 76 CH_4 yr^{-1} for the 1993–2004 period (Melton et al., 2013). In the following year, Kirschke et al. (2013) assessed a large emission range of 142–287 Tg CH_4 yr^{-1} from 1980 to 2010; Saunois et al. (2016) and Poulter et al. (2017) estimated global emissions of 153–227 Tg CH_4 yr^{-1} for the 2003–2012 decade and 184 ± 22 Tg

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CH_4 yr^{-1} for the 2000–2012 decade using ensemble process-based models (Poulter et al., 2017). Saunois et al. (2016) suggested that approximately 70% of the uncertainty was due to model structures and parameters.

Natural wetland ecosystems are greatly heterogeneous on a global scale. Wetlands vary widely by continent with respect to area and type (Kingsford et al., 2016; Keddy, 2010). Some wetland types have higher emissions, while some emit less CH_4; this difference is because the processes of and controls on CH_4 cycling differ among wetland types (Bridgham et al., 2013). For example, sedge-dominated marsh or fen often emit higher CH_4 fluxes because sedges can increase methanogenic substrates as part of their plant productivity and promote CH_4 transportation through their soft aerenchyma and lacunae tissues (McEwing et al., 2015; Jitka et al., 2017; Bhullar et al., 2013; Joabsson and Christensen, 2001; Kwon et al., 2017; King et al., 2002; Chanton, 2005). Bog soils with anaerobic incubations emit little CH_4 due to the particularly high CO_2: CH_4 ratios of the end products of anaerobic carbon (Bridgham et al., 1998; Galand et al., 2010; Keller and Bridgham, 2007). Coastal wetlands with high salinity usually emit less CH_4 because the sulfate in the sea water inhibits CH_4 production (Bartlett et al., 1985; Delaune et al., 1983; Li et al., 2016; Poffenbarger et al., 2011).

Model evaluation is a core part of model development and testing (Bennett et al., 2013). Based on the model evaluation, the modeler must be confident that the model will fulfill its purpose (Bennett et al., 2013; Rykiel, 1996). If applying process-based models for global-scale CH_4 estimations, it is necessary to evaluate its performance in different wetland types and regions. This process is also helpful for confirming the source of uncertainties and improving the model. However, previous studies have always focused on global assessments and have overlooked model performance in different wetland types or regions, which may have induced high uncertainties (Poulter et al., 2017; Saunois et al., 2016; Kirschke et al., 2013; Melton et al., 2013). $CH4MOD_{wetland}$ (Li et al., 2010) and TEM (Zhuang et al., 2004; Melillo et al., 1993; Zhuang et al., 2007; Zhuang et al., 2013) are two established process-based models that can be used to simulate regional and global wetland CH_4 emissions. Both models have been validated at specific sites (Zhu et al., 2013; Li et al., 2010; Li et al., 2017). However, we do not have information on the accuracy and generality of the models for different wetland types and on different continents. The objectives of this study were to comprehensively evaluate the model performances of $CH4MOD_{wetland}$

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and TEM for different wetland types and on different continents and then to use the models to estimate global CH_4 emissions from natural wetlands.

2 Methods and Materials

The performance evaluation should clearly depend on the model objectives (Bennett et al., 2013). The models considered in this study are aimed at estimating the annual emissions from global wetlands. Therefore, the accuracy and generality of the model in simulating annual CH_4 emissions for different wetland types and continents are very important in a performance evaluation. In this study, we collected CH_4 flux measurements from 30 wetlands spanning the main wetland types in the world from peer-reviewed literature (Table 1). A set of statistical methods was used to comprehensively evaluate the performance of $CH4MOD_{wetland}$ and TEM in different wetland types and on different continents. Finally, we extrapolated both models to estimate the global CH_4 emissions from 2000 to 2010.

2.1 Model overview

2.1.1 $CH4MOD_{wetland}$

The $CH4MOD_{wetland}$ model is a process-based biogeophysical model used to simulate the processes of CH_4 production, oxidation and emission from natural wetlands (Li et al., 2010). The model was established based on CH4MOD, which is used to predict CH_4 emissions from rice paddies (Huang et al., 1998; Huang et al., 1997). In $CH4MOD_{wetland}$, we focused on the different supply of methanogenic substrates between natural wetlands and rice paddies. The methanogenic substrates were derived from the root exudates, the decomposition of plant litter and the soil organic matter. The methane production rates were determined by the methanogenic substrates and the influence of environmental factors, including soil temperature, soil texture and soil Eh. Additionally, we adopted the influence of salinity on CH_4 production to improve the model performance for the coastal wetlands (Li et al., 2016). Inputs to the $CH4MOD_{wetland}$ model include the daily air/soil temperature, water table depth, annual above-ground net primary productivity (ANPP), soil sand fraction, soil organic matter, bulk density and soil salinity. The outputs are the daily and annual CH_4 production and emissions. We used the TOPMODEL hydrological model to simulate the water table depth as the inputs of $CH4MOD_{wetland}$ (Bohn et al., 2007;

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Li et al., 2015; Li et al., 2019; Zhu et al., 2013; Beven and Kirkby, 1979).

The main parameters that must be calibrated in $CH4MOD_{wetland}$ include the vegetation index (*VI*), the fraction of plant-mediated transport available (T_{veg}), the fraction of CH_4 oxidized during plant-mediated transport (P_{ox}), the proportion of below-ground net primary productivity (*BNPP*) to the total net primary productivity (*NPP*) (f_r), the fraction of nonstructural component in plant litter (F_N) (Table S1) and the empirical constant of the influence of salinity. The model parametrization and main parameters are described in Supplementary Material S1.

2.1.2 TEM

The terrestrial ecosystem model (TEM) is another process-based biogeochemical model that couples carbon, nitrogen, water, and heat processes in terrestrial ecosystems to simulate ecosystem carbon and nitrogen dynamics (Melillo et al., 1993; Zhuang et al., 2007; Zhuang et al., 2013). The methane dynamics module was first coupled within the TEM by Zhuang et al. (2004) to explicitly simulate the process of methane production (methanogenesis), oxidation (methanotrophy) and transport between the soil and the atmosphere. Methane production is assumed to occur only in saturated zones and is regulated by organic substrate, soil thermal conditions, soil PH, and soil redox potentials; methane oxidation, which occurs in the unsaturated zone, depends on the soil methane and oxygen concentrations, temperature, moisture and redox potential. Methane transport is described by three pathways in the TEM: (1) diffusion through the soil profile; (2) plant-aided transport; and (3) ebullition. The TEM has also been coupled with TOPMODEL (Zhu et al., 2013). The model calibration of TEM has been well documented in Supplementary Material S2 and Table S2.

2.2 Site information and data sources

2.2.1 Site information

We collected 30 wetland sites across the world (Table 1). The wetland sites included 6 marsh sites, 14 peatland sites, 6 swamp sites and 4 coastal wetland sites. Among the wetland sites, 5 sites are distributed in Europe (EU), 11 sites are distributed in Asia (AS), 2 sites are distributed in Africa (AF), 3 sites are distributed in South America (SA) and 9 sites are distributed in North America (NA). The

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observations were from the late 1980s to the early 2010s. For most of the wetland sites, the total amount of seasonal CH_4 fluxes during the observation period was calculated by summing the daily observations. The absence of CH_4 emission measurements between two adjacent days of observation was linearly interpolated. For a few wetland sites, the observed seasonal CH_4 fluxes were directly obtained from the literature. More details about the location, vegetation and observation periods are described in Table 1.

2.2.2 Wetland map

The global wetland distributions of different wetland types were based on the Global Lakes and Wetlands Database (GLWD-3) (http://www.wwfus.org/science/data.cfm) (Lehner and Döll, 2004) (Fig. 1). According to the GLWD-3, the wetland types include : 1. lakes, 2. reservoirs, 3. rivers (we combined lakes, reservoirs and rivers as a single wetland type, hereinafter referred to as lakes and rivers), 4. freshwater marsh and floodplain (hereinafter referred to as marsh), 5. swamp forest and flooded forest (hereinafter referred to as swamp), 6. coastal wetland, 7. saline wetland (we combined coastal wetland and saline wetland as a single wetland type, hereinafter referred to as coastal wetland), 8. bog, fen and mire (hereinafter referred to as peatland), 9. intermittent wetland and 10. no-specific wetland. All of the observed sites (Table 1) are distributed on the wetland map (Fig. 1).

The global wetland area (excluding rivers) was estimated by the "Global Review of Wetland Resources and Priorities for Wetland Inventory (GRoWI)" as 530-570 M ha (Spiers, 1999). We used an average value, as the wetland area excluded rivers in this study. The global wetland area of rivers was based on the GLWD-3. Therefore, we assumed that the global wetland area was 584 M ha, which represented the wetland area for the period from 2000 to 2010. The cartography-based GLWD-3 data provide a global distribution of natural wetlands at a 30-second resolution. Then, we aggregated the merged map up to $0.5° \times 0.5°$ (latitude × longitude) grids. The wetland area (excluding rivers) in each pixel was adjusted by the ratio of the global wetland area estimated by GRoWI and by the GLWD-3.

2.2.3 Driver data

The input climate data for the models include the daily air temperature, precipitation, cloudiness and vapor pressure. The historical daily climate data were developed from the latest monthly data sets of the Climatic Research Unit (CRU TS 3.10) of the University of East Anglia in the United Kingdom

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(Harris et al., 2014).

The soil properties needed by the $CH4MOD_{wetland}$ model include soil texture (percentage of soil sand), bulk density, soil organic carbon content, soil temperature and soil moisture. The additional information needed by the TEM model includes the percentage of soil silt and clay, soil pH and territorial elevation. The soil texture data were derived from the soil map of the Food and Agriculture Organization (FAO) (FAO, 2012). The soil organic carbon content and the reference bulk density of wetland soils were retrieved from the Harmonized World Soil Database (HWSD) (FAO, 2008) by masking the HWSD with the Global Lakes and Wetlands Database (GLWD) (Lehner and Döll, 2004). The daily soil temperature data were estimated by the TEM from spatially interpolated climate data. The daily soil moisture driving $CH4MOD_{wetland}$ coupled with TOPMODEL was developed from the monthly dataset (http://www.cpc.ncep.noaa.gov/soilmst/leaky_glb.htm) by temporal linear interpolation (Fan and van den Dool, 2004). The soil PH was also derived from the global soil property dataset of the International Geosphere-Biosphere Programme (IGBP) (Carter and Scholes, 2000).

The vegetation map of the IGBP was referenced to specify the vegetation parameters for $CH4MOD_{wetland}$ (Table S1) and the TEM. The map was derived from the IGBP Data and Information System (DIS) DISCover Database (Belward et al., 1999; Loveland et al., 2000). The 1 km × 1 km DISCover dataset was reclassified into the TEM vegetation classification scheme and then aggregated into 0.5° × 0.5° grids. The annual above-ground net primary productivity used to drive $CH4MOD_{wetland}$ was from the output of the TEM model.

For $CH4MOD_{wetland}$, a high resolution of the topographic wetness index dataset (Marthews et al., 2015) was used to calculate the changes in the water table. The global salinity database was from the World Ocean Atlas 2009 (Antonov et al., 2010). We also used the 1 km × 1 km global elevation data derived from the Shuttle Radar Topography Mission (SRTM) (Farr et al., 2007). The above data were resampled to 0.5° × 0.5° grids to match the resolution of the other input data.

2.3 Model evaluation

We compared the observed seasonal CH_4 fluxes in the wetland sites (Table 1) and the simulated seasonal CH_4 fluxes at the 0.5°×0.5° grid for the same period (described in Sect. 2.4). The statistics include the determination coefficient (R^2), the root mean square error (RMSE), the mean deviation

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(RMD), the model efficiency (EF) and the coefficient of determination (CD) and were used to evaluate model performance on a global scale, a continental scale and for each wetland type. Because of the site limitations in Africa and South America, we combined the two continents together.

Two simulations with the same RMSE values may not be considered equivalent because the distribution of the error among the sources may not be the same (Allen and Raktoe, 1981). We further analyzed the source of the RMSE by decomposing it into three components: the bias in the modeling procedure (UM), the errors due to regression (UR) and the error due to random disturbances (UE) (Allen and Raktoe, 1981). The detailed description and the equations used to calculate these statistics are described in Supplementary Material S3.

2.4 Model extrapolation

The $CH4MOD_{wetland}$ and the TEM were used to simulate the CH_4 emissions from global wetlands at a spatial resolution of 0.5°×0.5°. We established spatially explicit data for climate, soils, vegetation, land use and other environmental inputs at a 0.5°×0.5° spatial resolution to facilitate the models at the global scale. Both process-based models were conducted for the period of 1980-2010 in each pixel to simulate the temporal spatial variations in CH_4 fluxes. In this study, we focused only on the total CH_4 emissions for the period 2000-2010 because we assumed the wetland map represented the distribution of natural wetlands during this period. The total CH_4 emissions from the natural wetlands, excluding the lakes and rivers in each pixel, were calculated as the product of the CH_4 fluxes and the gridded wetland area. To make an overall global/continental CH_4 emissions assessment, we evaluated the CH_4 emissions from lakes and rivers using IPCC Tier 1 method based on the CH_4 emissions factor (IPCC, 1996) and the area of lakes and rivers in each pixel.

We aggregated the gridded values and obtained the annual mean CH_4 emissions from each wetland type and each continent by $CH4MOD_{wetland}$ combined with IPCC Tier1 method and the TEM combined with IPCC Tier1 method. Except for the two global assessments by $CH4MOD_{wetland}$ combined with IPCC Tier1 method (hereinafter referred to as "Method A") and the TEM combined with IPCC Tier1 method (hereinafter referred to as "Method B"), we made two other assessments of global CH_4 emissions by choosing the more accurate model ("Method C" and "Method D"). Based on the model performance evaluation (Sect. 2.3), we found a more accurate model for each wetland type and each continent. In the

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"Method C" approach, we chose the CH_4 emissions from each continent simulated by the more accurate model. In Oceania, we used the average simulated result by $CH4MOD_{wetland}$ and the TEM because there was no wetland site on this continent (Table 1). We summed the CH_4 emissions from all continents and made an assessment of the global CH_4 emissions. In the "Method D" approach, we chose the CH_4 emissions from marsh, peatland, swamp and coastal wetlands simulated by the more accurate model. The CH_4 emissions from intermittent wetlands and no-specific wetlands were used as the average result by $CH4MOD_{wetland}$ and the TEM. The CH_4 emissions from lakes and rivers were based on IPCC Tier 1 method. We summed the CH_4 emissions from all wetland types and made an assessment of the global CH_4 emissions.

3. Results

3.1 Model evaluation

3.1.1 Model evaluation for global wetland sites

Fig. 2 shows the correlation of the modeled versus observed total amount of seasonal CH_4 emissions by $CH4MOD_{wetland}$ (Fig. 2a) and the TEM (Fig. 2b). The result indicated that the variations in the CH_4 emissions between sites and in different years could be delineated by both process-based models. The regression of the observed versus computed total seasonal CH_4 emissions by $CH4MOD_{wetland}$ (Fig. 2a) resulted in an R^2 of 0.78, with a slope of 1.15 and an intercept of -0.83 g m^{-2} (n=37, p<0.001). The regression of the observed versus computed total seasonal CH_4 emissions by the TEM (Fig. 2b) resulted in an R^2 of 0.66, with a slope of 0.72 and an intercept of 5.70 g m^{-2} (n=37, p<0.001).

The statistics of the model performance of seasonal CH_4 emissions (Table 2) indicated that both process-based models had the capability to simulate seasonal CH_4 emissions from natural wetlands on a global scale (EF=0.58 for $CH4MOD_{wetland}$ and EF=0.63 for the TEM). However, a discrepancy still existed between the simulated and observed seasonal CH_4 emissions (RMSE=61.27% for $CH4MOD_{wetland}$ and RMSE=56.00% for the TEM). The $CH4MOD_{wetland}$ model systematically overestimated the seasonal CH_4 emissions on a global scale, with an RMD value of 11.1% (Table 2). The observed seasonal amount of CH_4 emissions ranged from 0.45 to 69.00 g m^{-2}, with an average of 20.45 g m^{-2}. The $CH4MOD_{wetland}$ model slightly overestimated the seasonal CH_4 emissions, with a range of

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0.20 -72.39 g m^{-2} and an average value of 22.73 g m^{-2} (Fig. 2a). The TEM described the average seasonal CH_4 emissions on a global scale very well. The modeled amount ranged from 0.49 to 56.37 g m^{-2}, with an average of 20.45 g m^{-2}, which was comparable with the observations (Fig. 2b). The RMD was estimated to be 0.00%, which meant there was almost no systematic deviation between the modeled and observed values (Table 2).

We further evaluated the model accuracy by estimating the source of the RMSE. On a global scale, both models had a lower U_M (0.03 and 0.00 for $CH4MOD_{wetland}$ and the TEM, respectively, in Table 2), which indicated that little bias was attributed to the model procedure. The TEM showed good performance because the RMSE was mainly due to random disturbances (U_R=0.93). For $CH4MOD_{wetland}$, the source of the RMSE was partly from the regression error, which was consistent with the RMD value (Table 2).

3.1.2 Model evaluation for different continents

We further analyzed the model predictions by $CH4MOD_{wetland}$ and the TEM among different continents (Fig. 3, Table 2). There was a good correlation between the simulated CH_4 fluxes and the observed values on most of the continents by the two models. The R^2 varied between 0.21 (Fig. 3e) and 0.94 (Fig. 3c) for $CH4MOD_{wetland}$ and between 0.26 (Fig. 3d) and 0.81 (Fig. 3h) for the TEM. However, there was no significant correlation between the simulated and observed values in South America and Africa for $CH4MOD_{wetland}$ (Fig. 3g) and in Europe for the TEM (Fig. 3f). The $CH4MOD_{wetland}$ model predicted more accurately in Asia and North America than did the TEM (Fig. 3b and 3a). The model efficiency reached 0.93 in Asia and 0.48 in North America (Table 2). The TEM predicted better in North America and South America and Africa than did the $CH4MOD_{wetland}$, with EF values of 0.79 and 0.49, respectively (Table 2). Negative values of EF were found in South America and Africa by $CH4MOD_{wetland}$ and in Europe by the TEM (Table 2).

$CH4MOD_{wetland}$ slightly overestimated the observed emissions (RMD = 13.24%) in North America and underestimated the observed emissions (RMD = -12.64%) in Asia and Europe (RMD = -29.91%) (Table 2). The TEM overestimated the CH_4 emissions in South America and Africa (RMD=15.31%) and underestimated the CH_4 emissions in North America (RMD=-13.03%) (Table 1). Random error was the main contributor to the RMSE in Asia and Europe in $CH4MOD_{wetland}$ and in Asia and North America in

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the TEM (Table 2). However, the regression error contributed most to the RMSE in North America in $CH4MOD_{wetland}$ and in South America and Africa in the TEM (Table 2).

3.1.3 Model evaluation for different wetland types

Marsh, swamp, peatland and coastal wetlands are the main types of natural wetlands. Although the process-based models showed good performance in simulating the seasonal CH_4 emissions at a global scale, these results do not certify that the models have good performance for each wetland type. Fig. 4 shows the regressions of the simulated against the observed total amount of seasonal CH_4 emissions from the different wetland types. Regression analysis indicated that both models showed good performance in modeling seasonal CH_4 emissions from the peatland sites (Fig. 4c and d). Most of the data points were near the 1:1 line (Fig. 4c and d). Both models could explain approximately 80% of the variability in the seasonal CH_4 emissions (R^2=0.84 and 0.77 for $CH4MOD_{wetland}$ and the TEM, respectively) (Fig. 4c and 4d). The TEM showed a better model efficiency (EF = 0.77) than the $CH4MOD_{wetland}$ (EF = 0.55), and the TEM had a lower RMSE and RMD than the $CH4MOD_{wetland}$ (Table 2) for peatland. For the other wetland types, $CH4MOD_{wetland}$ showed good performance in simulating the seasonal CH_4 emissions from coastal wetlands (EF = 0.72), followed by marsh (EF = 0.22) (Table 2). However, the model could not simulate the seasonal CH_4 emissions from swamps (EF = -0.08) (Table 2). Figs. 4a, e and d indicated the same conclusion, i.e., there was no significant correlation ($p>0.05$) between the simulated and observed seasonal CH_4 emissions from swamp sites (Fig. 4e). The TEM showed poor performance for the marsh sites (EF = -0.42) and coastal wetlands (EF = -2.26) (Table 2); however, it showed good performance for the swamp sites (EF = 0.71). There was no significant correlation ($p>0.05$) between the modeled and observed seasonal CH_4 emissions from the marsh sites (Fig. 4b) and coastal wetland sites (Fig. 4h). In conclusion, $CH4MOD_{wetland}$ performed better for marsh and coastal wetland, while the TEM performed better for peatland and swamp.

The sources of the RMSE varied between different wetland types during the simulation (Table 2). The $CH4MOD_{wetland}$ model had the ability to simulate CH_4 emissions from marsh, peatland and coastal wetland (EF>0), with RMSE values of 29.44%, 77.26% and 55.46%, respectively (Table 2). For marsh and peatland, the RMSE was mainly due to the regression error (Table 2). For coastal wetlands, the model error contributed 24%, the regression error contributed 30%, and the random error contributed 47%

to the RMSE (Table 2). The TEM performed well in peatland and swamps (EF>0 in Table 2). The RMSE was mainly due to the random error (Table 2).

3.2 Global CH_4 emissions from natural wetlands

3.2.1 Spatial pattern of global CH_4 emissions

Figs. 5a and 5b show the distribution of the annual mean CH_4 fluxes simulated by $CH4MOD_{wetland}$ and the TEM, respectively. The models yielded similar distribution patterns of CH_4 fluxes (Fig. 5a and 5b). 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°S–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°N–20°N latitudinal band (Fig. 5b). Lower fluxes under 15 g m^{-2} yr^{-1} were modeled in the 40°N–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°W–80°W and a secondary large peak at approximately 20°E–30°E (Fig. 5a and 5b).

The distribution of the simulated annual mean CH_4 emissions for the period 2000–2010 also showed similar patterns in $CH4MOD_{wetland}$ and the TEM. Large emissions were found in South America, South Africa and the border of Canada and the United States (Fig. 5c and 5d). The latitudinal sums of CH_4 emissions indicated that the strongest contribution came from the tropical zone (Fig. 5c and 5d). The latitudinal band of 10°S–0° contributed 22.77 Tg yr^{-1} and 23.23 Tg yr^{-1} CH_4 in $CH4MOD_{wetland}$ and the TEM, which accounted for 22% and 18% of the global emissions, respectively. A secondary large peak was simulated in the 40°N–50°N latitudinal band, with a value of 14.64 Tg yr^{-1} and 16.66 Tg yr^{-1} CH_4 according to $CH4MOD_{wetland}$ and the TEM, respectively. Generally, both models simulated a common decline in CH_4 emissions from lower latitudes to higher latitudes (Fig. 5c and 5d). The largest peak in CH_4 emissions was modeled in the 60°W–50°W meridional band, with values of 11.63 Tg yr^{-1} in $CH4MOD_{wetland}$ (Fig. 5c) and 13.83 Tg yr^{-1} in the TEM (Fig. 5d). This peak corresponded to the longitudes of the Amazon in South America. Both models simulated secondary peaks in the 30°E–40°E

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meridional band (Fig. 5c and 5d), which corresponded to the longitudes of Congo in Africa.

3.2.2 CH_4 emissions from different continents and wetland types

Table 3 provides an overview of the CH_4 emissions from different continents and wetland types simulated by $CH4MOD_{wetland}$ and the TEM. A comparison of simulated CH_4 fluxes from different continents by $CH4MOD_{wetland}$ and the TEM showed that the three highest fluxes were modeled in South America, Africa and Asia (Table 3). The CH_4 fluxes simulated by $CH4MOD_{wetland}$ were 25.8%, 18.5% and 9.7% lower than those simulated by the TEM in South America, Africa and Asia, respectively. The TEM simulated higher CH_4 fluxes in Europe than in North America, but the $CH4MOD_{wetland}$ simulations showed the opposite. The modeled CH_4 fluxes from European wetlands by $CH4MOD_{wetland}$ were only half of those simulated by the TEM (Table 3). For Oceania, the two models simulated similar fluxes.

Both models simulated the same sequence of CH_4 fluxes, which was swamp, marsh, intermittent wetland, no-specific wetland, coastal wetland, and peatland (Table 3). The simulated annual mean CH_4 fluxes from intermittent wetlands were almost equivalent in both models. For other wetland types, the TEM simulated higher CH_4 fluxes than the $CH4MOD_{wetland}$ model (Table 3). The annual mean CH_4 flux modeled by $CH4MOD_{wetland}$ was only 20% of that modeled by the TEM (Table 3). $CH4MOD_{wetland}$ also simulated values that were 30.7%, 27.7%, 25.1% and 18.8% less than those simulated by the TEM for the annual mean CH_4 fluxes from swamps, marsh, no-specific wetland and coastal wetland, respectively (Table 3).

The global CH_4 emissions simulated by the TEM were 29 Tg yr^{-1} higher than those simulated by $CH4MOD_{wetland}$ (Table 3). This difference depended on the differences in the CH_4 fluxes and on the wetland area. The simulated results showed that half of this difference was attributed to the marsh. South America contributed 30% to this difference because the simulated CH_4 fluxes differed greatly between the TEM and $CH4MOD_{wetland}$ (Table 3).

The two models simulated similar spatial distributions of the CH_4 emissions among different wetland types and continents (Table 3). Marshes emit higher CH_4 fluxes and had the largest area. Thus, marsh was the first contributor to global CH_4 emissions and contributed 36%–39% to the global CH_4 emissions (Table 3). Lakes and rivers as well as swamp were the second and third contributors, respectively (Table 3). The CH_4 emissions from peatland, coastal wetlands, intermittent wetlands and no-

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specific wetlands accounted for only approximately 20% of the global emissions (Table 3).

Although North America accounted for 36% of the global wetland area, it contributed only 22%–23% to global emissions (Table 3). In contrast, the wetland area in South America accounted for 15% of the global area and contributed 25%–26% to global CH_4 emissions. Asia and Africa also accounted for approximately 20% of global emissions. The lowest area and emissions were found in Oceania (Table 3).

3.2.3 Global CH_4 estimations

The global CH_4 emissions for the period 2000-2010 were estimated to be 105.31± 2.72 Tg yr^{-1} by "Method A" and 134.31 ± 0.84 Tg yr^{-1} by "Method B". Based on the evaluation of model performance (Table 2), $CH4MOD_{wetland}$ predicted more accurately in Asia and Europe, and the TEM predicted more accurately in North America and South America and Africa. Using this combination, the global CH_4 emissions were estimated to be 124.74 ± 1.22 Tg by "Method C". Similarly, in "Method D", $CH4MOD_{wetland}$ was used for simulations in marsh and coastal wetlands, and the TEM was used for simulations in peatland and swamp; as a result, the global wetland CH_4 emissions were estimated to be 116.99 ± 2.23 Tg.

4. Discussion

4.1 Generality of $CH4MOD_{wetland}$ and TEM

A lack of correspondence between the model output and observations could be partly due to the observed flux data, e.g., the inevitable gap-filling of missing data points to determine annual totals (Kramer et al., 2002). The results showed differences between the observed and simulated annual CH_4 fluxes by both $CH4MOD_{wetland}$ and the TEM on a global scale (Fig. 2) and continent scale (Fig. 3) and for different wetland types (Fig. 4). The reliability of the observed flux data was not under discussion in this study. We evaluated only the model accuracy and generality across different wetland types and continents.

On a global scale, both models fulfilled the criteria of sufficient accuracy for the ability to predict CH_4 fluxes (Table 2). However, this fuzzy analysis may miss some real model performance. For the

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model generality in different continents, $CH4MOD_{wetland}$ had the best performance in Asia, followed by North America and Europe. It had poor performance in South America and Africa, which was where swamps were mainly distributed (Table 2). The TEM performed best in North America, followed by South America and Africa and Asia. It had poor performance in Europe (Table 2). Each continent had its main wetland types; thus, the model generality in different continents depended on its generality for different types. $CH4MOD_{wetland}$ was suitable for marsh, peatland and coastal wetlands, but it could not be applied in swamps (Table 2). This limitation may be because in $CH4MOD_{wetland}$, only a semiempirical logistic model is used to simulate plant growth (Li et al., 2010). This characteristic may induce large uncertainties in simulating the growth of forests in swamps (Table 1). However, the TEM used the carbon nitrogen dynamics module (CNDM) to describe the effects of photosynthesis, respiration, decomposition and nutrient cycling on net primary productivity (NPP) (Melillo et al., 1993). Compared with $CH4MOD_{wetland}$, the TEM had good performance in simulating NPP in various vegetation types (Melillo et al., 1993). According to the model evaluation, the TEM was suitable for swamps and peatland but had large uncertainties in marsh and coastal wetlands (Table 2). This pattern may be because the TEM focused on two major wetland types: boreal tundra and forest wetland (Zhuang et al., 2004). The biochemical processes in the TEM model may suitable for peatland (tundra) and swamp (forest wetland) but not suitable for marshes. For coastal wetlands, the TEM did not consider the inhibition of salinity on CH_4 production (Poffenbarger et al., 2011; Bartlett et al., 1987) and greatly overestimated the CH_4 fluxes (Table 2). $CH4MOD_{wetland}$ introduced the influence of salinity on CH_4 production and had good performance for coastal wetlands (Table 2).

4.2 Reducing uncertainties in global estimations

The estimations of the global wetland CH_4 emissions had large ranges in previous studies (Zhu et al., 2015). The estimations by process-based models ranged from 92 Tg yr^{-1} (Cao et al., 1996) to 297 Tg yr^{-1} (Gedney et al., 2004) during the period of 1980–2012. Recently, an ensemble of process-based models driven by the same climatic data has commonly been used to estimate global wetland CH_4 emissions (Melton et al., 2013; Kirschke et al., 2013; Poulter et al., 2017; Saunois et al., 2016). However, the uncertainties in the model mean estimation range from 12% (Poulter et al., 2017) to 40% (Melton et al., 2013). The uncertainty mainly comes from the wetland distribution and model structure and

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parameters (Saunois et al., 2016). Estimating accurate wetland extent and its seasonal and annual variations is a major challenge in present studies. The global estimations of wetland area ranged from 4.3 M ha to 12.9 M ha during the period of 1990 to 2005 (Melton et al., 2013). The wetland extent of 9.2 M ha from the GLWD excluded water bodies, and this value was ~40% higher than the wetland area used in this study. That is, this difference was the main reason for the lower global estimations determined in this study than those reported in previous works (Zhu et al., 2015; Melton et al., 2013; Poulter et al., 2017; Saunois et al., 2016). Improving the accuracy of wetland extent and temporal variations is important in reducing uncertainties in global wetland CH_4 estimations.

In addition to wetland area, the model structure and parameters accounted for ~70% of the total uncertainties (Saunois et al., 2016). The results of the accuracy analysis showed that for $CH4MOD_{wetland}$, regression bias accounted for 66% of the RMSE in peatland, and modeling bias accounted for 39% of the RMSE in swamp; for the TEM, modeling bias and regression bias accounted for 29% and 42%, respectively, of the RMSE in coastal wetland (Table 2). This result indicated that there were still uncertainties in the modeling procedure, e.g., in the model mechanism or in parameterization (Zhang et al., 2017; Allen and Raktoe, 1981). In the existing process-based models, which are not limited to $CH4MOD_{wetland}$ and TEM, some important procedures should be focused on to reduce the bias due to the model mechanism. For example, the mechanism of the freeze-thaw cycle is important in process-based models(Wei and Wang, 2017) because of the large contribution of the CH_4 release during the nongrowing season in some frozen regions (Friborg et al., 1997; Huttunen et al., 2003; Mastepanov et al., 2008; Zona et al., 2016). In addition, quantifying CH_4 ebullition is important but difficult, which arises from uncertainty in estimates of CH_4 emissions from peatlands (Stanley et al., 2019). Moreover, although the importance of plants in CH_4 biogeochemical processes has been reported in many studies, better modeling and characterization of plant community structure is needed (Bridgham et al., 2013). Finally, most of the present process-based models do not have the ability to simulate CH_4 exchange from water bodies, such as lakes, rivers and reservoirs, although they contribute significantly to the global budget (Deemer et al., 2016). The use of the IPCC Tier method inevitably induced large uncertainties in the global estimates. The above mechanisms should be incorporated into existing process-based models to reduce the uncertainties in the current assessment.

The observational data related to processes of and controls on CH_4 production, consumption, and

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transport also limit the model calibration and validation. The flux data of 30 wetland sites used for model performance in this study are quite limited and do not represent all climatic, soil, hydrologic and vegetation conditions across global natural wetlands (Table 1). During recent years, eddy covariance method (Aubinet et al., 2012) is popular to observe CH_4 emissions from natural wetlands. The observations in this study were used chamber method, which is widely used for CH_4 observations before 2010 (Table 1). There are differences in measuring CH_4 fluxes between the two methods (Chaichana et al., 2018). Eddy covariance method may underestimate the fluxes (Twine et al., 2000; Sachs et al., 2010), while chamber method may overestimate the fluxes (Werle and Kormann, 2001). We didn't use eddy covariance data to validate the model in this study, partly because we used the chamber measurements to calibrate the model. Eddy covariance data should be used for model calibration and validation in future work, since it can give more accurate temporal resolution observed dataset. Furthermore, both process-based models were evaluated on an annual basis rather than on a daily scale. The validation of seasonal variation was not performed in this study, partly because we cannot obtain the daily step data for some of the sites. Fine temporal validation against more flux datasets, especially fluxes by eddy covariance experiments, and intermediate variables that control the CH_4 process are necessary in future studies (Wei and Wang, 2017).

5. Conclusion

Two process-based models, $CH4MOD_{wetland}$ and TEM, were used to simulate annual CH_4 emissions from different wetland types and continents, and their performances were evaluated. Model validation showed that both models could simulate variations between different wetland sites and years. The statistical analysis of model performance showed that $CH4MOD_{wetland}$ was capable of simulating CH_4 emissions from marsh, peatland and coastal wetlands, while the TEM was capable of simulating CH_4 emissions from peatland and swamps (model efficiency > 0). $CH4MOD_{wetland}$ had good performance in Asia, Europe and North America, while the TEM had good performance in North America, Asia, South America and Africa. The models were then used to make estimations of global wetland CH_4 emissions. The CH_4 simulations of both models had good agreement in terms of the latitudinal and meridional bands. The global CH_4 emissions for the period 2000–2010 were estimated to be 105.31± 2.72 Tg yr^{-1} by $CH4MOD_{wetland}$ and 134.31 ± 0.84 Tg yr^{-1} by the TEM. If we used a more accurate model to estimate each continent/wetland type based on the models' generality, the estimated global CH_4 emissions would be 116.99–124.74 Tg yr^{-1} for the period 2000–2010. The uncertainty of global wetland CH_4 assessments by the process-based model approach comes from the inaccuracy of the wetland mapping area, the modeling procedure and the observational limitations. Future research on accurately mapping wetland, improving model mechanism and parametrization and using more observations to evaluate model performance would improve global estimations.

Code and data availability.

The TEM and $CH4MOD_{wetland}$ model code and model data sets (input data and model results) are available on the website https://zenodo.org/record/3594988#.XglabvkzY2w.

Author Contribution

L.F. Yu pondered the rationale of the method. T. T. Li and YY. Lu developed the performed the simulations. W.J. Sun, Q. Zhang, W. Zhang, GC. Wang, L.J. Yu and R. Zhang made the data collection and processing. T.T. Li prepared the manuscript with contributions from all Coauthors.

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Competing Interests

The authors declare no competing interests.

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Table 1. Description of observation wetland sites

Wetland Name, Continent	Location	Wetland Type	Plant Species	Observation Period	Reference
Northeast Siberia, Russia, EU	72º22′N, 126º28′E	Peatland [a]	*Carex* spp., *Limprichtia revolvens, Meesia longiseta*	1999.5-1999.9	Wagner et al., 2003
Northeast Siberia, Russia, EU	71º30′N, 130º00′E	Peatland [a]	*Eriophorum, Carex* spp., *Sphagnum* spp., Salix spp.	1993.7-1993.8	Nakano et al., 2000
Northeast Siberia, Russia, EU	68º30′N, 161º24′E	Peatland [a]	*Larix, Alnus* spp., *Betula* spp., *Salix* spp.	1995.7-1995.8	Nakano et al., 2000
Zackenberg, Greenland, EU	74º30′N, 21º00′W	Peatland	*Cassiope tetragona, Salix arctica*	1996.6-1996.8 1999.7-1999.8 2000.7-2000.8	Christensen et al., 2000;Joabsson and Christensen, 2001
Abisko, Sweden, EU	68º22′N, 19º03′E	Peatland [a]	*Eriophorum angustifolium, Carex* spp.	1974.6-1974.9	Svensson and Rosswall, 1984
Sanjiang Plain, China, AS	47º35′N, 133º31′E	Marsh	*Carex lasiocarpa, Deyeuxia angustifolia*	2002.6-2005.11	Hao, 2006;Song et al., 2008
Ruoergai Plateau, China, AS	32º47′N, 102º32′E	Peatland	*Carex muliensis, Carex meyeriana*	2001.4-2001.10	Wang et al., 2002
Wuliangsu Lake, China, AS [&]	40º47′-41º03′ N, 108º43′-108º57′ E	Marsh	*Phragmites australis*	2003. 4-2003.10	Duan et al., 2005
Haibei alpine marsh, China, AS	37º29′N, 101º12′E	Marsh	*Carex allivescers*	2002.7-2002.9	Hirota et al., 2004
Zhalong Wetland, China, AS	46º52′N-47º32′N, 123º47′E-124º37′E	Marsh	*Phragmites australis*	2009.5-2009.10	Huang et al., 2011
Liao River delta, China, AS	40º40′-41º25′N, 121º35′- 122º55′E	Coastal wetland [b]	*Phragmites australis*	1997.4-1997.11	Huang et al., 2005
Chongming Island, China, AS [&]	31º15′N, 121º30′E	Coastal wetland [b]	*Scirpus*	2004. 5-2004.12 2011.2-2011.12	Li et al., 2014
Guangzhou, China, AS [*]	23º01′N, 113º46′E	Coastal wetland [c]	*Aegiceras corniculatum etc.*	2005.3-2005.12	Kang et al., 2008
Haikou, China, AS [*]	19°51′ N, 110°24′ E	Coastal wetland [c]	*Bruguiera sexangula*	1996.1-1997.12	Ye et al., 2000
Sarawak, Malaysia, AS [&]	2º49′N, 111º51′E	Swamp	Flooded forest[$]	2002.8-2003.7	Melling et al., 2005
Kalimantan, Indonesia, AS	2º20′S, 113º55′E	Swamp	*Shorea balangeran*	1994.9-1995.9	Page et al., 1999; Jauhiainen et al., 2005
Congo River basin, Congo, AF [*]	4º00′S-0º00′, 14º00′- 18º00′E	Swamp	Flooded forest[$]	1988	Tathy et al., 1992
Congo River basin, Congo, AF [*]	0º00′-4º00′N, 14º00′- 18º00′E	Swamp	Flooded forest[$]	1988	Tathy et al., 1992
Pantanal, Brazil, SA	19º30′S, 57º00′W	Marsh	*Paspalum repens*	1998.1-1998.12	Alvalá and Kirchhoff, 2000; Melack et al., 2004
Lago Calado, Brazil, SA [*]	3º15′S, 60º34′W	Swamp	Flooded forest[$]	1985	Crill et al., 1988
Central Brazilian Amazon, SA [*]	5º00′S-0º00′, 50º00′-70 º00′W	Swamp	Flooded forest[$]	1985	Devol et al., 1988
Alaska bethel, USA, NA	60º45′N, 161º45′W	Peatland [a]	*Empetrum nigrum, Carex aquatilis, Sphagnum spp.*	1988.7-1988.8	Bartlett et al., 1992

Alaska Prudhoe Bay, USA, NA*	70º30′N, 149º00′W	Peatland [a]	*Sphagnum* spp.	1984	Sebacher et al., 1986
Alaska arboretum, USA, NA	64º52′N, 147º51′W	Peatland [a]	*Eriophorum vaginarum*, *Carex* spp., *Sphagnum* spp.	1987.6-1987.10 1988.6-1988.10 1989.6-1989.10	Whalen and Reeburgh, 1992
Saskatchewan, Canada, NA	53°57′N,105°57′W	Peatland	*Buckbean-Carex* spp.	1994.5-1994.9	Suyker et al., 1996
Michigan, USA, NA	42°27′N, 84°01′W	Peatland	*Scheuchzeria palustris*, *Carex oligosperma*	1991.1-1993.12	Shannon et al., 1996
Toolik Lake, USA, NA	68°38′N,149°38′W	Peatland [a]	*Eriophorum*, *Carex* spp.	1990.6-1990.8	Christensen, 1993
Hudson Bay, Canada, NA	51°18′-51°31′N, 80°28′-80°38′W	Peatland	*Larch*, *Black spruce*, *Sphagnum* spp.	1990.6-1990.10	Moore et al., 1994
Quebec, Canada, NA	54°48′N, 66°49′W	Peatland	*Carex* spp.	1989.6-1989.9	Moore et al., 1990
Mississippi, USA, NA	34°24′ N, 89°50′W	Marsh	*Carex hyalinolepis*, *Hydrocotyle umbellata*, *Festuca obtusa*	2005.5-2006.7	Koh et al., 2009

* We used the average yearly CH_4 flux of the experimental year from the literature.
& Wetland sites used for calibration.
$ These swamp sites do not have plant species information in the literature.
[a] Tundra.
[b] Tidal marsh.
[c] Mangrove.

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Table 2. Model performance for $CH4MOD_{wetland}$ and the TEM for different continents and wetland types

Wetland type/Continent	$CH4MOD_{wetland}$								TEM								n
	R^2	RMSE	RMD	EF	CD	U_M	U_R	U_E	R^2	RMSE	RMD	EF	CD	U_M	U_R	U_E	
North America	0.80	65.82	13.24	0.48	0.46	0.04	0.60	0.36	0.80	41.93	-13.03	0.79	1.45	0.10	0.04	0.87	14
Asia	0.94	55.79	-12.64	0.93	0.96	0.28	0.02	0.70	0.26	72.56	1.71	0.32	1.93	0.00	0.03	0.97	11
Europe	0.21	63.66	-29.91	0.07	1.13	0.22	0.06	0.71	NS	155.88	2.42	-4.55	0.38	0.00	0.88	0.12	7
South America & Africa	NS	59.42	42.44	-0.92	0.74	0.51	0.03	0.46	0.81	30.55	15.31	0.49	3.15	0.25	0.48	0.37	5
Marsh	0.75	29.44	0.52	0.22	0.37	0.00	0.73	0.27	NS	39.76	-18.77	-0.42	0.95	0.22	0.17	0.61	8
Peatland	0.84	77.26	7.60	0.55	0.47	0.01	0.66	0.33	NS	55.20	-1.64	0.77	1.09	0.01	0.02	0.97	20
Swamp	0.32	75.22	46.68	-0.08	0.50	0.39	0.14	0.47	0.70	38.83	16.77	0.71	0.93	0.19	0.02	0.79	6
Coastal wetland	0.80	55.46	-26.97	0.72	2.09	0.24	0.30	0.47	0.77	188.26	101.00	-2.26	0.35	0.29	0.42	0.29	4
Global	0.78	61.27	11.13	0.58	0.58	0.03	0.43	0.54	0.66	56.00	-0.00	0.63	1.26	0.00	0.02	0.98	37

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Table 3. CH_4 simulations by $CH4MOD_{wetland}$ and the TEM for different continents and wetland types. All units are Tg CH_4 yr^{-1} ± 1σ, where the standard deviation represents the interannual variation in the model estimates.

Continent/Wetland type	CH_4 Flux ($g\ m^{-2}\ yr^{-1}$)		CH_4 Emissions (Tg)		Area ($10^4 \times km^2$)
	$CH4MOD_{wetland}$	TEM	$CH4MOD_{wetland}$	TEM	
Asia	23.27 ± 0.67	25.78 ± 0.14	25.37 ± 0.73	28.81 ± 0.15	109.04
Africa	27.64 ± 1.55	33.92 ± 0.27	21.12 ± 1.18	25.91 ± 0.20	76.39
N. America	11.48 ± 0.47	14.10 ± 0.18	24.38 ± 1.00	29.95 ± 0.38	212.35
S. America	29.61 ± 0.52	39.91 ± 0.54	26.24 ± 0.46	35.36 ± 0.48	88.60
Europe	7.77 ± 0.11	16.04 ± 0.28	6.48 ± 0.09	13.38 ± 0.23	83.40
Oceania	12.08 ± 2.52	11.31 ± 0.57	1.72 ± 0.27	1.61 ± 0.06	14.23
Lake, river *	15.57	15.57	27.32	27.32	175.46
Marsh	28.64 ± 1.06	39.60 ± 0.28	37.47 ± 1.39	51.80 ± 0.37	131.61
Peatland	1.99 ± 0.09	9.87 ± 0.27	0.42 ± 0.02	2.06 ± 0.06	21.00
Swamp	31.58 ± 0.57	45.59 ± 0.91	17.37 ± 0.32	25.08 ± 0.50	55.34
Coastal wetland	9.44 ± 0.25	11.63 ± 0.14	2.85 ± 0.08	3.51 ± 0.04	30.32
Intermittent wetland	18.49 ± 2.08	18.29 ± 0.19	5.81 ± 0.65	5.75 ± 0.06	31.60
No-specific wetland	10.21 ± 0.68	13.63 ± 0.25	14.07 ± 0.93	18.79 ± 0.34	138.67
Global	18.03 ± 0.49	23.00 ± 0.15	105.31± 2.72	134.31 ± 0.84	584.00

* IPCC Tier 1 method was used to estimate the CH_4 emissions from lakes and rivers. The CH_4 emission factor was from the IPCC (1996).

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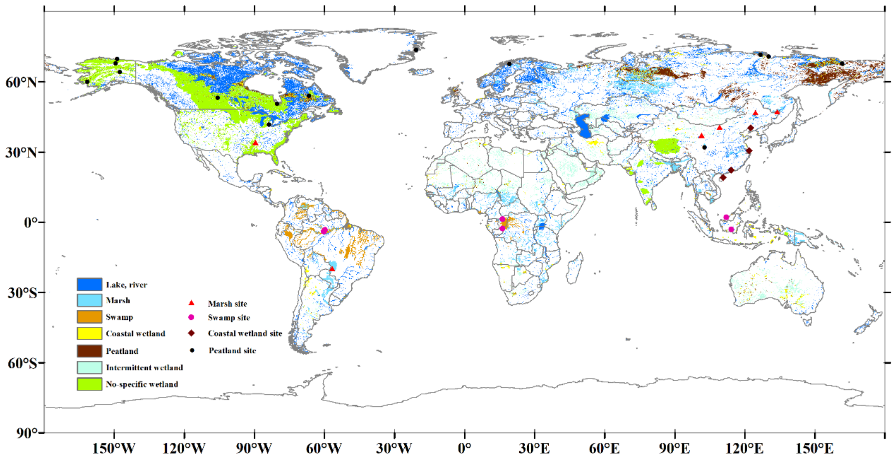

Figure 1: Wetland site distribution (Table 1) and global wetland maps of GLWD-3 (Lehner and Döll, 2004).

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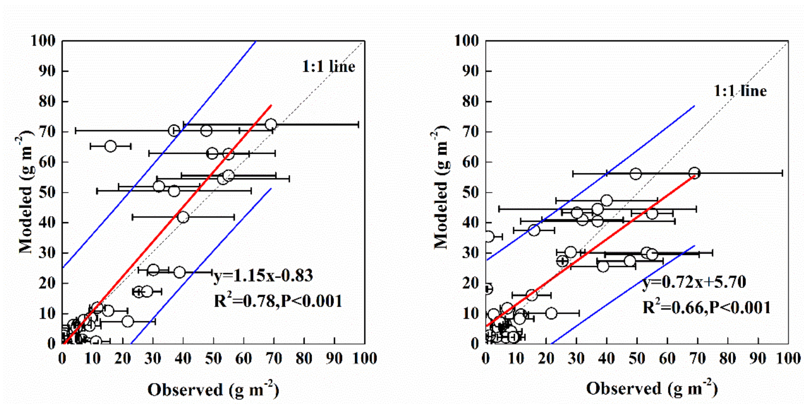

Figure 2: Regression of simulated against observed total amount of seasonal CH_4 emission from global wetland sites by $CH4MOD_{wetland}$ (a) and the TEM (b). The horizontal bars are the standard errors from the sampling replicates at the wetland site. The blue line is the prediction correspondence. The dashed line is the 1:1 line.

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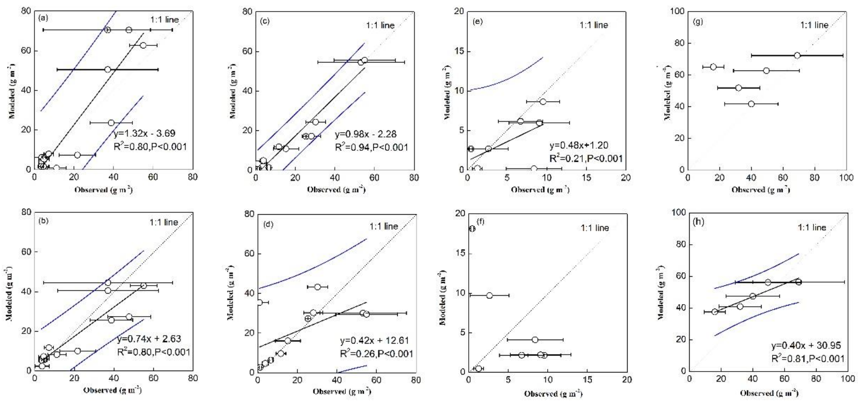

Figure 3: Regression of simulated against observed total amount of seasonal CH_4 emissions from North American wetland sites by $CH4MOD_{wetland}$ (a) and the TEM (b), from Asian wetland sites by $CH4MOD_{wetland}$ (c) and the TEM (d), from European wetland sites by $CH4MOD_{wetland}$ (e) and the TEM (f), and from South American and African wetland sites by $CH4MOD_{wetland}$ (g) and the TEM (h). The horizontal bars are the standard errors from the sampling replicates at the wetland site. The blue line is the prediction correspondence. The dashed line is the 1:1 line.

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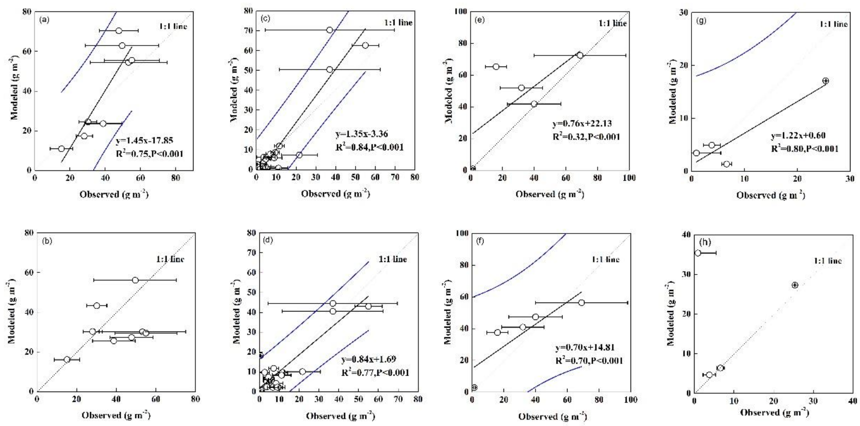

Figure 4: Regressions of simulated against observed total amount of seasonal CH_4 emissions from marsh sites by $CH4MOD_{wetland}$ (a) and the TEM (b), from peatland sites by $CH4MOD_{wetland}$ (c) and the TEM (d), from swamp sites by $CH4MOD_{wetland}$ (e) and the TEM (f), and from coastal wetland sites by $CH4MOD_{wetland}$ (g) and the TEM (h). The horizontal bars are the standard errors from the sampling replicates at the wetland site. The blue line is the prediction correspondence. The dashed line is the 1:1 line.

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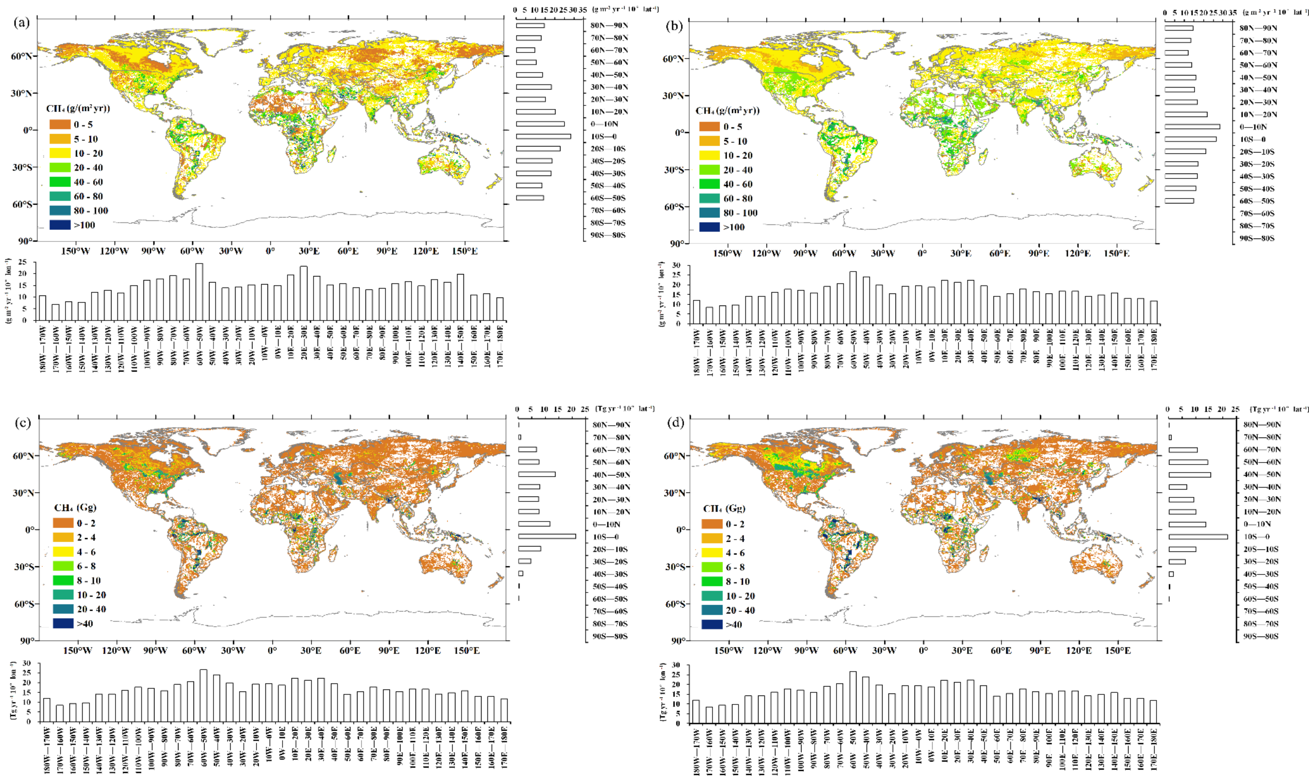

Figure 5: Spatial pattern of annual mean CH_4 fluxes for 2000–2010, with latitudinal and longitudinal distributions of annual mean CH_4 fluxes by $CH4MOD_{wetland}$ (a) and the TEM (b). Spatial pattern of annual mean CH_4 emissions for 2000–2010, with latitudinal and longitudinal distributions of annual mean CH_4 emissions by $CH4MOD_{wetland}$ (c) and the TEM (d). The CH_4 fluxes and emissions are aggregated in steps of 10°.