Institute of Atmospheric Physics

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Dear editor：

The manuscript (bg-2015-154) entitled "**Impacts of climate and reclamation on temporal variations in CH_4 emissions from different wetlands in China: From 1950 to 2010**" by Tingting Li, Wen Zhang, Qing Zhang, Yanyu Lu, Guocheng Wang, Zhenguo Niu, Maarit Raivonen and Timo Vesala has been revised according to your comments.

Thank you for your suggestions and detailed instructions for the revision of the MS. Correspondence regarding the MS should be directed to W. Zhang using the following address, phone number, or e-mail address:

Address: Institute of Atmospheric Physics, CAS. No.3, Huayanli, Chaoyang District,
Beijing, 100029, China
Tel: 86-10-62071389
Fax: 86-10-62071389
E-mail: zhw@mail.iap.ac.cn

Yours sincerely，

Wen Zhang

I would like to warmly acknowledge the authors' efforts to improve their manuscript and their thorough consideration of the previous comments and suggestions. The reviewed version is better targeted and scientifically more robust, in my opinion. We are, however, still one step away from its acceptance, since some further changes are needed (please check for individual comments in the attached pdf: bg-2015-154-manuscript-version2_editor comments.pdf, and address those most important)

1. The English is very good for a non-English speaker but the use of a native editor would be desirable.

RE: We acknowledge the fallacy in the English writing of the MS. The have made the English improvement via "American Journal experts" after every revision of the MS. Now we believe they did not make it well. We are grateful if you are kingly to recommend an English cosmetic agency to essentially improve the MS.

2. Introduction: It is much better but it is too long as it is now, it needs shortening (1/5). A few ideas are not well connected and other are too developed (the warming potential of CH4 can be summarized in 1 line).

RE: We have shortened the introduction by about 1/5. We also modified the introduction according to your specific comments. We inserted the responses one by one according to your comments with the detailed modification in the manuscript.

You expose the importance of your research at the end of the introduction, but it is unclear why a backward extrapolation of wetland area to 1950 is important for current emission estimates, please briefly explain (e.g. current emissions are not your goal, but the the evolution of CH4 fluxes from 1950 to 2010.). Also offer information not only on the variability of the current estimates but on its mean value. On your main questions you should also include: to produce less uncertain estimates of national CH4 fluxes for the last 60 years, by reproducing national wetland area estimates back to 1950.

RE: At the end of the introduction, we clearly pointed out that "The objectives of the present study are (1) to model spatial and temporal changes in CH_4 emissions across China's natural wetlands (including inland marshes/swamps, lakes, rivers and coastal wetlands) from 1950 to 2010". According to the editor's suggestion, we also modified the introduction in page 3, lines 22-26. Firstly, we pointed out that "To date, there has been no comprehensive study on national CH_4 emissions from all kinds of natural wetlands in China from 1950 to 2010" in order to emphasize that our goal is the evolution of CH_4 emissions from 1950 to 2010, but not the current emission estimate. Then we explained that "In order to produce less uncertain estimates of national CH_4 fluxes for the last 60 years, reproducing national wetland area estimates back to 1950 is necessary". This may eliminate the ambiguity that the backward extrapolation of the wetland area to 1950 is important to the estimation of national CH_4 emissions during the past 60 years, but not to the current emission estimates. In addition, this also make the main questions include: to produce less uncertain estimates of national CH_4 fluxes for the last 60 years, by reproducing national wetland area estimates back to 1950.

We offered the information of the mean value of the current estimates in page 3, line 14 in the revised manuscript.

Also please note that wetland area might have decreased by changes in land use (e.g. wetland to agriculture, wetland to forests) but it is unlikely that the changed areas are emission free (you overestimate the emission reductions). Also note that when drying wetlands, CH4 decreases, but N2O increases, so in a more general balance, GHG emissions might not be fully decreasing. These last comments are to observed at some point, but not in the introduction.

RE: We added this as a discussion in section 4.1 (page 12, lines 28-30)

3. Material and Methods: This is currently your weakest point. It currently has 7 pages. Please reduce to 4 and move the rest to SOM. Mental aggregation and summarizing are truly needed here (use tables to summarize data input if needed). The subsections are well design, but are too long. The description of the model is good though. Use the diagramme flow to explain the most important steps and avoid details.

RE: According to the reviewer's suggestions, we have reduced the material and methods to 4 pages. We modified Fig. 1 to a diagramme flow to explain the most important steps of the methods and materials. The modified Fig.1 shows the relationship of each step. In addition, it includes all of the steps of the methods and most of the important input datasets. We also summarized the data sources into Table 1. In addition, we moved some methods to the Supplementary materials: 1, we moved some detailed methods of the model calibration, model upscalling and model uncertainty analysis to Supplementary material S2, S4 and S6, respectively; 2, we moved the section 2.6 (estimate CH_4 emissions from lakes & rivers) to supplementary material S7, because this method just repeats Chen's study (Chen et al., 2013); 3, we moved section 2.7 (Time series of the wetland area) to supplementary material S8 because the main work of this section is Niu's work (Niu et al., 2012), we just estimate the initial wetland area of 1950. Both of section 2.6 and section 2.7 are not the innovation of this study, so we moved them to the supplementary materials.

4. Results: It is quite good but you include discussions elements in the results (e.g. why the fluxes peak in certain months, etc). Make sure that the discussion is left in the discussion section, and that the results are not repeated in the discussion, as it currently happens. Aggregate results and focus on the most interesting, the key messages. Move the rest to SOM. You have ran lots of analyses for multiple time and spatial scales, it is a complex paper, but summarizing is needed to favor the readers' interest. Do not offer all details, just most important and novel results, also those that are less known (e.g effect of freezing, frosting, on CH4 emissions)

RE: Thanks very much for the editor's valuable suggestions. We made modifications according to your guidance as followed:

1) We added a map of the wetland area location of 1950 as Fig. S3 in the supplementary material.
2) We changed the title of section 3.1 to "Spatio-temporal variations in CH_4 fluxes in China". We didn't use CH_4 emissions because this section focused on the CH_4 fluxes.
3) We add a section "3.2 Climate and CH_4 fluxes" according to your guidance. Here we also used the CH_4 fluxes but not emissions to illustrate that only the CH_4 fluxes are influenced by the climate.
4) According to your guidance, we moved the discussion to the discussion section or eliminated the discussion from the results section. (We made responses one by one to your comments. Please see the annotations in the modified manuscript).
5) We aggregated the results and tried our best to give the key messages according to your guidance. We responded your comments along the modifications in the manuscript.

5. Discussion: It is quite good but please see comments on the manuscript. Use the same order of captions than in the results, and avoid repeating the results again. Summarize and aggregate.

RE: We have modified the discussion under your guidance. The main modification includes:

1) We merged section 4.2 and 4.3 into one section.
2) We summarized section 4.4 of the original manuscript according to your guidance.
3) We removed the summaries and added a section of “Projection of wetland changes in China and the management tips”.

Please see the one to one response in the revised manuscript.

Impacts of climate and reclamation on temporal variations in CH_4 emissions from different wetlands in China: From 1950 to 2010

Running title: CH_4 from Chinese natural wetlands

Tingting Li[1], Wen Zhang[1,*], Qing Zhang[1], Yanyu Lu[2], Guocheng Wang[1], Zhenguo Niu[3], Maarit Raivonen[4], Timo Vesala[4,5]

[1] LAPC, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, 100029, China

[2] Anhui Climate Center, Hefei, 230031, China

[3] State Key Laboratory of Remote Sensing Science, Jointly Sponsored by Institute of Remote Sensing Applications, Chinese Academy of Sciences and Beijing Normal University, Beijing 100101, China;

[4] Department of Physics, P.O. Box 48, FI-00014 University of Helsinki, Finland

[5] Department of Forest Sciences, P.O. Box 27, FI-00014 University of Helsinki, Finland

Correspondence to: Wen Zhang (Email: zhw@mail.iap.ac.cn, Tel: 86-10-62071389)

Keywords: CH_4 emissions, wetland, modelling, temporal variation, China

Abstract

Natural wetlands are among the most important sources of atmospheric methane and thus important for better understanding the long-term temporal variations in the atmospheric methane concentration. During the last 60 years, wetlands have experienced extensive conversion and impacts from climate warming which might result in complicated temporal and spatial variations in the changes of the wetland methane emissions. In this paper, we present a modelling framework, integrating $CH4MOD_{wetland}$, TOPMODEL and TEM models, to analyze the temporal and spatial variations in CH_4 emissions from natural wetlands (including inland marshes/swamps, coastal wetlands, lakes and rivers) in China. Our analysis revealed a total increase of 25.5%, averaging 0.52 g m^{-2} per decade, in the national CH_4 fluxes from 1950 to 2010, which was mainly induced by climate warming. Larger CH_4 flux increases occurred in Northeastern, Northern and Northwestern China where there have been higher temperature rise. However, decreases in precipitation due to climate warming offset the increment of CH_4 fluxes in these regions. The CH_4 fluxes from the wetland on the Qinghai Tibetan Plateau exhibited a lowest CH_4 increase (0.17 g m^{-2} per decade). Although climate warming has accelerated CH_4 fluxes, the total amount of national

CH_4 emissions decreased by approximately 2.35 Tg (1.91—2.81 Tg), i.e., from 4.50 Tg in the early 1950s to 2.15 Tg in the late 2000s, due to the wetland loss of totally 17.0 million ha. Of this reduction, 0.26 Tg (0.24—0.28 Tg) was derived from lakes and rivers, 0.16 Tg (0.13—0.20 Tg) from coastal wetlands, and 1.92 Tg (1.54—2.33 Tg) from inland wetlands. Spatially, Northeastern China contributed the most to the total reduction, with a loss of 1.68 Tg. The wetland CH_4 emissions reduced by more than half in most regions in China except for the Qinghai Tibetan Plateau, where the CH_4 decrease was only 23.3%.

1. Introduction

Atmospheric methane (CH_4) is the second-most important trace greenhouse gas (GHG) after carbon dioxide (CO_2). In IPCC (2013), the radiative forcing of CH_4 was revised to 0.97 W m^{-2} when its indirect global warming effect was incorporated. The atmospheric CH_4 concentration has increased by ~150% from 1750 to 2011 (IPCC, 2013), but remained nearly constant from 1999 to 2006 and then continually increased after 2007 (Nisbet et al., 2014). However, the temporal variation in the inventory-based estimates of methane emissions exhibited a different trend. Human-derived CH_4 emissions substantially increased (10%) from 2000 to 2005 due to rapid economic growth and increasing demand for food and energy, implying inaccuracies in the inventories, simultaneously offsetting of the decreases in natural emissions or a comparable increase in atmospheric CH_4 removals such as OH radical (Montzka et al., 2011).

Natural wetland emissions are the largest natural source as well as the most uncertain source in the global CH_4 budget (Denman et al., 2007; Potter et al., 2006; Whalen, 2005), ranging from 115 (Fung et al., 1991) to 237 Tg CH_4 yr^{-1} (Hein et al., 1997) , and representing 20% to 40% of the global source. However, it has been reported that the long-term loss of natural wetlands was approximately 50% during the 20th century (Moser et al., 1996; Revenga et al., 2000), and as high as 87% since 1700 AD (Davidson,2014). And the wetland loss may have offset the increase in human-derived CH_4 emissions from 2000 to 2005 (Bousquet et al., 2006).

China has the world's fourth largest wetland area (Wang et al., 2012a) and consists of a wide variety of representative types of the world's natural wetlands. The Chinese natural wetlands have also experienced a serious loss, with 23% in freshwater

批注 **[f1]:** Comment: the warming potential of CH4 can be summarized in 1 line
RE: we have summarized this sentence.

批注 **[f2]:** Comment : For clarification purposes could you please, substitute the "and" for a comma, and include "increase in atmospheric CH4 removals such as OH-"
RE: We have modified according to your comment

批注 **[f3]:** Comment :This is wrongly stated. The contribution of wetlands dominates the NATURAL CH4 emissions but natural wetlands are not the largest source in the global CH4 (these are agriculture and fossil fuels)
RE:We added the word "natural" since wetlands are the largest natural source.

批注 **[f4]:** Comment: lines 30-33 (on wetland area): Please shorten and link better to the ideas before.
RE: We have shorten this sentence. We also added "however" to link to the previous idea. In this paragraph, we want to show that natural wetlands are the biggest natural source, but the loss of area may have offset the increase in human-derived CH4 emissions (This is the idea of the previous paragraph).

批注 **[f5]:** Comment : may have offset
RE: revised

批注 **[f6]:** Comment: Too long. Why the decrease of wetland area in China is important?
RE: We have shorten these sentences. The decrease of wetland area in China would inevitably decrease the national CH4 emissions. However, there was no comprehensive estimate on the influence of wetland loss on the national CH4 emissions in China during the last 60 years.
Comment: You expose here two different ideas: the contribution of wetland area loss to the CH4 budget, and the non-inclusion of natural wetlands in Streets et al. (2001)----is this researcher working in CHinese CH4? Are these ideas relavant to the goal of your research? (the first idea could be, but should come with a better explanation: why not accounting reclamation in the national CH4 estimates is important? why would it be?
RE: We removed theStreets et al. (2001), althogh this is the research about Chinese CH4. We just retained the importance of the contribution of wetland area loss to the CH4 budget.

swamps, 16% in lakes, 15% in rivers and 51% in the coastal wetlands during the past 60 years based on census data (An et al., 2007), attributed primarily to reclamation (An et al., 2007; Niu et al., 2012; Huang et al., 2010; Xu and Tian, 2012). Analysis with the remote sensing data also reported that ~30% of the wetlands were lost during the past 30 years (Niu et al., 2012). Accounting reclamation in the national CH_4 estimates is important because it has inevitably reduced CH_4 emissions.

Most studies estimating the national CH_4 emissions from natural wetlands have involved the extrapolation of site-specifically measured methane fluxes (Wang et al., 1993; Khalil et al., 1993; Jin et al., 1999; Ding et al., 2004; 2007; Chen et al., 2013; Wang et al., 2012b). Induced by the substantial heterogeneity in wetland CH_4 fluxes (e.g., Christensen et al., 2003; Ding et al., 2004; Yang et al., 2006) and the disagreement in data of the wetland area (e.g., Zhao & Liu, 1995; Xu et al., 1995; Wang et al., 2012b; Zhao, 1999), there are large uncertainties in the national wetland CH_4 emission inventories of 4.4 (1.7–10.5) Tg CH_4 yr^{-1}. In addition, the measured fluxes may also yield biased estimations when temporally extrapolated to the distant past, such as the 1905s, when no experiment data was available. The process-based models are capable of reducing the bias by quantifying the impacts of environmental changes on wetland methane emissions in the modelling mechanism. A few modelling studies have simulated the national CH_4 emissions from the inland marshes/swamps of China (Xu and Tian, 2012; Tian et al., 2011). However, lakes, rivers and coastal wetlands are also non-negligible in estimating national CH_4 budget and the temporal trend (Bastviken et al., 2004; Yang et al., 2011; Chen et al., 2013). To date, there has been no comprehensive study on national CH_4 emissions from all kinds of natural wetlands in China from 1950 to 2010.

批注 **[f7]:** Comment: Could you also offer a mean, median or centered value, so that readers can understand better what are China's CH4 mean emissions estimates?
RE: The mean value was added.

批注 **[f8]:** Comment: extrapolation that really matters is to the distant future not to the distant past (for the past we have the atmospheric emissions already assessed as empirical atmospheric data collection).

RE: extrapolation may induce bias to the estimation in distant future and past when no measurement was available. In this study, our objective is to estimate the historical CH4 emissions. For the period before 1990, there were no measurement available in China. Extrapolation have to use the measurements after 1990 to the distant past, which may induce bias in the estimate.

To make an estimation of the national CH_4 fluxes for the last 60 years, reproducing the time series of the national wetland area back to 1950 is primarily necessary. Recently, Niu et al. (2012) developed maps of the natural wetlands (including inland marshes/swamps, lakes, rivers and coastal wetlands) in 1978, 1990, 2000 and 2008, respectively. In addition, a biogeophysical model validated against the CH_4 flux measurements representative of the wetlands around the world, i.e., $CH4MOD_{wetland}$ (Li et al., 2010), facilitates the long-term modelling of the methane emissions from all types of the natural wetlands in China. Thus the objectives of the present study are (1) to model spatial and temporal changes in CH_4 emissions across China's natural wetlands (including inland marshes/swamps, lakes, rivers and coastal wetlands) from 1950 to 2010 and (2) to quantify the impacts of climate change and reclamation on the CH_4 emissions from the natural wetlands in different regions of China.

2. Materials and Methods

In this study, we used an integrated modelling framework centered on $CH4MOD_{wetland}$ (Li et al., 2010) to simulate the CH_4 emissions from inland and coastal wetlands. Directly extrapolated field measurements were used to calculate the CH_4 emissions from lakes and rivers (Chen et al., 2013). A diagram in Fig. 1 shows the main steps of the methods for estimating the national CH_4 emissions from the natural wetlands from 1950 to 2010.

2.1 Modelling framework

Three models were included in the model framework with a spatial resolution of 0.5 ° for the period from 1950 to 2010 (Fig. 1). The center of the modelling framework is $CH4MOD_{wetland}$ (Li et al., 2010). $CH4MOD_{wetland}$ is a biogeophysical model that aims to simulate the CH_4 production, oxidation and emissions from natural wetlands (Li et al., 2010). In $CH4MOD_{wetland}$, methane production rates are calculated by the availability of methanogenic substrates and the parameterized influences of environmental factors, e.g., soil temperature, soil texture and soil redox potential. The methanogenic substrates are derived from the root exudation of wetland plants and the decomposition of above- and below-ground litters and the soil organic matter. The CH_4 emissions to the atmosphere via diffusion, ebullition and plant transportation are all simulated in the model. Oxidation occurs when CH_4 diffuses to the atmosphere or is transported via the plant aerenchyma.

The model inputs include the soil texture (soil sand fraction, soil organic carbon and bulk density), aboveground net primary productivity (ANPP), daily soil temperature, water table depth and salinity. With the modelling outputs of the daily CH_4 emissions (g m^{-2} d^{-1}), we multiplied the CH_4 fluxes by the wetland area in each 0.5 °×0.5 ° grid and summed up the CH_4 emissions from all grids to yield the total national CH_4 emissions (Fig. 1).

The validation of $CH4MOD_{wetland}$ against the field measurements of CH_4 fluxes from wetlands across China, Canada and the U.S.A. presents details of the model performance (Li et al., 2010; 2012). At present, however, the insufficiency of the model mechanism, e.g., lacking the influence of thawing permafrost on CH_4

批注 **[f9]:** Comment : You cannot have 7 pages of Material and methods. Use SOM and synthesize the most important ideas, using, if necessary, a flow diagram to show the sequence of steps (model framework, model calibration, model validation (shouldnt validation come at the final upscaled level of data?, upscaling, uncertainties, etc.
RE: We have shortend the material and methods for 4 pages by moving the detailed and unimportant methods to the SOM. We also modified Fig. 1 to a flow diagram to show the main steps of the methods. We changed the order of model validation and upscaling.

批注 **[f10]:** The paragraph between lines 19-21 was removed.

production will result in distorted CH_4 simulations during the winter and freeze-thaw period. The dynamics of the water table and the growth of wetland plants, also limits its upscaling to regions where no measurements of the water tables and ANPP are available. We, therefore, integrated two other models, i.e. TEM and TOPMODEL to facilitate upscaling of $\mathrm{CH4MOD_{wetland}}$.

The TEM model (Melillo et al., 1993; Zhuang et al., 2004; 2006; 2007; 2013) is a process-based biogeochemistry model that couples carbon, nitrogen, water, and heat processes in terrestrial ecosystems to simulate ecosystem carbon and nitrogen dynamics. This model has been widely used to investigate regional and global NPP (e.g., Melillo et al., 1993; Cramer et al., 1999; McGuire et al., 1992). With this model framework (Fig. 1), the soil temperature and net primary productivity (NPP) outputs from the TEM model were used as inputs to $\mathrm{CH4MOD_{wetland}}$. The fraction of ANPP to NPP was determined based on Gill and Jackson (2003). Further descriptions of the model and the inputs are described in Zhuang et al. (2013).

The TOPMODEL (Beven and Kirby, 1979) is a rainfall-runoff model that is designed to work at the scale of large watersheds using the statistics of topography. In previous research (Bohn et al., 2007; Kleinen et al., 2012; Lu and Zhuang et al., 2012; Zhu et al., 2013), TOPMODEL has been used to simulate water table variations in natural wetlands. The TOPMODEL inputs included soil moisture and the topographic wetness index (Fig. 1). More details on simulating water table depth using TOPMODEL are provided in Supplementary Material S1.

Previous studies (Atkinson and Hall, 1976; King and Wiebe, 1978; Bartlett et al., 1985; 1987; Magenheimer et al., 1996) have indicated that methane emissions from various coastal salt marshes in the temperate zone vary with salinity. To improve the capacity to simulate methane emissions from coastal wetlands, we adopted the relationship between salinity and methane fluxes according to Poffenbarger et al. (2011):

$$f(s) = 10^{a \times s} \tag{1}$$

where $f(s)$ represents the effect of salinity on CH_4 production, s is the salinity (psu, practical salinity unit), and a is an empirical constant.

2.2 Model calibration

The natural wetlands in China have complex plant species. Considerable spatial variations in fluxes related to vegetation have been found (Ding et al., 2004; Hirota et al., 2004; Song et al., 2007; Duan et al., 2005; Huang et al., 2005). Such variations have been ascribed mainly to the differences in the plant NPP, the capacity of transferring labile organic carbon into anoxic environments, and the capacity for the plant transport and oxidation of CH_4 (Berrittella and Huissteden, 2011). Sufficient calibration and parametrization of the vegetation parameters in the model is important for reliably reproducing CH_4 emissions at wetland sites. *Carex* and *Phragmites* are dominant plant species in Chinese natural wetlands (Lang & Zu, 1983). Previous site measurements (Table S1) on the wetlands with *Carex* and *Phragmites* provide the data for model calibration and validation.

In the present study, the recalibrated parameters of $CH4MOD_{wetland}$ are mainly related to the vegetation (Table S2). Among these parameters, the proportion of the roots to the total production (f_{root}) and the fraction of available plant-mediated transport (T_{veg}) were obtained from the literature. *VI* is a vegetation index that can identify the relative differences in methane production among vegetation types, and P_{ox} recognizes the different fractions of CH_4 oxidized when transported by different plant species. Both *VI* and P_{ox} were calibrated to account for the differences between plant species.

In our previous studies, we parameterized *VI* and P_{ox} using the CH_4 flux measurements collected from the Sanjiang Plain (SJ site in Table S1) in Region I (Fig. 2), where the dominant plant species is *Carex* (Supplementary Material S3) (Li et al., 2010, 2012). In this study, we used the minimum RMSE method to recalibrate *VI* and P_{ox} for the wetlands dominated by *Phragmites* (Table S2). More details about the calibration and minimum RMSE method were in Supplementary material S2. Table S2 shows the values and sources of the model parameters.

批注 **[f11]:** We moved the detailed RMSE method to Supplementary material S2

2.3 Upscaling of the model framework

批注 **[f12]:** We changed the order of model upscaling and model validation in this revision according to your comment.

Lang and Zu (1983) divided the Chinese wetlands into five regions according to the environmental conditions and dominant vegetation type (Fig. 2). Supplementary Material S3 describes details about the climate, soil and vegetation type of the regions. For national model simulations of CH_4 fluxes, we adopted this spatial partition and assigned the vegetation-related parameters of $CH4MOD_{wetland}$ with the calibrated values in Table S2 to each division. Upscaling of the model parameters were explained in Supplementary material S4.

批注 **[f13]:** We moved the details about the upscaling of model parameters to Supplementary material S4

We established gridded (0.5°×0.5°) and geo-referenced time-series input datasets of climatic, soil and salinity data to drive the modelling in each grid (Fig. 1). The total CH_4 emission from the inland and coastal wetlands in each grid cell was calculated as the product of the CH_4 fluxes and the gridded wetland area.

2.4 Model validation

Model validation evaluates the model performance at the "site-scale" using individual CH4MOD$_{\text{wetland}}$ simulations and at the "grid-scale" using the proposed model framework (Fig. 1). More details regarding the "site-scale" and the "grid-scale" validations are described in Supplementary Material S5.

The "site-scale" validation were carried out at the wetland sites on the Sanjiang Plain (Figure S1a, S1b), the Ruoergai Plateau, (REG in Table S1; Figure S1d, S1e), the Haibei alpine marsh (HB in Table S1; Figure S1g), the Zhalong wetland (ZL in Table S1; Figure S1i) and the Liao River delta (LRD in Table S1; Figure S1k). The comparison of the simulated versus the observed monthly CH_4 fluxes resulted in an R^2 of 0.79, with a slope of 0.86 and an intercept of 0.73 ($n=41$, $p<0.001$) (Figure S2a). The RMSE, mean deviation (RMD) and the model efficiency (EF) between the simulated and observed monthly CH_4 fluxes were 48.5%, 0.9% and 0.78, respectively.

The "grid-scale" validation showed that the integrated model framework (CH4MOD$_{\text{wetland}}$/TEM/TOPMODEL, Fig. 1) was able to simulate the seasonal variations in monthly CH_4 emissions at the SJ (Figure S1c) and LRD (Figure S1l). Though there are some underestimations in the CH_4 fluxes predicted by the model framework for the other 3 sites (Figure S1f, S1h and S1j), the measured monthly CH_4 fluxes fell in or near the range of the modeled CH_4 emissions (Figure S2b). For the "grid-scale" validation, the regression of simulated versus observed monthly CH_4 emissions resulted in an R^2 of 0.79, with a slope of 0.84 and an intercept of -0.11 ($n=41$, $p<0.001$). The RMSE, RMD and EF between the simulated and observed monthly CH_4 fluxes were 51.3%, -17.8% and 0.75, respectively, for the integrated model framework.

2.5 Uncertainty analysis

Uncertainty in the estimated regional CH_4 emissions from natural wetlands may originate from many sources. The Monte Carlo method has been widely used in uncertainty analysis. However, because the Monte Carlo method is computationally expensive. In this study, we focused on the uncertainties induced by the inputs of ANPP, the water table depth and the soil sand fraction, using the extreme condition approach (Du and Chen, 2000; Li et al., 1996; 2004; 2012; Giltrap et al., 2010; Kesik et al., 2005). The comparison of these two methods is in Supplementary material S6. We designed eight extreme scenarios with a cross combination of the maximum and minimum values of ANPP, water table depth and the soil sand fraction, ±10% from their baseline values. The simulated minimum and maximum CH_4 fluxes of the eight scenarios were considered representative to the modelling uncertainty range. For more details of the estimate under the baseline and scenarios, please see supplementary material S6.

2.6 Data sources

The data sources include site-specific observations for model calibration and validation, the gridded input datasets for driving model framework as well as the wetland area. Table S1 provides detailed site descriptions. The CH_4 emissions were measured weekly or monthly at these sites. Most of the sites have synchronous measurements of the climate and water table depth. Fig. 2 shows the locations of the sites.

The gridded input datasets are related with the climate, soil, vegetation and the hydrology. We summarized the sources of the datasets in Table 1.

The gridded wetland maps of 1950, 1978, 1990, 2000 and 2008 were used in the regional modelling. The gridded wetland maps for 1978, 1990, 2000 and 2008 were obtained from Niu et al. (2012). The initial gridded wetland map of 1950 was estimated based on the remote sensing data of 1978 (Niu et al., 2012) and the census data (An et al., 2007). Supplementary material S8 describes more details about the way of obtaining the time series of the wetland area.

3. Results

3.1 Spatio-temporal variations in CH_4 fluxes in China

The temporal change in CH_4 fluxes (CH_4 emissions per wetland area) were primarily driven by climate changes. In this section, we analyzed the seasonal and inter-annual variations in CH_4 fluxes from the inland wetlands and the coastal wetlands from 1950 to 2010.

Fig. 3 shows the seasonal variations of the modeled average CH_4 fluxes from 1950s to 2010s. A consistent pattern of the CH_4 flux peak occurred at the end of July across all regions and decades (Fig. 3). CH_4 fluxes were very low in January and February, especially in northern China and in the Qinghai Tibetan Plateau (Fig. 3a, b and c), when the soil froze. In the warmer regions, such as Region V, CH_4 fluxes were much greater (Fig. 3e). The highest intra-annual flux variability was in Northeastern

批注 [f14]: We moved the details of comparison Mote Carlo and extreme condition approach

批注 [f15]: Comment: Mental aggregation and summarizing are truly needed here (use tables to summarize data input if needed).
RE: We summarized the sources of the datasets in Table 1

批注 [f16]: Comment: It would be good if you could offer in SOM a map with the new wetland area location you have produced, and contrast it to figure 2. Researchers will use it!
RE: We added Fig. S3 in the supplementary materials.

批注 [f17]: Comment: spatio-temporal variations in CH4 emissions in China would be a better title
RE: We changed the title of the section according to your comment.

批注 [f18]: Comment: this is discussion not results
RE: We have moved it to the discussion (please see section 4.2)

and Southern China (ca. 6.35—7.37 mg m^{-2} h^{-1}) (Fig. 3a and 3e), with the Qinghai Tibetan Plateau showing the lowest variability (1.72—1.98 mg m^{-2} h^{-1}, Fig. 3b). Temporally, the highest intra-annual variability was in 2000s for all regions, with 1970s and 1960s showing the lowest (Fig. 3).

Fig. 4f provides the inter-annual variations and trends in the national annual CH_4 fluxes in China. The national annual CH_4 fluxes significantly increased over the last 60 years, especially since 1980s. The national annual CH_4 flux was 16.9 g m^{-2} yr^{-1} in 1950 and increased to 21.2 g m^{-2} yr^{-1} in 2010, with the average rate of 0.52 g m^{-2} per decade and a total increase of 26% during the period from 1950 to 2010. The annual CH_4 fluxes fluctuated between 16.0 g m^{-2} yr^{-1} and 19.0 g m^{-2} yr^{-1} before 1980, then increasing rapidly in the 1990s. The highest annual CH_4 flux (22.5 g m^{-2} yr^{-1}) occurred in 1998, whereas the lowest (15.7 g m^{-2} yr^{-1}) occurred in 1954.

The estimated annual CH_4 fluxes in different regions are illustrated in Fig. 4. The highest CH_4 fluxes occurred in the Northeastern (Fig. 4a, Region I) and Southern (Fig. 4e, Region V) regions (24.8 and 20.0 g m^{-2} yr^{-1}, respectively), with the Qinghai Tibetan Plateau (Fig. 4b, Region II) showing the lowest (6.2 g m^{-2} yr^{-1}) and the other regions (e.g. Region III and IV) showed intermediate results (e.g. 8.8 and 13.5 g m^{-2} yr^{-1}, respectively) (Fig. 4c and 4d).

Fig. 4 also provides the trends in the annual CH_4 fluxes in different regions. There are significant increase ($p<0.001$) in Regions I, II, III and V (Fig. 4). The greatest increase in CH_4 fluxes occurred in Region I and Region V (0.67 and 0.54 g m^{-2} per decade, respectively) (Fig. 4a and 4e), with Region II showing the lowest (0.17 g m^{-2} per decade, Fig. 4b), Region III and Region IV showed intermediate increase rate (0.42 and 0.52 g m^{-2} per decade, respectively) (Fig. 4c and 4d).

3.2 Climate and CH_4 fluxes

Fig. 5 presents the regional responses of CH_4 fluxes to temperature and precipitation. The simulated CH_4 fluxes increased by ~12%, as a result of the air temperature increase of ~1.35 ℃ during the past 60 years (Fig. 4f). The modeled five-year CH_4 fluxes exhibited linear trends that closely follow the trends in air temperature in Region I (Fig. 5a), Region II (Fig. 5b), Region III (Fig. 5c) and Region V (Fig. 5e). The contribution of precipitation to the trends in CH_4 fluxes differed among the regions. During the past 60 years, Region I and Region III experienced temperature increases by 0.29 ℃ per decade and 0.34 ℃ per decade, respectively.

批注 **[f19]:** Comment: is hour a reasonable unit for seasonal variation? seems too detailed too me...but I might be wrong.
RE: most of the relevant observational studies adopted this unit to show the seasonal variations of CH4 fluxes. This unit is also used in the model validation (Fig. S1). So we didn't change it here. But if you do think it is necessary to be changed, we will change it to mg m^{-2} day^{-1}
Comment: Also note that Regions V and I have the same responses, shorten the text by aggregating results and ideas : The highest intra-annual flux variability was for Northern and Southern China (ca. 6.35-7.37 mg. m-2.h-1), with the Tibetan region showing the lowest variability (1.72-1.98 mg.m-2.h-1) Year 2000 showed the highest intra-annual variabilities for all regions, with 1970 and 1960 showing the lowest. An enhanced response of the intra-annual variability was observed from 1950-2000 (Fig 3a)
RE: We have shortened the text according to your guidance.

批注 **[f20]:** Comment: "in response to" would be part of the discussion.
RE:We removed this sentence.

批注 **[f21]:** Comment: SUMMARIZE: In absolute value, the highest CH4 fluxes correspond to the Northern and Southern regions (24.8 and 20 g.m-2.yr-1, respectively), with the Tibetan region showing the lowest (6.2 g.m-2.yr-1), the other regions (e.g. Region I and IV) showed intermediate results (e.g. give numbes usng the same units)
RE:We modified this paragraph according to your comment. The absolute value

批注 **[f22]:** Comment: Merge this information with the absolute value results exposed in lines 17-23 and summarized in my notes.

eg. Region I and V showed the largest annual emissions fluxes and rates of change for the perod 1950-2010...

RE: We have merged this information with the absolute value results.

批注 **[f23]:** Comment: Include a section header such as: Climate and CH4 emissions
And start with "Figure 5 presents the regional responses of CH4 fluxes to temperature and precipitation". Fig 5 cannot be seen, needs improvement.

RE: We added the title and started with this sentence.

批注 **[f24]:** Comment: this is discussion not results
RE: We changed this sentence to "The simulated CH4 fluxes increased by ~12%....."

The warming trend resulted in CH_4 fluxes increasing by 0.67 g m^{-2} per decade (Fig. 4a) and 0.42 g m^{-2} per decade, respectively (Fig. 4c). In Region I, the CH_4 fluxes were predominantly positively correlated with air temperature ($R^2=0.35$, $p<0.001$) (Fig. 5a). Although no correlation was found between the CH_4 fluxes and the precipitation in Region I, the linear precipitation decrease of 38.3 mm per decade ($p<0.001$) may have offset the increase in CH_4 fluxes due to the air temperature (Fig. 5a) before 1980. The linear precipitation decrease of 1.7 mm per decade ($p=0.4$, not significant) in Region III may also have a negative impact on CH_4 fluxes (Fig. 5c). CH_4 fluxes in Region II showed a positive correlation with both temperature and precipitation (Fig. 5b). A slight temperature increase of 0.19 ℃ per decade and precipitation increase of 6.7 mm per decade resulted in a flux increase of 0.17 g m^{-2} per decade. In Region V, the positive correlation between CH_4 fluxes and temperature was more significant than with precipitation (Fig. 5e), suggesting that the temperature was the dominant factor in the acceleration of CH_4 fluxes during the past 60 years. The increase in the precipitation, at a rate of 16.6 mm per decade, though not significant ($p=0.24$), may have benefited the CH_4 fluxes in this region. In Region IV, CH_4 fluxes were less responsive to temperature than precipitation (Fig. 5d). The increase in temperature also promoted CH_4 fluxes to increase at a rate of 0.50 g m^{-2} per decade (Fig. 4d).

Inter-annual or inter-decadal variations in CH_4 fluxes were found to be closely aligned with variations in precipitation (Fig. 5). The lowest CH_4 fluxes usually accompanied with the periods of low precipitation. For example, the lowest CH_4 fluxes and precipitation occurred simultaneously during the period 1980—1985 in Region IV (Fig. 5d) and the period 1965—1970 in Region V (Fig. 5e). In Region I, the five-year averaged CH_4 fluxes showed a trend that was synchronous with the five-year average precipitation trend (Fig. 5a), decreasing before 1980 and then increasing until 1995. In Region I and Region II, there was excessive amounts of precipitation in the 1990s (Fig. 5a) and 2000s (Fig. 5b) in conjunction with the relatively high air temperatures, which resulted in the highest CH_4 fluxes. In contrast, when the greatest amount of precipitation occurred (Fig. 5c: from 1955 to 1960 in Region III, Fig. 5d: from 1960 to 1975 in Region IV, and Fig. 5e: from 1970 to 1975 in Region V), the CH_4 fluxes remained low due to the lower air temperatures. The linear regression (not shown) suggested that the CH_4 fluxes of 1950—2010 increased 1.7 g m^{-2} yr^{-1} per 100 mm precipitation ($R=0.35$; $p<0.05$) from the inland and coastal wetlands in China.

3.3 Changes in natural wetlands area

The total wetland area in China was approximately 35.6 million ha in 1950 (Table 2). Our results show that there had been 17.0 million ha wetland loss from 1950 to 2010, mostly during the first 50 years when the wetland areas decreased by 16.1 million ha. Since 2000, wetland loss has been limited (Table 2).

A large wetland loss of 7.8 million ha occurred in Region I, accounting for approximately 45.7% of the total wetland loss of the nation (Table 2). Compared with 1950, the wetland areas decreased by 56.9%, 24.6%, 48.4%, 65.3% and 46.7% in Region I, Region II, Region III, Region IV and Region V (Table 2), respectively.

Among the wetland types, the inland wetlands underwent the major part of the area loss with 10.3 million ha from 1950 to 2010, accounting for 60.6% of the total wetland loss. More than 95% of the inland wetland loss occurred in Region I, Region II and Region III (Table 2). In contrast, coastal wetland loss occurred primarily in Eastern and Southern China (Region IV and Region V in Table 2). The coastal wetland losses were 68.5% in 2008 compared to the area in 1950. The total area loss was 4.94 million ha for lake and river wetlands between 1950 and 2008. Substantial loss of lakes/rivers occurred in Eastern China (Region IV).

3.4 Changes in the regional CH_4 emissions due to climate change and wetland loss

Along with the wetland loss, our results show that the CH_4 emissions decreased by approximately 2.35 Tg (1.91－2.81 Tg) in China's wetlands, i.e., from 4.50 Tg in the early 1950s to 2.15 Tg in the late 2000s (Table 2), contrasted to the averaged increase in the CH_4 fluxes of 3.43 g m^{-2} due to climate changes (Fig. 4f). More than 99% of the CH_4 reduction occurred before 2000 (Table 2).

The wetlands in Region I were the greatest contributor to the decreased CH_4 emissions, by holding the largest wetland area losses (Table 2) but also having the largest CH_4 flux increase due to climate warming and wetting which, however, did not compensate for the CH_4 decrease from 1950 to 2010 (Fig. 2b) . In Region I, the CH_4 emissions decreased by 58.3% in the late 2000s compared with the early 1950s, with an aggregated loss of 1.68 Tg (1.36－2.03 Tg, Table 2). In other regions, the reduction in CH_4 emissions was 0.13－0.19 Tg, with a loss fraction of 23.3－57.6% (Table 2). Among the regions, the lowest CH_4 reduction occurred in Region II, where

批注 [t25]: Comment: can you quantify the increase of CH4 emissions per precipitation?
RE: We made a linear regression between the annual CH4 fluxes and the annual precipitation to quantify the CH4 increase per 100 mm precipitation.

批注 [t26]: Comment: Cite the authors behind this result, and if the result is yours expose it at the beginning: our results show...
RE: This is part of the result in this study, because we estimated the wetland area in 1950. We added "Our results show that" at the beginning of this sentence.

批注 [f27]: Comment: large or extended (eliminate tremendous)
RE: We changed tremendous to large

批注 [f28]: Comment: our results show that..
RE: We have added this

批注 [f29]: Comment: It would be useful that you contrasted the effect of wetland area versus climate on the aggregated ncreases or decreases of CH4 for the period 195-2010
(e.g. ...contrasted to aggregated increased CH4 emissions of XX due to climate conditions
RE: We compared the effect of changes in wetland area against climate on the increases/decreases of CH4 for the period 1950-2010.

批注 [f30]: Comment: by holding the largest wetland area losses, but also having the largest CH4 flux increases due to climate warming and wetting which, however, did not compensate for the CH4 decrease from 1950 to 2010.
RE: We modified the sentence according to your comment.

批注 [f31]: Comment: an aggregated loss of...
RE: We have modified.

only a slight loss in wetlands occurred. The loss of CH_4 emissions was 23.3%, which is comparable to the wetland loss (Table 2).

Among the wetland types, the methane emissions decreased by 54.4%, 62.9% and 37.1% from inland wetlands, coastal wetlands and lakes/rivers, respectively (Table 2). Region I was the most important contributor to the decreased CH_4 emissions, which contributed 85.4% to the regional CH_4 reduction for inland wetlands (Table 2). For the coastal wetlands, the substantial CH_4 reduction occurred in Region V where CH_4 fluxes decreased by ~82%. The loss of coastal wetland was larger in Region IV than in Region V, but fluxes were 2.4 times larger in Region V, favoring its larger CH_4 emissions decrease.

4. Discussion

4.1 Regional estimates of CH_4 emissions in Chinese wetland

China has the world's fourth largest wetland area (Wang et al., 2012a) and contributes 4.4 (1.7–10.5) Tg CH_4 yr^{-1} to the atmosphere (Khalil et al., 1993; Jin et al., 1999; Ding et al., 2004; Ding and Cai, 2007; Chen et al., 2013; Wang et al., 1993; 2012b). On a national scale, this amount is comparable to coal-bed emissions (5.45 Tg CH_4 yr^{-1}), residential biofuel combustion (2.28 Tg CH_4 yr^{-1}), landfills (4.35 Tg CH_4 yr^{-1}), biomass burning (1.6 Tg CH_4 yr^{-1}) (Streets et al., 2001), the emissions from rice cultivation (~8 Tg CH_4 yr^{-1}) (Yan et al., 2009; Li et al., 2006a; Chen et al., 2013; Zhang et al., 2011) and livestock (8.55 Tg yr^{-1} Tg CH_4 yr^{-1}) (Streets et al., 2001).Our model resulted in 2.17—3.03 Tg of the national CH_4 emissions from wetlands with an area of 19.5—23 M ha during the same period. In addition, the present study suggested that the substantial CH_4 emissions reduction simulated by $CH4MOD_{wetland}$ between 1950 and 2000 (2.35 Tg CH_4) was however half compensated by the increase of paddy rice CH_4 emission over the same period (1.2 Tg in Zhang et al., 2011). When the wetland was reclaimed to cropland other than rice cultivation, there would be more N_2O emissions and the net greenhouse effect has yet been understood well.

Previous studies have estimated the national wetland CH_4 emissions by simply extrapolating the field measurements of CH_4 fluxes to the national scale (Wang et al., 1993; 2012b; Khalil et al., 1993; Jin et al., 1999; Ding et al., 2004; Chen et al., 2013; Cai, 2012). The estimations of both Ding et al. (2004) and Chen et al. (2013) were primarily based on measurements from Ruoergai at the eastern edge of the Tibetan

批注 [f32]: Comment: ...where CH4 fluxes decreased by ca. 82% .
(eliminate line 12-13, the time period is understood)

For the rest of the paragraph: coastal wetland loss was larger in Region IV than in Region V, but fluxes were 2.4 larger in this last region, favoring its larger CH4 flux decrease (eliminate lines 13-16)
RE: We modified this paragraph according to your comment.

批注 [f33]: Comment: Avoid re-explaining the results, simply comment them.
Discuss in the same order than the results.
RE: We tried our best to avoid the re-explaining the results. We designed the subsection according to your guidance in the manuscript.

批注 [t34]: We aggregated these three paragraphs into one. We gave the average national CH4 emissions of previous studies to show that our results reduced the uncertainty. We also compare the change of CH4 emissions between the natural wetlands and rice paddies according to your comments. In addition, all of the details were modified.

批注 [t35]: Comment: Please add center value
RE: We have added the mean value

批注 [t36]: Comment: less? the upper threshold is 10.5 so it is in the same range.
RE: We have modified the sentence

批注 [t37]: Comment : please change word by: suggest, resulted in, etc.
RE: We have changed demonstrated by resulted in
Comment: Was this range exposed in the results? why not? This is a fundamental result that reduces the uncertainty of chinese CH4 emissions.
RE: Yes, this is the range exposed in the results, and it indeed reduced the ...

批注 [t38]: Comment: Also, this phrase is too long and has already been written in the results: change for something more dynamic: the substantial CH4 emissions reduction in 1950-2000 (2.35 Tg CH4) was however half compensated by the ...

批注 [t39]: Comment: "was double" substitute by "doubled"
RE: This sentence has been changed.

批注 [t40]: Comment: Also note that when drying wetlands, CH4 decreases, but N2O increases, so in a more general balance, GHG emissions might not be fully decreasing. These last comments are to observed at some point, but not in the ...

批注 [t41]: Comment: very repeated idea
RE: We have eliminated the followed paragraph.

Plateau. Chen et al. (2013) used an observation of CH_4 fluxes that was much higher than the observation of Ding et al. (2004) during the 2000s, resulting in substantially higher emissions estimates from the wetlands of the Tibetan Plateau (Table 3). Moreover, the spatial characteristics show that Ruoergai has a higher CH_4 flux (Fig. 3) than other places on the Qinghai-Tibetan Plateau, e.g., Huashixia (5.3—6.7 g m^{-2} yr^{-1}) with an altitude of 4000 m in the central Qinghai-Tibetan Plateau (Jin et al., 1999) and Namuco (0.6 g m^{-2} yr^{-1}) with an altitude between 4718 and 7111 m in the hinterlands of the Qinghai-Tibetan Plateau (Wei et al., 2015). This is because Ruoergai has a lower altitude and continuous flooding (Chen et al., 2008; Hirota et al., 2004). Extrapolating the measurements at the eastern edge of the Tibetan Plateau to the whole plateau would inevitably result in estimation biases. The simulated average CH_4 flux from the Qinghai-Tibetan Plateau in 1990 by $CH4MOD_{wetland}$ is 6.2 g m^{-1} yr^{-1} (5.0—7.2 g m^{-2} yr^{-1}), which is close to the observation at Huashixia and between the observations from Namucuo and Ruoergai.

Extrapolating measurements to the region can only be used to estimate the CH_4 emissions after the 1990s because measurement data were not available for earlier periods. Using the DLEM model, Xu and Tian (2012) (Table 3) inferred a reduction of approximately 1.3 Tg CH_4 from Chinese marshlands between 1949 and 2008 due to marshland conversion and climate change. However, the study of Xu and Tian (2012) focused only on marshlands (natural wetlands excluding coastal wetlands, lakes and rivers), which is equivalent to the inland wetlands in this study. However, our analysis showed that the coastal wetlands, lakes and rivers represented approximately 40% of the total wetland loss (Table 2) and thus is not negligible. The inclusion of the coastal wetlands, lakes and rivers consolidates the estimation of the long-term changes in the CH_4 emissions from wetlands on regional/national scales.

Moreover, in Northeastern China, the dominant vegetation is *Carex*. However, in Inner Mongolia, northwestern China, the North China plain and the Middle-Lower Yangtze Plain, *Phragmites* represents the primary vegetation type (see Supplementary Material S3). Although *Phragmites* usually has a larger biomass than *Carex*, the CH_4 fluxes are lower (according to a comparison between CH_4 fluxes in the perennial inland wetlands in WLS, ZL and SJ in Fig. S1; Table S1). If the observations of methane fluxes from the marshland dominated by *Carex* are used for the model calibration and used in the regions dominated by *Phragmites* (Xu and Tian, 2012), the national estimation might be overestimated. This is why the CH$_4$ reduction contributed 21.2% in Northwestern and Northern China (including Region III and Region IV in this study) in the study of Xu and Tian (2012) while the contribution was only 7.3% in this study.

4.2 Temporal variations of CH$_4$ emissions

Both the intra-annual and inter-annual CH$_4$ flux trends are largely influenced by the temperature and precipitation. The simulated seasonal variations of the CH$_4$ fluxes from the sites agreed with the observed values well (Fig. S1). The CH$_4$ flux and NPP peaked coincidently with the air temperature. The lowest CH$_4$ fluxes occurred during the winter or dry period, and the highest fluxes appeared during the summer and flooding period (Fig. S1). The intra-annual variations (Fig. 3) are similar to the simulated seasonal cycles in West Siberia (Bohn et al., 2015) or the northern Hemisphere (Melton et al., 2013). The simulated fractions of CH$_4$ flux in the winter and freeze-thaw period in this study is similar to the observations of Yang et al. (2006).

Warming is expected to promote CH$_4$ fluxes from wetlands in the future (Zhuang et al., 2006; Christensen and Cox, 1995; Shindell et al., 2004). According to China's National Assessment Report on Climate Change (Ding and Ren, 2007), compared with the period 1961—1990, there will be a pronounced air temperature increase of 3.6—4.9 ℃ in the A2 and B2 scenarios (IPCC, 2000) by the end of this century in China. Based on our statistics, an increase of 3.6 ℃ would mean the national CH$_4$ flux increase ~30%. The air temperature is expected to increase more rapidly in Northeastern China (Region I), Northwestern China (Region III) and the North China Plain (the inland wetlands in Region IV) (Ding and Ren, 2007), which indicates that there will be a larger promotion of CH$_4$ fluxes from the inland wetlands in these regions. For the Qinghai Tibetan Plateau (Region II), Eastern China (the coastal wetlands in Region IV), and Southern China (Region V), the climate-induced increase in CH$_4$ fluxes from inland and coastal wetlands will be lower.

The precipitation is expected to increase by 9—11% by 2100, especially in northern China (Region I, Region III and the inland wetlands in Region IV) and on the Qinghai Tibetan Plateau (Region IV) (Ding and Ren, 2007). Based on the linear correlation analysis between the precipitation and CH$_4$ fluxes of the modelling results, an increase of 10% (approximately 45 mm) would increase the national CH$_4$ fluxes by

批注 [t42]: Comment : The main driver behind the observed intra and inter-annual flux variability was related to climate (both temperature and precipitation). A long term warming signal was behind the increased intra-annual flux variability in all regions, while a shorter-term temperature response was behind 2000 and 1960-70s variability ???. NPP is a response, not an influencing factor. The same for water table depth (it depends on precipitation). Please expose future climate trends in here, do not create a separate section.
RE: We merged the two sections. We also modified this paragraph according to your guidance.

批注 [f43]: Comment: Too detailed. It would suffice to say that your seasonal variations matched well other authors research in the region (cites), and then expose the winter and freeze-thaw period emissions, which is a unique contribution of your research.
RE: We have shortened this paragraph according to your comment.

批注 [t44]: Comment: This is results and not discussion. And it is an important result (8% aggregated flux increase for the last 60 years, as a result of a temperature increase of xx, meaning that the chinese warming has increased CH4 fluxes at a rate of 0.52 g m-2 per decade from 1950 to 2010
RE: We have moved this result to section 3.2. We were sorry that the value is not 8%, it's 12%. We have corrected this value

批注 [f45]: We modified these two paragraphs according to your comment.

批注 [t46]: Comment: please use statistics from your own data. "based on our statistics, an increase of 3.6 degrees would mean national CH4 flux increases of...
RE： We have added based on our statistics..

批注 [t47]: Comment: This section is hypothetical or real? Which regions are predicted to suffer drought? You start the paragraph predicting increased precipitation in China. if predictions are increased precipit. please eliminate the effects of drought completely. And change it by the opposite: increased precipitation will result in increased emissions through wetland area expansion. Can you quantify the effect of very wet years on CH4 emissions in China using your data? if so, please provide in the results an statistical projection (flux CH4 increase by increase in precpitation) and mention it here.
RE: We have removed the effects of drought and changed it to the increased precipitation. We also mentioned the flux increase CH4 by increase in precipitation

批注 [t48]: Comment: eliminate obvious
RE: We have eliminated obvious

0.8 g m^2 yr^{-1}.

For the coastal wetlands, rising sea levels resulted from climate warming will reduce the area of coastal wetlands by inundation. Consider the Jiangsu Province in eastern China (Region IV) as an example, where 396, 617 and 1390 km^2 is expected to be lost in the next 30, 50 and 100 years, respectively (Li et al., 2006b). Moreover, rising sea levels will increase the invasion of salt water to estuarine wetlands (Shen et al., 2003; Hu et al., 2003; Huang and Xie, 2000), which will reduce CH_4 fluxes due to the higher salinity.

4.3 Present state and research gaps in CH_4 modelling

Nowadays, there are still research gaps that need to be narrowed in simulating the national CH_4 emissions from natural wetlands by the improvement in process-based models.

The first improvement should focus on the fallacy of model mechanism. Most of the existed process-based models, e.g., $CH4MOD_{wetland}$, CLM4Me (Rieley et al., 2011), LPJ-WhyMe (Wania et al., 2010), DLEM (Tian et al., 2010; 2015; Xu et al., 2010), ORCHIDEE (Krinner et al., 2005), SDGVM (Woodward et al., 1995; Beerling and Woodward, 2001) described the process of CH_4 production, oxidation and transport processes in wetlands. In most of the models, the methane production rates are determined by the availability of methanogenic substrates and the influence of environmental factors. Most models use net primary production as an index to represent substrate availability for CH_4 production, thus they do not consider organic carbon in deep soils or in permafrost. In $CH4MOD_{wetland}$, the methanogenic substrates include root exudates, plant litter and the soil carbon, which is a mechanism advantage over the DLEM, CLM4Me and ORCHIDEE model. DLEM only considers CH_4 production from dissolved organic carbon (DOC). In CLM4Me, the CH_4 production is related to the heterotrophic respiration from soil and litter. ORCHIDEE uses a fraction of the most labile “Litter + soil C” pool. Upon the methanogenic substrates, the influence of soil temperature, soil texture and redox potential and PH are also incorporated in the models. But the influence of soil salinity was usually ignored (e.g., CLM4Me, LPJ-WhyMe, DLEM, ORCHIDEE and SDGVM) or be simply processed (e.g., $CH4MOD_{wetland}$). The effect of thawing permafrost on the complex dynamics of hydrology and carbon substrates is now considered very important to the permafrost region (e.g., the Qinghai Tibetan Plateau).

At present, the parameterization related to the vegetation in wetlands was loosely constrained by the limited number of observations and the distribution of the plant species. The parameters in the CH_4 models usually refer to the production of labile organic compounds from gross primary production (GPP) (e.g., f_{exu} in LPJ-WhyMe and *VI* in $CH4MOD_{wetland}$) and the CH_4 transportation and oxidation via plant aerenchyma (e.g., f_{oxid} in in LPJ-WhyMe, P_{ox} in $CH4MOD_{wetland}$ and F_a in CLM4Me). These vegetation parameters are different among plant species but are usually unified in regional simulations. The differences in vegetation effectively influence the CH_4 fluxes as reported by King and Reeburgh (2002), documenting the relation between CH_4 and net primary production (NPP) in tundra vegetation. Verville et al. (1998) and Busch and Lösch (1999) have also shown the difference in the plant transport of CH_4 through aerenchymous tissues between vegetation types. In this study, the herbaceous plant species other than *Carex* and *Phragmites* were not specifically considered. To reduce the uncertainty in estimating regional and national CH_4 emissions, the model parameterization concerning the wetland plants should get more attentions in modelling works.

The poor availability of the model inputs, especially the spatial variability in the water table depth also accounts for a large proportion of the uncertainty in regional estimations. The TOPMODEL-based scheme (Beven and Kirkby, 1979) has been used to model regional water table depth in natural wetlands to drive the process-based models (Bohn et al., 2007; Kleinen et al., 2012; Lu and Zhuang et al., 2012; Zhu et al., 2013). It is based on the topographic wetness index (TWI) and assumes that water tables follow topographic holds (Haitjema and Mitchell-Bruker, 2005). However, the TWI is static and relies on the assumption that the local slope is an adequate proxy for the effective downslope hydraulic gradient, which is not necessarily true in low-relief terrains (Grabs, et al., 2009). Therefore, this algorithm is less suitable in flat areas and will induce uncertainties in the simulated water table depth. Moreover, the HYDRO1k global values for the TWI provided by the USGS in 2000 (USGS, 2000) are the most commonly used data for the TOPMODEL method. However, the limited resolution and quality of the data can induce uncertainties, especially in tropical wetlands (Marthews et al., 2015; Collins et al., 2011). More accurate descriptions of the hydrology process and higher-resolution datasets are needed to reduce the error in the simulated water table depth.

Last but not least, the change in wetland area is a key factor that must be considered seriously. Unfortunately, time series data on wetland changes at regional scales are often unavailable. Popular methods for defining the extent of wetlands include using “Prescribed constant wetland extents” and the “Hydrological model” (Melton et al., 2013; Wania et al., 2013). Using different methods, Melton et al. (2013) reported that the estimate of global wetland area ranged from 7.1×10^6 to 26.9×10^6 km^2. The TOPMODEL scheme was extensively used to predict wetland distribution dynamics (Kleinen et al., 2012; Stocker et al., 2014; Melton et al., 2013). It is true that the “Hydrological model” can reflect the annual or seasonal variations of the wetland area, which were considered to be the dominant cause of the seasonal variations of regional CH_4 emissions (Ringeval et al., 2010). However, this method is not suitable for simulating the historical wetland area in China. The reason is because the simulated wetland extent will not be sensitive to the influences of anthropogenic changes to the land surface (Wania et al., 2013), which could lead to an overestimate of the wetland area. In China, the annual marshland area had been temporally interpolated using a negative correlation between the Chinese population and the marshland area of 1950 and 2000 (Liu and Tian, 2010; Xu and Tian, 2012). However, this relationship inevitably resulted in large uncertainties because human activity was, though important, not the only driving factor in wetland changes (Niu et al., 2012). Furthermore, the influence of human disturbance should also be considered to improve the performance of the “Hydrological model” (Melton et al., 2013; Wania et al., 2013) to more accurately delineate variations of the wetland extents at different temporal scales.

5 Projection of wetland changes in China and the management tips

批注 **[t49]:** Comment: Eliminate section and change it for management and polict tips (e.g considering mitigation efforts which regions should promote increased wetland areas and which not e.g. those wth extra rain and warming wll have more emissons than those with less extra rain and warming, but how does this relate to adaptation needs, biodiversity and food security?)
RE: We eliminated the summary remarks, and changed this section into “Projection of wetland changes in China and the management tips”. We modified the original discussion (page 20, lines 9-24 in the original manuscript), and added some management tips as your guidance.

Restoration of wetlands has been one of the multiple measures of China to suppress the environmental degradation. The national plan to establish wetland reserves of more than 1.4×10^9 ha in NWCP (Editorial Committee, 2009) will inevitably enhance methane emission to the atmosphere, as has been implied in the present study. However, regional appropriate planning of the wetland restoration may suppress the methane emission as less as possible. The rivers, lakes and costal zones should be the first consideration for wetland restoration owing to the low methane fluxes. In Qinghai Tibetan Plateau, the warming climate has resulted in melting of the permafrost soils and expansion of the lakes and rivers (Niu et al., 2012), in spite that higher temperature also stimulates evapotranspiration. While the wetland methane flux in Qinghai Tibetan Plateau was less than the other regions of China, conservation of wetlands here should take priority to benefit the ecosystem diversities. Northeastern China is the most important food production region after wetland reclamation since 1950. The wetland there also has the highest CH_4 fluxes as shown in the present study. So it is reasonable to keep the wetlands and croplands unchanged in this region and drain the wetland seasonally by proper management to mitigate the methane emissions. It is also worth noted that more and more wetlands are established in urban areas of China to improve the inhabitance of urban population. The methane emission from the reclaimed-water-flooded wetlands needs necessary attention from further studies.

Author contribution

T. Li, W. Zhang, T. Vesala. and M. Raivonen designed the research; T. Li, Q. Zhang and G. Wang performed the CH_4 modelling; Y. Lu performed the TEM modelling; Z. Niu prepared the time series of the wetland area; T. Li and W. Zhang prepare the manuscript with contribution from all coauthors.

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Table 1 Summary of the gridded input datasets for driving the model framework

Gridded input datasets		Sources
Climate	Air temperature[*,2]	The Climatic Research Unit (CRU TS 3.10) of the University of East Anglia in the United Kingdom (Harris et al., 2014)
	Precipitation[*,2]	
	Vapor pressure[*,2]	
	Cloudiness[*,2]	
Soil	Soil texture[1,2]	Food and Agriculture Organization (FAO, 2012)
	Soil organic carbon[1]	Harmonized World Soil Database (HWSD) (FAO, 2008)
	Soil bulk density[1]	
	Soil salinity[*,1]	World Ocean Atlas 2009 (Antonov et al., 2010)
	Soil moisture[*,3]	Fan and van den Dool (2004)
	Soil temperature[*^,2]	Outputs of TEM (this study)
Hydrology	Topographic wetness index[3]	HYDRO1k Elevation Derivative Database (USGS, 2000)
	Water table depth[*^,1]	Outputs of TOPMODEL (this study)
Vegetation	Vegetation map[4]	DISCover Database (Belward et al., 1999; Loveland et al., 2000)
	ANPP[#,1]	Outputs of TEM (this study)
	Plant phenology[#,1]	Outputs of TEM (this study)

[1] Driving CH4MODwetland; [2] Driving TEM; [3] Driving TOPMODEL; [4] Specify the vegetation parameters for $\text{CH4MOD}_{\text{wetland}}$ and TEM; [*] Monthly data from 1950 to 2010; [#] Annual data from 1950 to 2010; [^] We used the linear interpolation to develop the daily datasets.

Table 2 Regional CH_4 emissions and the wetland area

		Region CH_4 emissions[$] (Tg)						Area[*] (M ha)					
		I	II	III	IV	V	China	I	II	III	IV	V	China
Inland Wetland	1950	2.80	0.31	0.25	0.06	0.11	3.53	12.26	4.78	2.66	0.30	0.27	20.27
	1980	2.06	0.27	0.22	0.06	0.10	2.71	9.71	4.61	2.57	0.29	0.26	17.44
	1990	1.90	0.23	0.14	0.09	0.08	2.44	7.73	3.42	1.77	0.44	0.18	13.54
	2000	1.13	0.23	0.13	0.05	0.07	1.61	5.40	3.43	1.41	0.23	0.15	10.62
	2010	1.16	0.22	0.12	0.05	0.06	1.61	5.09	3.20	1.36	0.20	0.13	9.98
	Decrease[#]	-58.6%	-29.0%	-50.40%	-16.7%	-45.5%	-54.4%	-58.2%	-33.3%	-48.1%	-33.3%	-66.7%	-50.8%
Coastal Wetland	1950	--	--	--	0.09	0.18	0.27	--	--	--	1.52	1.02	2.54
	1980	--	--	--	0.08	0.09	0.17	--	--	--	0.78	0.53	1.31
	1990	--	--	--	0.05	0.07	0.12	--	--	--	0.75	0.4	1.15
	2000	--	--	--	0.05	0.06	0.11	--	--	--	0.54	0.37	0.91
	2010	--	--	--	0.06	0.04	0.10	--	--	--	0.53	0.27	0.80
	Decrease[#]	--	--	--	-33.3%	-77.8%	-62.9%	--	--	--	-65.1%	-73.5%	-68.5%
Lakes and Rivers	1950	0.08	0.29	0.08	0.22	0.04	0.70	1.38	5.19	1.49	4.05	0.68	12.79
	1980	0.07	0.26	0.07	0.20	0.03	0.62	1.20	4.62	1.27	3.55	0.56	11.21
	1990	0.05	0.22	0.04	0.13	0.03	0.47	0.91	3.83	0.78	2.32	0.51	8.35
	2000	0.04	0.22	0.04	0.11	0.03	0.45	0.76	3.87	0.77	1.93	0.61	7.94
	2010	0.04	0.25	0.04	0.07	0.04	0.44	0.79	4.32	0.78	1.31	0.65	7.85
	Decrease[#]	-50.0%	-13.8%	-50.0%	-68.2%	0.0%	-37.1%	-42.8%	-16.8%	-47.7%	-67.7%	-4.4%	-38.6%
Total Wetland	1950	2.88	0.60	0.33	0.37	0.33	4.50	13.64	9.97	4.15	5.87	1.97	35.60
	1980	2.13	0.53	0.29	0.34	0.22	3.50	10.91	9.23	3.84	4.62	1.35	29.96
	1990	1.95	0.45	0.18	0.27	0.18	3.03	8.64	7.25	2.55	3.51	1.09	23.04
	2000	1.17	0.45	0.17	0.21	0.16	2.17	6.16	7.3	2.18	2.7	1.13	19.47
	2010	1.20	0.47	0.16	0.18	0.14	2.15	5.88	7.52	2.14	2.04	1.05	18.63
	Decrease[#]	-58.3%	-23.3%	-51.5%	-51.4%	-57.6%	-52.2%	-56.9%	-24.6%	-48.4%	-65.3%	-46.7%	-47.7%

[$] The average CH_4 fluxes of three consecutive years (including 1950—1952, 1979—1981, 1989—1991, 1999—2001 and 2008—2010) were used to calculated regional CH_4 emissions. For example, regional CH_4 emissions in 1980 were the production of the area of 1980 and the average CH_4 fluxes from 1979 to 1981.

[*] Data of 1980, 1990, 2000 and 2010 were from the remote sensing data (Niu et al., 2012). The area of 1978 and 2008 were regarded as the area of 1980 and 2010, respectively.

[#] Decrease means the reduce fraction in 2010 compared with 1950.

-- little or no wetland

Table 3 Estimation of CH_4 emissions from natural wetland in China.

Region	This study			Other studies			References
	CH_4 (Tg)	Period	Area (Mha)	CH_4 (Tg)	period	Area (Mha)	
China$^{\$}$	3.0	1990	23.0	2.2	1988－2000	Nm	Wang et al., 1993
China$^{\$}$	3.0	1990	23.0	1.7	1988	Nm	Khalil et al., 1993
China$^{\$}$	3.0	1990	23.0	2.0	1996	18.7	Jin et al., 1999
China$^{\$}$	3.0	1990	23.0	10.5	1990s	38.0	Wang et al., 2012b
China$^{\$}$	3.0	1990	23.0	6.65	1990	35.5	Cai, 2012
China$^{\$}$	2.2	2000	19.5	5.71	2000	30.5	Cai, 2012
China$^{\$}$	2.2	2000	19.5	3.15	2000	Nm	Chen et al., 2013
China$^{\$}$	2.2	2000	19.5	4.76	2003－2009	9.0	Zhang et al., 2013
China$^{\#}$	3.5	1950	20.3	3.2	1950	17.9	Xu and Tian, 2012
China$^{\#}$	2.7	1980	17.4	2.3	1980	13.0	Xu and Tian, 2012
China$^{\#}$	2.4	1990	13.5	2.0	1990	11.0	Xu and Tian, 2012
China$^{\#}$	1.6	2000	10.6	1.9	2000	9.4	Xu and Tian, 2012
China$^{\#}$	1.6	2010	10.0	1.9	2008	9.4	Xu and Tian, 2012
China$^{\#}$	1.6	2000	10.6	1.9	1995－2004	9.4	Tian et al., 2011
China$^{\#}$	1.6	2000	10.6	1.8	1995－2004	9.4	Ding and Cai, 2007
NYC$^{\#}$	2.8	1950	12.3	2.2	1950	10.1	Xu and Tian, 2012
NYC$^{\#}$	1.2	2010	5.1	1.2	2008	4.7	Xu and Tian, 2012
NYC$^{\#}$	1.1	2000	5.4	1.2	2001－2002	2.8	Ding et al., 2004
NYC$^{\#}$	1.1	2000	5.4	0.9	2000	Nm	Chen et al., 2013
QHT$^{\#}$	0.3	1950	4.8	0.07	1950	0.8	Xu and Tian, 2012
QHT$^{\#}$	0.2	2008	3.2	0.06	2008	0.6	Xu and Tian, 2012
QHT$^{\$}$	0.45	1990	7.3	0.8	1996	3.5	Jin et al., 1999
QHT$^{\#}$	0.23	2000	3.4	0.56	2001－2002	4.8	Ding et al., 2004
QHT$^{\#}$	0.23	2000	3.4	1.25	2000	Nm	Chen et al., 2013

[$] Natural wetland

[#] Natural wetland exclude coastal wetland, lakes and rivers.

Nm, not mentioned in the literature

NYC, Northeast China

QTH, Qinghai Tibetan Plateau

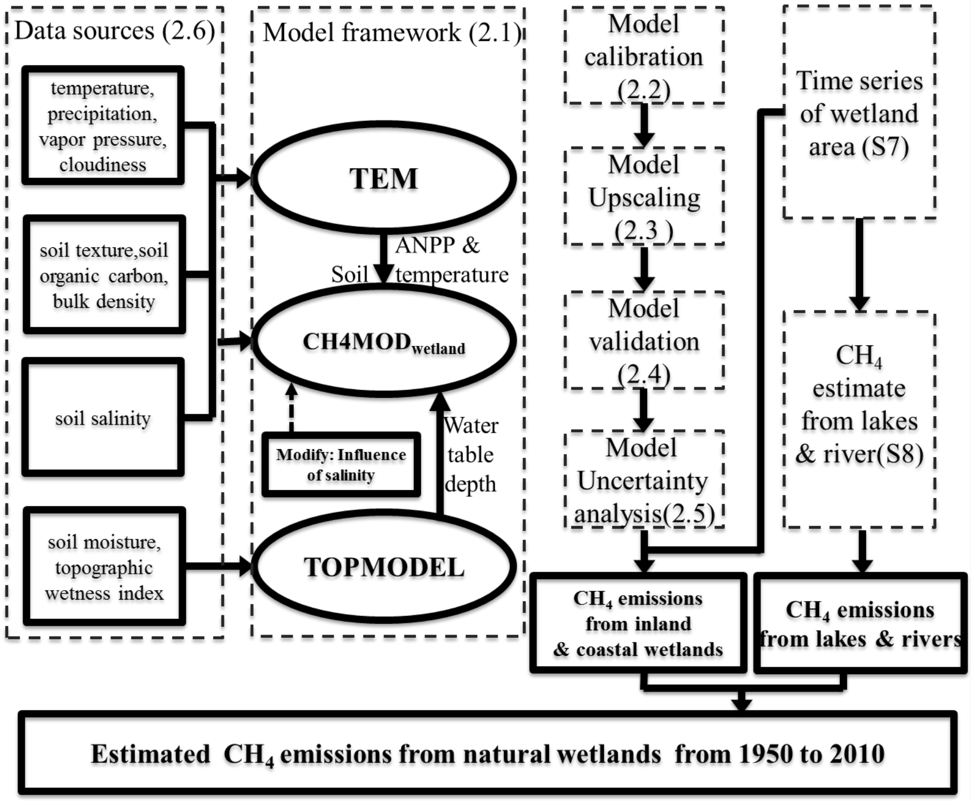

Fig. 1 Framework of simulating CH_4 emissions from natural wetlands between 1950 and 2010 in China. $CH4MOD_{wetland}$ is a biogeophysical model to simulate CH_4 fluxes from natural wetlands. TEM is a process-based biogeochemistry model that couples carbon, nitrogen, water, and heat processes in terrestrial ecosystems to simulate ecosystem carbon and nitrogen dynamics. TOPMODEL is a conceptual rainfall-runoff model that is designed to work at the scale of large watersheds using the statistics of topography.

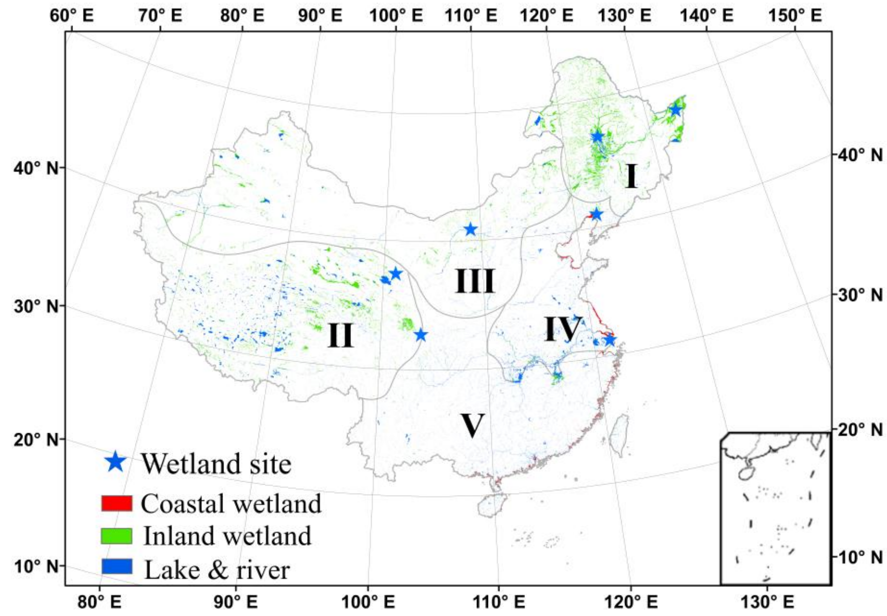

Fig. 2 Wetland regions across China. The blue stars are the locations of the wetland sites. The wetland distribution map is from the remote sensing data in 1978.

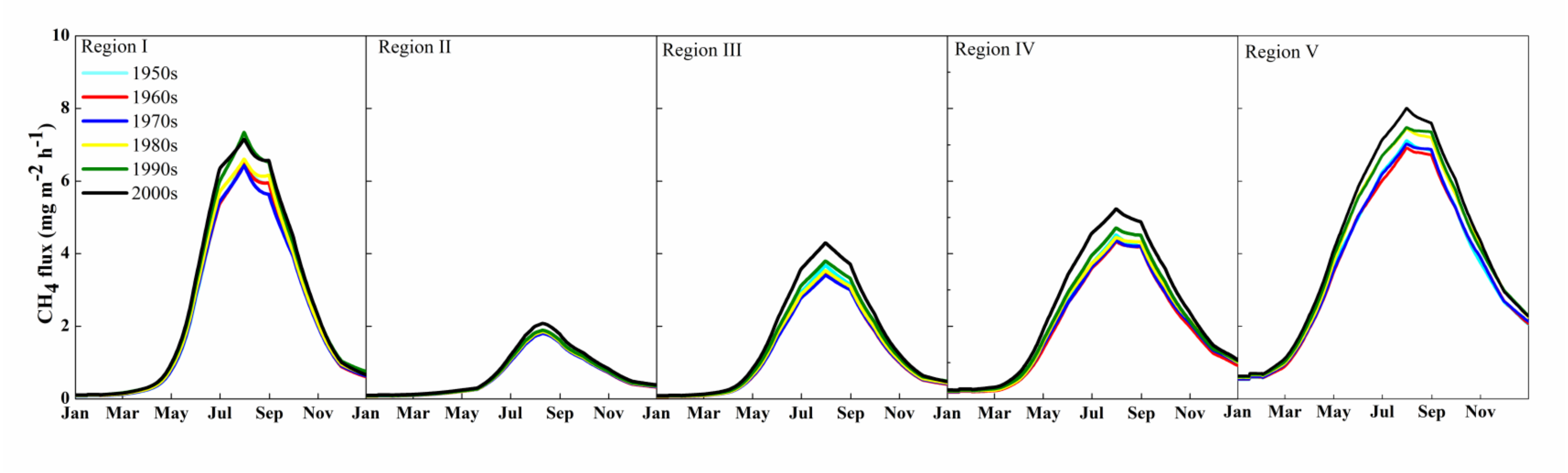

Fig. 3 Seasonal variations of methane fluxes in the five regions.

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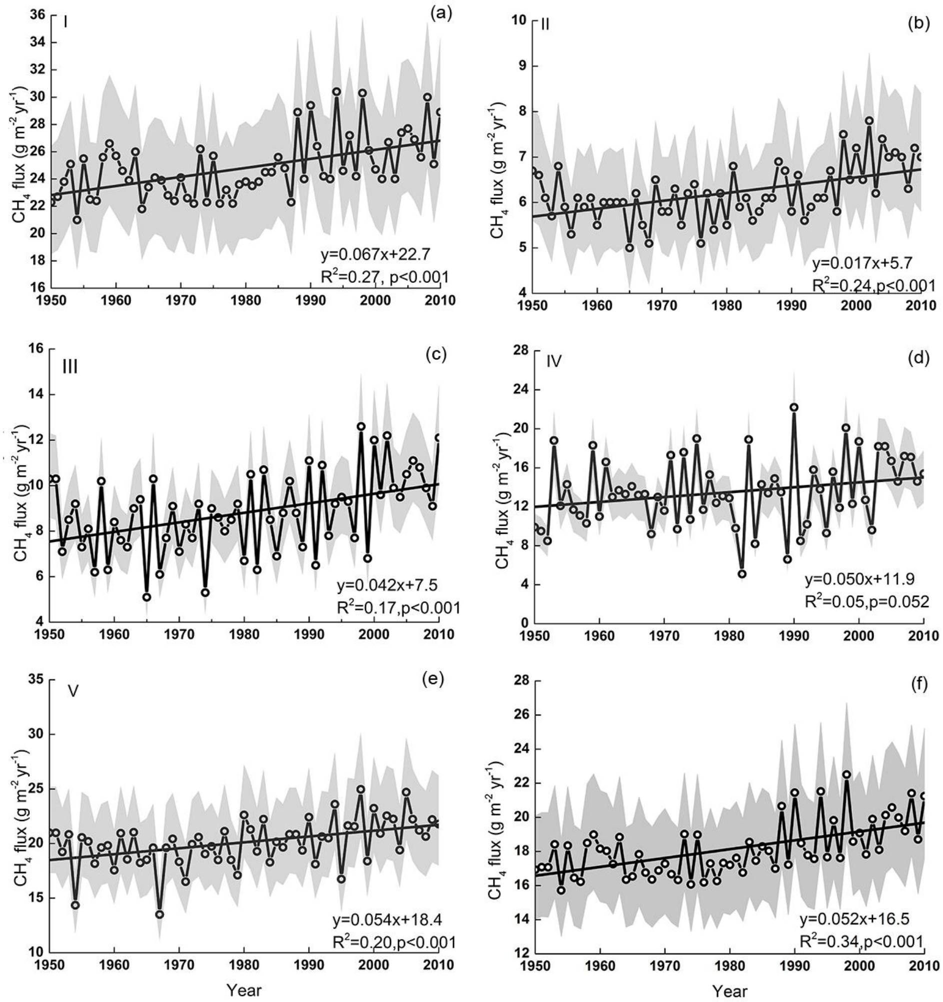

Fig. 4 Methane fluxes from inland and coastal wetlands between 1950 and 2010 in: (a) Region I; (b) Region II; (c) Region III; (d) Region IV; (e) Region V. (f) China.

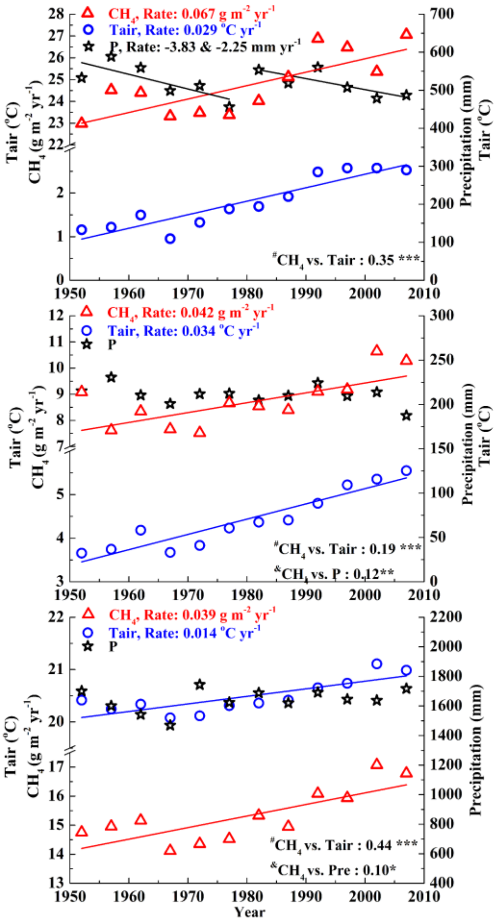

Fig. 5 Impact of the climate factors on CH_4 fluxes from 1950 to 2010 in: (a) Region I; (b) Region II; (c) Region III; (d) Region IV; and (e) Region V. The red triangles, blue circles and the black stars are 5-year average CH_4 fluxes (the same data as in Fig. 4), air temperature and precipitation, respectively. The slope represents the significant linear rate ($p<0.05$). CH_4 vs. Tair: the correlation coefficient between the annual mean CH_4 fluxes and air temperature. CH_4 vs. P: the correlation coefficient between the annual mean CH_4 fluxes and the precipitation. Only correlations with statistical significance are shown ($p<0.05$).

批注 **[t51]:** We have modified this Figure