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LETTER

Attribution of changes in global wetland methane emissions from pre-industrial to present using CLM4.5-BGC

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Abstract

An understanding of potential factors controlling methane emissions from natural wetlands is important to accurately project future atmospheric methane concentrations. Here, we examine the relative contributions of climatic and environmental factors, such as precipitation, temperature, atmospheric CO_2 concentration, nitrogen deposition, wetland inundation extent, and land-use and land-cover change, on changes in wetland methane emissions from preindustrial to present day (i.e., 1850–2005). We apply a mechanistic methane biogeochemical model integrated in the Community Land Model version 4.5 (CLM4.5), the land component of the Community Earth System Model. The methane model explicitly simulates methane production, oxidation, ebullition, transport through aerenchyma of plants, and aqueous and gaseous diffusion. We conduct a suite of model simulations from 1850 to 2005, with all changes in environmental factors included, and sensitivity studies isolating each factor. Globally, we estimate that preindustrial methane emissions were higher by 10% than present-day emissions from natural wetlands, with emissions changes from preindustrial to the present of +15%, −41%, and −11% for the high latitudes, temperate regions, and tropics, respectively. The most important change is due to the estimated change in wetland extent, due to the conversion of wetland areas to drylands by humans. This effect alone leads to higher preindustrial global methane fluxes by 33% relative to the present, with the largest change in temperate regions (+80%). These increases were partially offset by lower preindustrial emissions due to lower CO_2 levels (10%), shifts in precipitation (7%), lower nitrogen deposition (3%), and changes in land-use and land-cover (2%). Cooler temperatures in the preindustrial regions resulted in our simulations in an increase in global methane emissions of 6% relative to present day. Much of the sensitivity to these perturbations is mediated in the model by changes in methane substrate production and the areal extent of wetlands. The detrended interannual variability of high-latitude methane emissions is explained by the variation in substrate production and wetland inundation extent, whereas the tropical emission variability is explained by both of those variables and precipitation.

1. Introduction

Methane is a powerful greenhouse gas with 32–45 times the warming potential of carbon dioxide (CO_2) over a 100 year time frame (IPCC 2013, Neubauer and Megonigal 2015). Natural wetlands, the largest single source of atmospheric methane, accounts for ~30% of mean global emissions (IPCC 2013, Kirschke *et al* 2013), and make a significant contribution to the interannual variability (IAV) of atmospheric methane

concentrations (Spahni *et al* 2011). Kirschke *et al* (2013) reported a wide range of global wetland emissions estimated using bottom-up approaches for the decade of 2000–2009 (177–284 Tg CH$_4$ yr^{-1}) indicating that the global emissions remain highly uncertain. Some studies have concluded that methane emissions will increase considerably in the future in a warmer climate, potentially inducing climate-methane feedbacks from wetlands (Ringeval *et al* 2011, Gao *et al* 2013), while other studies have shown the opposite (Koven *et al* 2015, Zhu *et al* 2013). Wetland methane fluxes have substantial inter-annual variability (Melton *et al* 2013) and are driven by changes in several controlling factors related to climate and the environment, such as precipitation (Bohn *et al* 2007), temperature (Christensen *et al* 2003, Bloom *et al* 2010), atmospheric CO$_2$ concentration (Van Groenigen *et al* 2011), and nitrogen deposition (Granberg *et al* 2001). Improved understanding of the influence of changes in these factors on methane emissions is crucial for more accurate projections of atmospheric methane concentrations. While these factors play an important role in determining the future evolution of methane concentrations, the relative importance of each factor is not well understood. Anthropogenic activities such as wetland conversion may also impact methane emissions through changes in wetland inundated area (Chappellaz *et al* 1993, Maltby and Immirzi 1993, Watts *et al* 2014, Knox *et al* 2014). An understanding of the attribution of the changes in different greenhouse gases is increasingly important (Ciais *et al* 2013), as scientists try to understand how to best reduce anthropogenic drivers for climate change (Allen *et al* 2009, Unger *et al* 2010).

Prior modeling studies have attempted to quantify the influence of future climate change (in particular surface temperature and precipitation) and atmospheric CO$_2$ on wetland methane emissions (Gedney *et al* 2004, Shindell *et al* 2004, Eliseev *et al* 2008, Volodin 2008, Ringeval *et al* 2011, Riley *et al* 2011). There remains substantial uncertainty concerning the effects of these factors on global as well as regional methane emissions (Bloom *et al* 2010, Bohn *et al* 2015). Wetland methane emissions are predicted to increase by 50%–150% during the 21st century (Gedney *et al* 2004, Shindell *et al* 2004, Volodin 2008, Ringeval *et al* 2011), but previous studies have not focused on attributing the causes of the changes in emissions between preindustrial and current. A better understanding of the change in natural methane emissions between preindustrial and present day can inform the reasons behind ongoing increases in atmospheric methane concentration and how they might continue in the future.

Herein, we apply a mechanistic methane emission model within the Community Land Model (CLM4.5) of the Community Earth System Model (CESM) to attribute the relative importance of various factors controlling methane emissions, such as atmospheric

CO$_2$ concentration, nitrogen deposition, climate, wetland inundation extent, and land-use and land-cover change on wetland methane emissions from pre-industrial to present day (from 1850 to 2005).

2. Models and datasets

2.1. Model description
We use version 4.5 of the CLM (CLM4.5) within the CESM version 1.2 (CESM1.2) (Hurrell *et al* 2013). CLM4.5 represents detailed biophysics, hydrology, biogeochemistry, and dynamic vegetation (Oleson *et al* 2013, Koven *et al* 2013). The biogeochemical model (CLM4.5-BGC) is coupled to the simulated biophysics and hydrology and is prognostic with respect to carbon, nitrogen, and methane dynamics (Riley *et al* 2011, Bonan *et al* 2013, Koven *et al* 2013). A mechanistic methane biogeochemical model (CLM4Me') integrated into CLM4.5-BGC (Riley *et al* 2011, Meng *et al* 2012) is used. CLM4Me' explicitly simulates the physical and biogeochemical processes regulating terrestrial methane fluxes such as methane production, oxidation, ebullition, transport through aerenchyma of wetland plants, and diffusion through soil (Riley *et al* 2011) (see supplementary materials for process representations). Wetlands are not represented with unique plant functional types in CLM4.5, but the portion of the gridcell that is inundated year round is considered to have aerenchyma (Meng *et al* 2012). We make this assumption here to improve our ability to simulate soil methane dynamics without adding a new wetland plant functional type. Formation of aerenchyma may not be controlled in some plants by flooding conditions; therefore, it may underestimate the aerenchyma area in unflooded plants (Fabri *et al* 2005). Meng *et al* (2012) added additional constraints on methane emissions by including a pH and redox functional dependence for methane production as well as the ability to simulate a satellite-derived inundation fraction (Prigent *et al* 2007, Ringeval *et al* 2010). The simulated methane fluxes have been evaluated against: the rather limited site-level observations of methane fluxes (Riley *et al* 2011, Meng *et al* 2012, Müller *et al* 2015); observations and atmospheric inversion estimates of methane fluxes in the West Siberian Lowlands (Bohn *et al* 2015); three recent global atmospheric inversion estimates of methane wetland fluxes (Riley *et al* 2011); and the measured IAV in atmospheric methane concentrations at 14 locations across the globe in Community Atmospheric Model with Chemistry (CAM-Chem) simulations (Meng *et al* 2015). Wetland emissions are a primary source of IAV in atmospheric methane emissions (Meng *et al* 2015).

2.2. Model configuration and experiments
Performing a full global sensitivity analysis for CLM4.5-BGC is computationally intractable.

Table 1. Set of simulation experiments to estimate the sensitivity of methane emissions in response to various climatic and environmental factors. For each factor, preindustrial forcing at 1850 (PI) or transient datasets (Tr) are used.

Case names	Controlling factors				
	Atmospheric CO_2	Nitrogen deposition	Wetland areal extent	Climate	Land-use and land-cover change
BASE	Tr	Tr	Tr	Tr	Tr
PI_CO2	PI	Tr	Tr	Tr	Tr
PI_NDEP	Tr	PI	Tr	Tr	Tr
PI_CLIM	Tr	Tr	Tr	PI	Tr
PI_PRECIP	Tr	Tr	Tr	Tr[c]	Tr
PI_LULCC	Tr	Tr	Tr	Tr	PI
PI_WETL	Tr	Tr	PI[a]	Tr	Tr
PI[b]	PI	PI	PI[a]	PI	PI
CURR[d]	Tr	Tr	Tr-Sat[e]	Tr	Tr

[a] Preindustrial wetland areal extent is estimated based on the inventories from the literature; however, transient wetland areal extent is calculated using CLM4.5.

[b] Preindustrial simulation over the period 1850–1869, in which we fix CO_2 concentration, nitrogen deposition, wetland inundation fraction and land-use and land-cover change at their 1850 values and we use a subset of the 20 year meteorological forcing from 1901 to 1920.

[c] Transient climate forcing data is used except for precipitation where a subset of 20 year precipitation data from 1901 to 1920 is cycled.

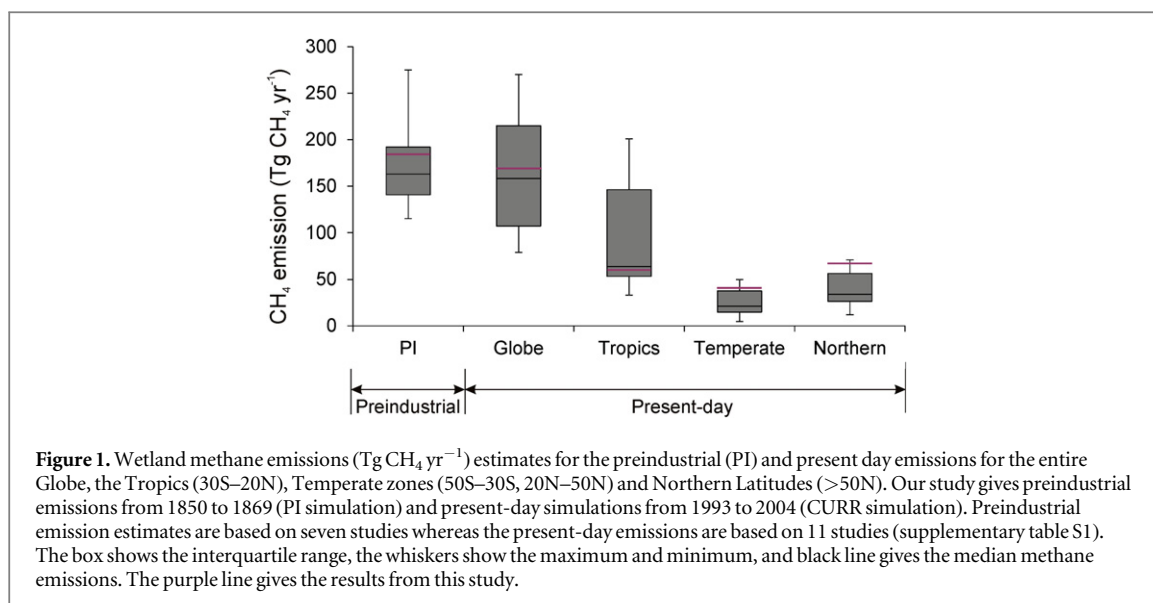[d] CURR simulation is performed for the period of 1993–2004.

[e] Tr-Sat represents the multi-satellite observations of wetland inundation extent for 1993–2004 (Prigent *et al* 2007).

Therefore, to disentangle the impacts of each climatic and environmental factor (e.g., atmospheric CO_2 concentrations, nitrogen deposition, wetland areal extent, precipitation, temperature, and land-use and land-cover change) on wetland methane emissions, we conduct model simulations over the period 1850–2005 using a simple sensitivity analysis approach (table 1). The initial state (1850) of the terrestrial carbon-nitrogen state variables within the CLM is generated using the standard spin-up procedure (Oleson *et al* 2013) bringing the carbon-nitrogen cycles close to steady-state conditions when the forcing datasets such as atmospheric CO_2, nitrogen deposition, aerosol deposition, land-use and land-cover change, and wetland inundation fraction, are held fixed at their 1850 values. For transient simulations from 1850 through 2005, we prescribe transient atmospheric CO_2 (as used by Randerson *et al* 2009), nitrogen deposition (Lamarque *et al* 2005), aerosol deposition (Lawrence *et al* 2011), and land-use and land-cover change (including harvest) (Hurtt *et al* 2006, Lawrence *et al* 2012). The transient climate data uses the 113 year (1901–2012) CRUNCEP reanalysis atmospheric forcing dataset, interpolated to a ½ h time step from a 6 h time step (http://dods.extra.cea.fr/store/p529viov/cruncep/V4_1901_2012/). The CRUNCEP is a combination of the CRU TS3.2 $0.5° \times 0.5°$ monthly climatology covering the period from 1901 to 2012 and the $2.5° \times 2.5°$ NCEP reanalysis datasets available for 1948–2010 (Oleson *et al* 2013). Prior to 1901 the 20 year subset of the transient climate dataset (1901–1920) is repeatedly cycled.

The BASE simulation (i.e., the control simulation, table 1) is driven by transient CO_2 concentrations, nitrogen deposition, land-use and land-cover change, and climate from 1850 to 2005. Since the wetland methane emissions are highly uncertain (Kirschke *et al* 2013) we use current climate as our base simulation to evaluate the relative changes between preindustrial and present-day. In the PI_CO2, PI_NDEP, and PI_LULCC simulations (PI = Pre-Industrial), the climate forcing is unchanged from the BASE simulation, but the CO_2 concentration, nitrogen deposition, and land-use and land-cover change are held fixed at their 1850 values. In the PI_CLIM simulation, we repeatedly cycle the 20 year (1901–1920) climate data from 1850 to 2004, but the other transient forcing datasets are the same as the BASE simulations. In the PI_PRECIP simulation, precipitation data from 1901 to 1920 is cycled, but the remaining climate forcing data such as solar radiation, temperature, specific humidity, air pressure, and wind are allowed to vary throughout the simulation period. Of course, in the real atmosphere, changes in meteorological forcings will occur simultaneously. However, these sensitivity studies allow a separation of the different mechanisms driving methane changes, and thus can be illuminating. The PI_WETL simulation uses the same transient forcing as the BASE simulation except preindustrial wetland extent is used, as explained in detail below. In addition we conduct a PI simulation from 1850 to 1869 by fixing all the forcing at preindustrial values in 1850 (see table 1) and using the 1901–1920 climate forcing data. The preindustrial wetland fraction is also used in the PI simulation.

Except for the PI_WETL and PI simulations all simulations use the model-calculated transient wetland inundation fraction from 1850 to 2005. In these simulations the model calculated inundation fraction is tuned following the methodology of Riley *et al* (2011) to the current wetland extent, so that the tuned

Figure 1. Wetland methane emissions (Tg CH$_4$ yr^{-1}) estimates for the preindustrial (PI) and present day emissions for the entire Globe, the Tropics (30S–20N), Temperate zones (50S–30S, 20N–50N) and Northern Latitudes (>50N). Our study gives preindustrial emissions from 1850 to 1869 (PI simulation) and present-day simulations from 1993 to 2004 (CURR simulation). Preindustrial emission estimates are based on seven studies whereas the present-day emissions are based on 11 studies (supplementary table S1). The box shows the interquartile range, the whiskers show the maximum and minimum, and black line gives the median methane emissions. The purple line gives the results from this study.

inundation matches as closely as possible the inundation fraction derived from multi-satellite observations (Prigent *et al* 2007) for the time period available 1993–2004 (see supplementary figure S1a). Although we calculate the transient wetland inundation fraction using a prognostic analysis based on changes in surface hydrology (e.g., surface runoff and water table depth), the lack of ability to simulate all inundation processes (such as flooding across multiple grid cells) might underestimate some of our attributions. Since preindustrial time humans have modified the wetland hydrology particularly by converting wetlands for development and agricultural activities, which directly reduced the overall wetland area. To evaluate the impact of the changes in wetland extent from human changes in hydrology, we estimate the preindustrial wetland extent based on existing studies of wetland loss data since the preindustrial (supplementary materials and figure S1b). In the PI_WETL and PI simulations a fixed preindustrial wetland extent is used. The CURR simulation is driven by transient datasets from 1993 to 2004. We specify satellite measured wetland inundation fraction available for the period from 1993 to 2004.
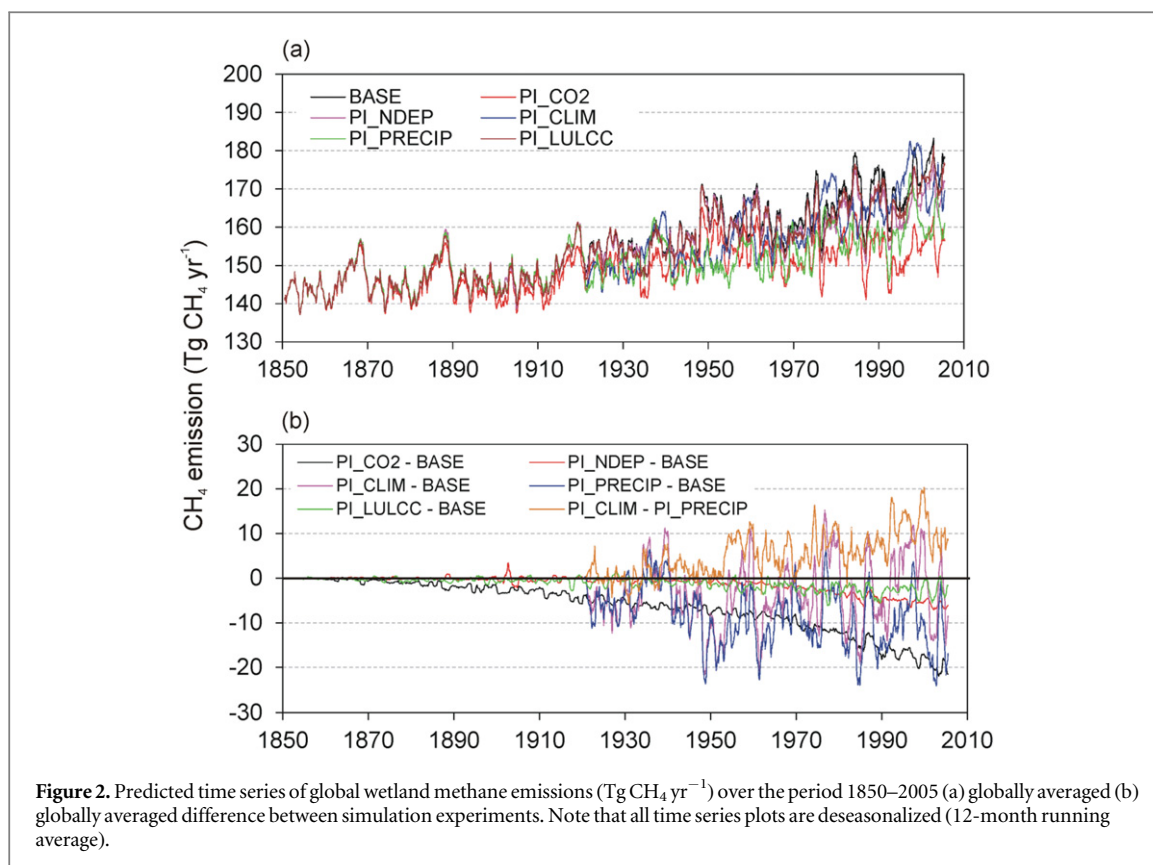
We estimate preindustrial inundated wetland area to be 4.36×10^6 km^2 based on the literature (supplementary materials), 34% higher than the present-day estimates derived from multi-satellite observations of 3.25×10^6 km^2 (Prigent *et al* 2007). Chappellaz *et al* (1993) estimated an approximately 20% larger areal wetland extent during the preindustrial time than today while Zedler and Kercher (2005) estimated the global wetland extent was 34% larger during the preindustrial due to wetland drainage for agricultural use. Other studies estimated that about 50% of the global wetland area has been lost as a result of human activities (Dugan 1993, OECD 1996) with much of the loss occurring in the northern midlatitudes (30N–60N). Uncertainties in the estimates of wetland loss are high

as estimates of historical wetland area are crude, at best: only a few countries have accurate maps and information with regard to wetland extent a century or two ago (Zedler and Kercher 2005), and our estimate lies within the published range.

3. Results

3.1. Comparison with other studies

To assess the performance of our model, we compare the preindustrial and the present-day annual average methane emissions from natural wetlands with existing studies using the PI and CURR simulations (figure 1, supplementary table S1). Although there remains a considerable uncertainty in global wetland emissions, our preindustrial estimates (187 Tg CH$_4$ yr^{-1}) fall well within the range of emissions (115–275 Tg CH$_4$ yr^{-1}) reported by previous studies. These studies have used different approaches to estimate preindustrial emissions: for example estimating the preindustrial methane sources by determining their consistency with atmospheric concentrations (Chappellaz *et al* 1993); employing a three-dimensional chemistry transport model and using methane mixing ratios and δ^{13}CH$_4$ from ice cores as constraints to quantify the source strengths (Houweling *et al* 2000, Mischler *et al* 2009, Monteil *et al* 2011; see table S1c), and process-based modeling (e.g., Ringeval *et al* 2013). Our present-day methane emissions are estimated to be 174 Tg CH$_4$ yr^{-1} for 1993–2004, also within the range of current estimates (80–270 Tg CH$_4$ yr^{-1}) (figure 1). Our estimates are particularly close to current estimates by Bloom *et al* (2010), and Bousquet *et al* (2006); but lower than the estimates by Riley *et al* (2011) and Meng *et al* (2012) who used an older version of CLM (the CLM4-CN model). The large variation in estimated global emissions is not surprising, as these studies used different methodologies to

Figure 2. Predicted time series of global wetland methane emissions (Tg CH$_4$ yr^{-1}) over the period 1850–2005 (a) globally averaged (b) globally averaged difference between simulation experiments. Note that all time series plots are deseasonalized (12-month running average).
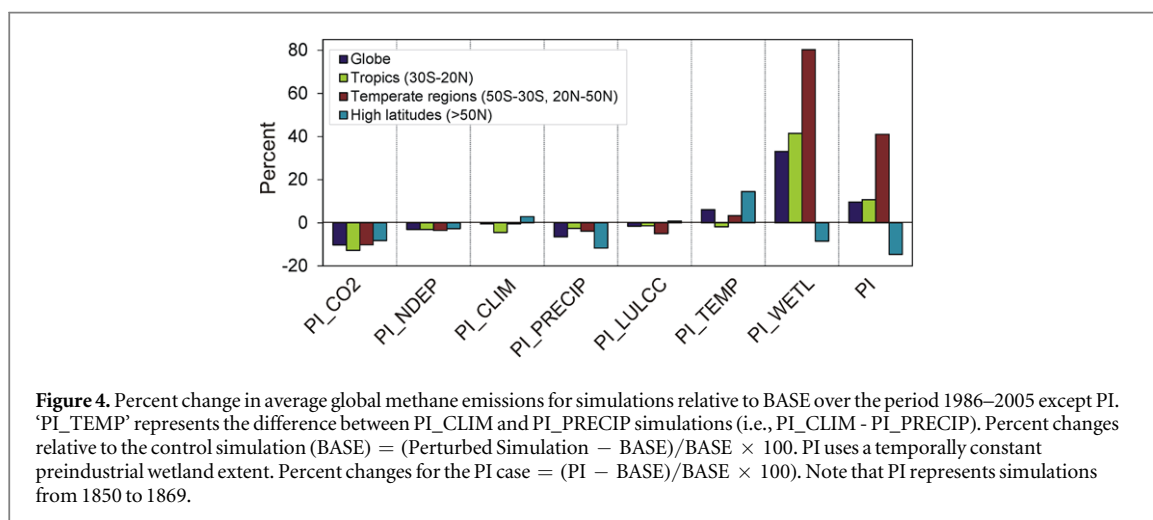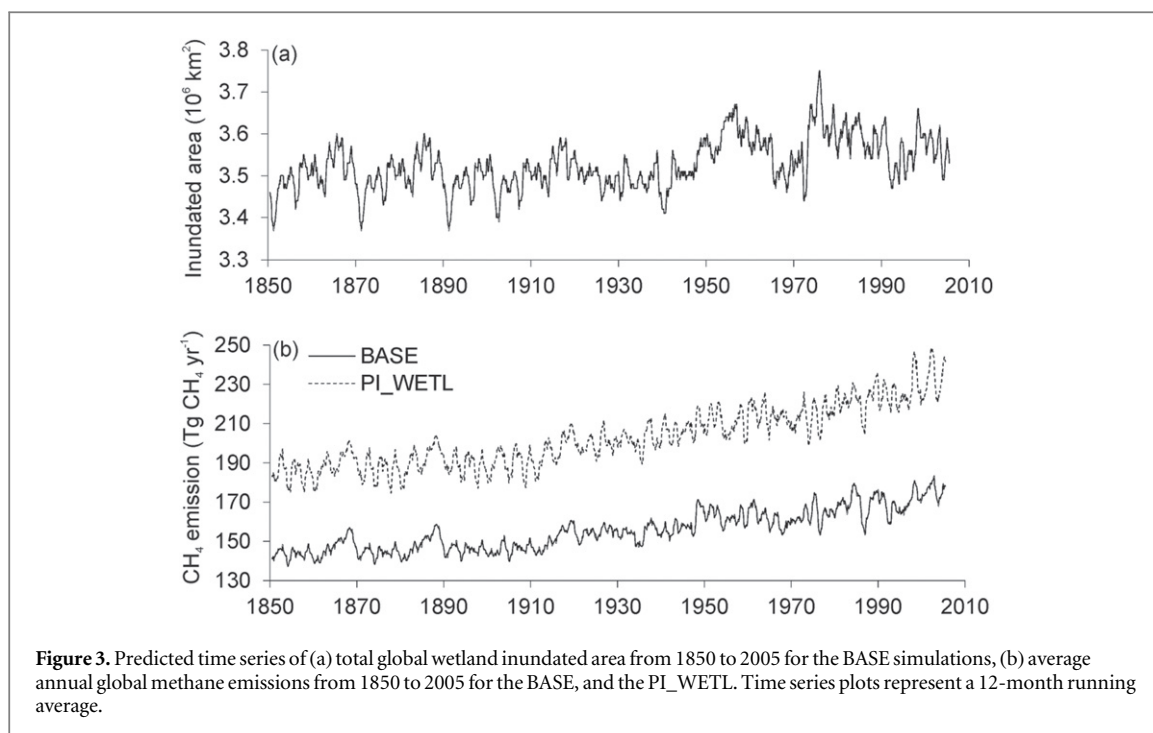
calculate inundated wetland extent (Melton *et al* 2013), and different modeling approaches to predict wetland methane emissions. For example, Matthews and Fung (1987) used a constant global wetland distribution from a wetland inventory and estimated the resulting methane fluxes, Cao *et al* (1996) and Walter *et al* (2001) used process-based model using global wetland distribution from Mathews and Fung (1987), while Bousquet *et al* (2006) and Bloom *et al* (2010) used a top-down approach where wetland extent is not explicitly utilized.

The present-day emissions over different latitudinal regions estimated in the current study also fall within the range of previous estimates (figure 1); however, our emissions are close to the upper bound of estimates in the temperate zone (20N–50N and 50S-30S) and in the high latitudes (>50N) and slightly lower than the median value in the tropics (30S–20N). The relatively high emissions in the high latitudes and low emissions in the tropics compared to previous versions with the same model (CLM4-CN; Riley *et al* 2011, Meng *et al* 2012) are consistent with the changes in the simulation of productivity in the CLM4.5-BGC (see Meng *et al* 2015): compared to the previous version of the CLM, the CLM4.5-BGC has increased ecosystem productivity in high latitudes and reduced productivity in the tropics (Koven *et al* 2013). Overall, these results suggest that there is still considerable uncertainty in the estimates of wetland methane emissions with some of the uncertainty due to the model simulation of the carbon cycle.

3.2. Changes in methane emissions

The temporal evolution of annual average global wetland methane emissions for all simulations except PI_WETL and PI from 1850 to 2005 is given in figure 2(a), with differences between simulations given in figure 2(b). Significant interannual temporal variability is evident in all simulations. The PI_CO2 simulation shows the smallest increase in methane emissions followed by PI_PRECIP. Elevated CO$_2$ concentration tends to increase the methane emissions monotonically over the period of simulation (viz. PI_CO2—Base, figure 2(b)). Although both increasing nitrogen deposition and land-use and land-cover change increase methane emissions from 1850 to 2005, the difference in emissions between BASE and these simulations is relatively small (figure 2(b)). Simulations with transient climate include both changes in temperature and changes in precipitation. We investigate the effects of varying temperature alone on methane emissions for 1850–2005 by evaluating the output from PI_CLIM minus PI_PRECIP (hereafter referred to as PI_TEMP).

Using sensitivity studies we quantify the role of several controlling mechanisms in determining changes in present-day global methane emissions from the preindustrial period. The sensitivity to preindustrial wetland extent is evaluated in the PI_WETL simulation. Assuming the present-day wetland extent is the same as the preindustrial gives present day (1986–2005) globally averaged emissions (PI_WETL) that are 56 Tg CH$_4$ yr^{-1} higher than the BASE

Figure 3. Predicted time series of (a) total global wetland inundated area from 1850 to 2005 for the BASE simulations, (b) average annual global methane emissions from 1850 to 2005 for the BASE, and the PI_WETL. Time series plots represent a 12-month running average.

Figure 4. Percent change in average global methane emissions for simulations relative to BASE over the period 1986–2005 except PI. 'PI_TEMP' represents the difference between PI_CLIM and PI_PRECIP simulations (i.e., PI_CLIM - PI_PRECIP). Percent changes relative to the control simulation (BASE) = (Perturbed Simulation − BASE)/BASE × 100. PI uses a temporally constant preindustrial wetland extent. Percent changes for the PI case = (PI − BASE)/BASE × 100. Note that PI represents simulations from 1850 to 1869.

simulation (a 33% increase) (figures 3 and 4), with a larger increase in methane fluxes in the northern temperate zone (79%) and smaller reduction in the high latitudes (9%), consistent with changes in wetland areal extent (e.g., draining and converting wetlands for agricultural, residential and other uses) during the twentieth century (Dugan 1993, Lehner and Doll 2004), as discussed in section 2.

Accounting for changes in both wetland area and the various forcing factors since the preindustrial (table 1), the simulated preindustrial wetland emissions (simulation PI) are approximately 10% larger than the present-day (1986–2005) emissions in the BASE simulation. The emissions in the temperate zones are significantly higher (41%); they are modestly higher in the tropics (11%), but 15% lower in the high latitudes (figure 4). Our global emissions changes from preindustrial are consistent with estimates from

previous studies. Houweling *et al* (2000) reported present-day wetland emissions to be ~10% smaller than preindustrial emissions due to changes in forcing factors and wetland extent. Similarly, Chappellaz *et al* (1993) reported 15% smaller wetland emissions today than in the pre-industrial Holocene due to changes in wetland extent.

The sensitivity to changes in CO_2 is evaluated using the PI_CO2 simulation. In the case where preindustrial CO_2 levels are used (PI_CO2), the total global methane emissions decrease by 17.4 Tg CH_4 yr^{-1} compared to those in the present day BASE simulation, which is equivalent to the 10% reductions from the BASE simulation. The highest percentage reduction occurs in the tropics (13%), and the lowest in the high latitudes (8%). CO_2 affects methane emissions primarily through the changes in amount of biomass available for decomposition (Van Groenigen

et al 2011, Cox *et al* 2013). Enhanced plant growth due to increasing CO_2 increases the amount of soil organic matter due to the stimulation of plant and litter biomass production (Berendse *et al* 2001, Reich *et al* 2001), which in turn can increase methane production (Whiting and Chanton 1993, Van Groenigen *et al* 2011). Elevated CO_2 may stimulate methane fluxes in a direct proportion to net plant photosynthesis (Megonigal *et al* 2004). The emission enhancements with increased CO_2 are consistent with enhanced growth from CO_2 fertilization effects (Gifford 1994, Long *et al* 2004). Van Groenigen *et al* (2011) shows an increase in methane emissions due to increased CO_2 concentration using meta-analysis. Although the CO_2 fertilization of this model has not yet been calculated within a coupled model context, based on a recent model intercomparison (Arora *et al* 2013), models with nitrogen limitation tend to have lower CO_2 fertilization effects than models without it. Thus, we expect the impact of CO_2 fertilization estimated here will be lower than land models that do not incorporate the nitrogen limitation. For example, Ringeval *et al* (2011) reports an increase of 134% in global wetland emissions from preindustrial time (1860–1869) by the end of the 21st century in response to increasing CO_2 (SRES-A2 scenario) using ORCHIDEE-WET model. This corresponds to a 0.23% increase in methane emissions per ppmv increase in CO_2 concentration, which is 0.11% per ppmv larger than this study. Their carbon-only model does not account for the nitrogen limitation, which may lead to their estimates higher than ours.

Changing the amount of nitrogen deposition or the amount of forest vs. crop areas (PI_NDEP and PI_LULCC cases) results in small reductions of global emissions by 4.2 and 2.7 Tg CH_4 yr^{-1} (−3% and −2%) relative to the BASE simulation. Increased nitrogen deposition may influence the methane emissions through positive effects on plant growth (similar to CO_2 effects) and therefore the amount of available soil organic matter for decomposition (Berendse *et al* 2001, Reich *et al* 2001). In PI_LULCC simulation, changes in methane emissions are due to the changes in the carbon cycle but not directly through changes in wetland extent. Since CLM4.5 does not have a wetland representation the biogeochemical impacts of LULCC are simulated through changes in carbon pool and fluxes.

Climate effects on methane emissions are complex, with the effects of precipitation and temperature slightly offsetting each other. In PI_CLIM there is a reduction in global methane emissions by 0.5% at present day (1986–2005) compared to the BASE simulation; however, high-latitude emissions are increased by 3%. In contrast, the preindustrial temperature (PI_TEMP) simulation increases global emissions by 6% compared to the BASE simulation, which represents a large increase in high-latitude emissions of 15%, and a smaller decrease in tropical emissions of 2%, emphasizing the role of cooler temperatures in

high latitudes in generating more methane fluxes. This is likely due to the lowered water tables in the unsaturated portions of the gridcell and a nearly constant trend in saturated inundated area in response to the preindustrial temperature (figures S6 and S7), resulting in a higher methane oxidation from the soil. If only precipitation is changed (PI_PRECIP), global emissions are decreased by 7% compared to the BASE simulation, including a 3% decrease in the tropics and 12% decrease in the high latitudes. Between the present-day time period and the preindustrial precipitation increased by 10.5% in high latitudes, 4.5% in the northern temperate zone and 2% in the tropics.

While these results are roughly consistent with previous studies (e.g. Cao *et al* 1998, Gedney *et al* 2004, Shindell *et al* 2004, Eliseev *et al* 2008, Volodin 2008, Ringeval *et al* 2011), our study is the first to evaluate the relative contributions of these processes for current climate. These studies are generally focused on evaluating the future impacts of changing CO_2 and climate, but did not include the effects of nitrogen limitations, and therefore overestimating terrestrial carbon uptake (i.e., increasing the CO_2 fertilization effect). Also, these studies did not examine the effects of human changes in wetland extent, nitrogen deposition, and land-use-land-cover change on methane emissions from preindustrial to current.

3.3. Spatial patterns

The spatial pattern of annually average methane emissions for preindustrial time (1850–1869) and present day (1986–2005) is broadly consistent with previous estimates of preindustrial (Ringeval *et al* 2013) and current (Walter *et al* 2001, Bloom *et al* 2010) emissions (figures 5(a) and (b)). Results show the largest emissions over Southeast Asia, the boreal region of North America, northern Europe, central Siberia and some places of South America during the present day. Since the preindustrial period, humans have mostly altered wetlands in the northern tropics and temperate zone (10N–40N; Lehner and Doll 2004), which has resulted in large reductions in methane emissions in this region (figures 5(a) and (b)).

There are spatial heterogeneities in the responses to different forcing factors. In these simulations, CO_2 has the largest impacts on tropical emissions, particularly in Southeast Asia (figure 5(c)). Changes in climatic variables have both positive and negative spatial contributions to methane emissions (figure 5(e)). A similar heterogeneous pattern can be seen in the response to precipitation (figure 5(f)) (PI_PRECIP), with a decrease in emissions in eastern Siberia, mid- and high latitudes regions of North America, but increases in the western Siberia boreal region and in most places of Africa. Precipitation has decreased since the preindustrial period in most places of Africa and increased in mid- and high latitudes regions of North America and Western Europe (supplementary

Figure 5. Annually averaged methane emissions (mg CH_4 m^{-2} d^{-1}) for (a) BASE (1986–2005), (b) PI (1850–1869), and difference between (c) PI_CO2 and BASE (i.e., PI_CO2 minus BASE), (d) PI_NDEP and BASE, (e) PI_CLIM and PI_BASE, (f) PI_PRECIP and BASE, (g) PI_LULCC and BASE, (h) PI_CLIM and PI_PRECIP, and (i) PI_WETL and BASE.
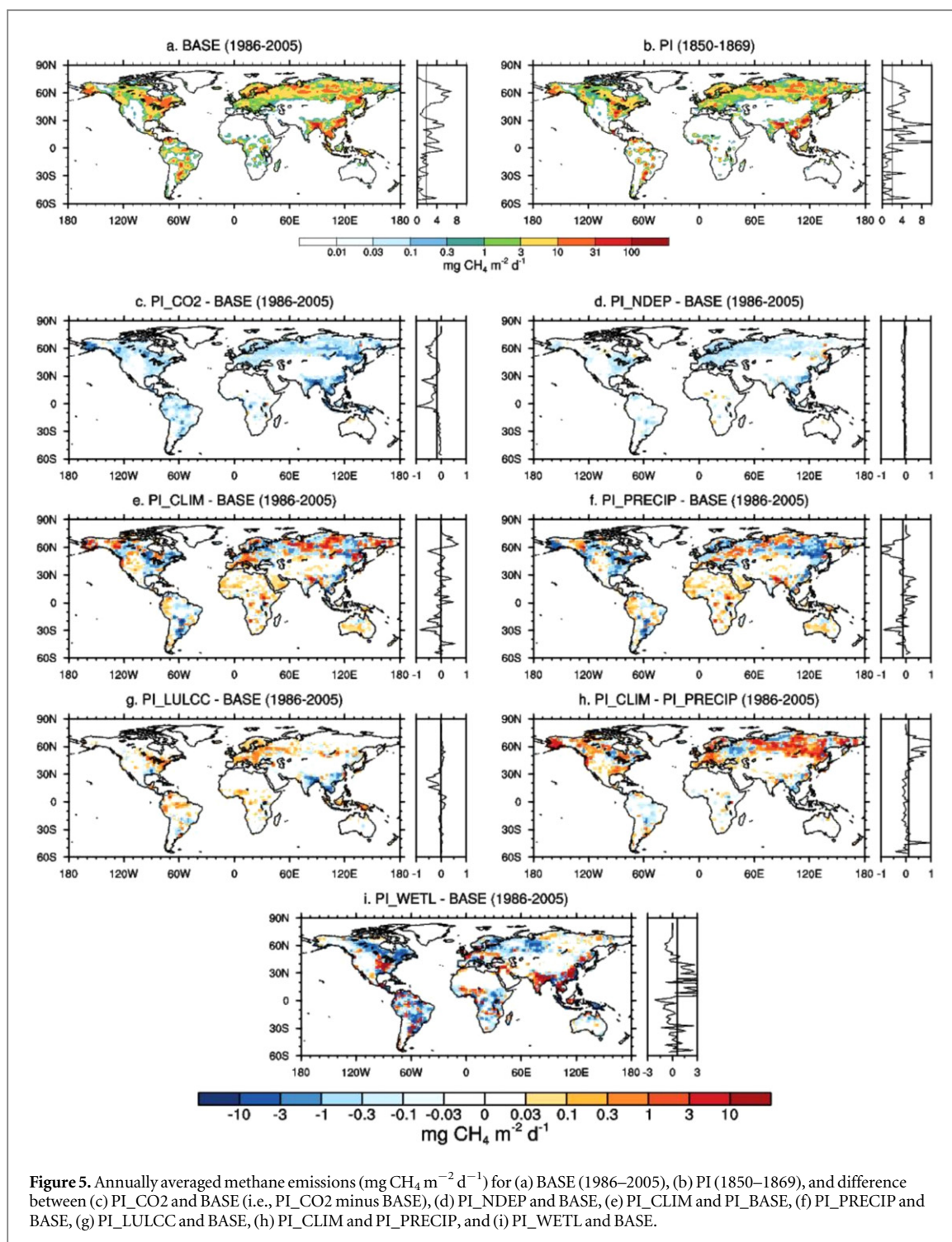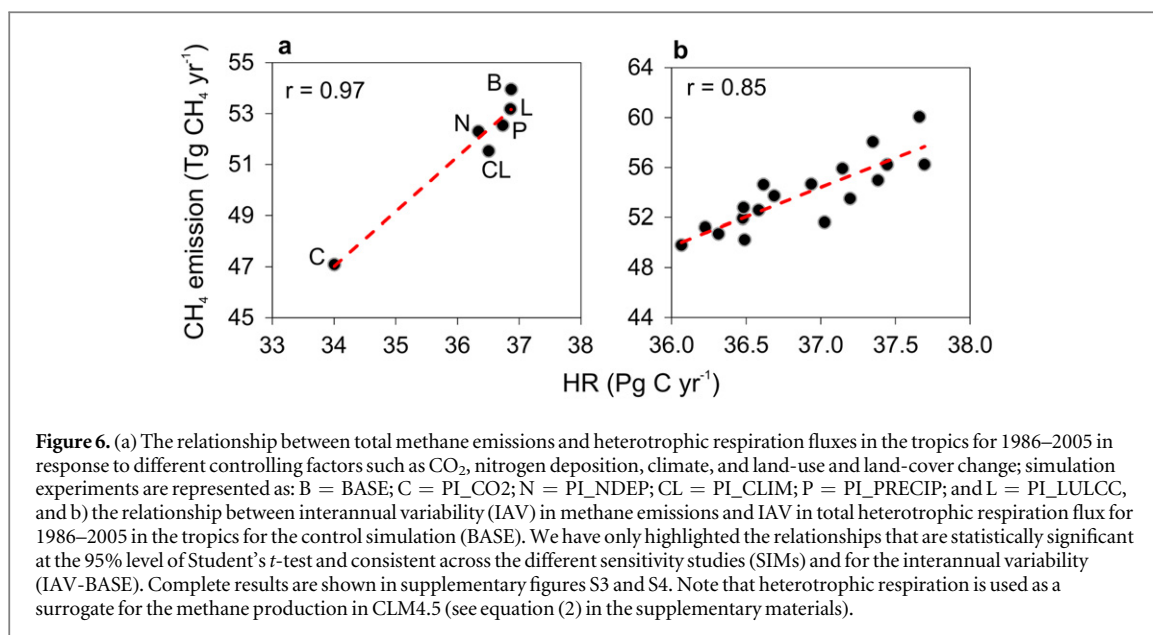
figure S2); these precipitation changes are consistent with changes in methane emissions. On the other hand, temperature shows a strong influence on the high-latitude methane emissions with considerable differences in Alaska, most of Siberia, and Western Europe (figure 5(h)). Changes in land-use and land-cover change (PI_LULCC) result in reduced emissions particularly in Southeast Asia. The larger areal wetland extent during preindustrial time particularly within the northern hemisphere (e.g., Southeast Asia, Central America, and Western Europe) results in a locally large changes in methane emissions (figure 5(g)).

3.4. Relationship between methane emissions and potential drivers (substrate production, inundated area, near-surface temperature, and precipitation)

Methane emissions from wetlands have significant inter-annual variability depending on changes in substrate production for methanogenisis and changes in inundated area, as well as on the partitioning between methane and carbon dioxide emissions. It is straightforward to understand how changes in inundated area affect methane fluxes (e.g. Ringeval *et al* 2010, Watts *et al* 2014) as, all else equal, a larger inundated area directly produces a larger methane

Figure 6. (a) The relationship between total methane emissions and heterotrophic respiration fluxes in the tropics for 1986–2005 in response to different controlling factors such as CO_2, nitrogen deposition, climate, and land-use and land-cover change; simulation experiments are represented as: B = BASE; C = PI_CO2; N = PI_NDEP; CL = PI_CLIM; P = PI_PRECIP; and L = PI_LULCC, and b) the relationship between interannual variability (IAV) in methane emissions and IAV in total heterotrophic respiration flux for 1986–2005 in the tropics for the control simulation (BASE). We have only highlighted the relationships that are statistically significant at the 95% level of Student's *t*-test and consistent across the different sensitivity studies (SIMs) and for the interannual variability (IAV-BASE). Complete results are shown in supplementary figures S3 and S4. Note that heterotrophic respiration is used as a surrogate for the methane production in CLM4.5 (see equation (2) in the supplementary materials).

flux. The inundated area and substrate production rate are in turn impacted by changes in the forcing variables (e.g., temperature and precipitation). To better understand how different factors impact methane fluxes, we examine the relationship between methane emissions and their potential drivers in the model in two ways (1) the relationship between globally averaged methane emissions and changes in forcing between the different sensitivity simulations (hereafter referred to as SIMs), and (2) the relationship between IAV in the BASE simulation and variations in drivers over the period 1986–2005 (hereafter referred to as IAV-BASE). In the model, we describe heterotrophic respiration as a proxy for methanogenesis substrate production, which represents the dominant long-term control on methane production variability. Since we do not have a wetland representation that includes details related to methane production, we assumed that the production in the anaerobic portion of the soil column is related to the gridcell estimate of heterotrophic respiration from soil and litter as used by other studies (Wania *et al* 2010, Spahni *et al* 2011, Zhu *et al* 2014). In these studies, soil carbon for methanogenesis is considered as a fraction of soil heterotrophic respiration. Therefore we refer to this sensitivity analysis with the term 'substrate production'. The relationship between the drivers and the IAV is presented in the supplement (figure S4 and table S4).

Figure 6(a) presents the statistically significant relationships that drive the methane emissions in both IAV and across the various sensitivity studies. In the sensitivity studies the only significant correlation is between the methane emissions and heterotrophic respiration in the tropics ($r = 0.97$, $p < 0.05$) (figure 6(a)). This result suggests that changes in tropical methane emissions are mainly mediated by changes in tropical substrate production in response to

changes in CO_2, nitrogen deposition, climate, and land-use and land-cover change. This result is consistent with the drivers of IAV derived from IAV-BASE for the tropics ($r = 0.85$, $p < 0.05$) (figure 6(b)), confirming results from the IAV simulation. Besides the correlation between tropical methane emissions and substrate production in the SIMs, the next highest correlations are between methane emissions and substrate production in the northern temperate zone ($r = 0.57$, $p > 0.05$) and methane emissions and surface temperature in the high latitudes ($r = 0.52$, $p > 0.05$) (figure S3). However, both these latter two correlations are statistically insignificant.

4. Conclusions

Our simulated preindustrial global wetland emissions (187 Tg CH_4 yr^{-1}) are approximately 10% larger than present-day emissions, with significantly higher emissions in the temperate zones (41%), and modestly higher in the tropics (11%), but 15% lower in the high latitudes. Our preindustrial global estimates are consistent with estimates by Houweling *et al* (2000) and Chappellaz *et al* (1993). Differences between present-day and prehistoric emissions are driven by changes in wetland extent and in various forcing variables, including CO_2, nitrogen deposition, precipitation, temperature, and land-use and land-cover change. Thus, to a first approximation, natural emissions of methane from wetlands have remained constant since the preindustrial period, suggesting the observed increases in methane concentrations can almost exclusively be attributed to changes in anthropogenic emissions. However, the constancy of emissions is the result of two competing factors: the change in wetland areal extent has decreased the present day emissions

relative to the preindustrial while various environmental forcings have acted to increase the emissions.

Here we attribute for the first time the different factors that change the preindustrial wetland methane emissions compared to those from the current climate. Sensitivity studies suggest that atmospheric CO_2 have increased present day methane emissions by 17.4 Tg CH_4 yr^{-1} (+10%) compared to the preindustrial. The mechanism whereby higher CO_2 drives higher methane fluxes has been noted previously (Gedney *et al* 2004, Shindell *et al* 2004), although we know of no study that has quantified this impact between the preindustrial and present day. Shindell *et al* (2005) report a ~0.22% increase in global methane emissions per ppmv increase in CO_2 while Gedney *et al* (2004) reports a ~0.28% increase in emissions per ppmv CO_2 increase for the IS92a scenario. However, our study shows a substantially lower response: a 0.12% increase in emissions per ppmv increase in CO_2. Our model is likely to be less sensitive than previous estimates because of the nitrogen limitation on the CO_2 fertilization effect included in this model (Thornton *et al* 2009, Arora *et al* 2013, Koven *et al* 2013). Nitrogen deposition and land-use and land-cover change effects are found to contribute modestly to increases in present day emissions (+3% and +2%) but could be important regionally. For example, most of the impacts in response to land-use and land-cover change occur in Southeast Asia.

The combined effects of climate on methane emissions are small, but the effects of temperature and precipitation individually are larger and partially offsetting. Precipitation changes from preindustrial to present day tend to increase both tropical emissions (3%), and high-latitude emissions (12%), while temperature changes tend to decrease high-latitude emissions (15%) but increase tropical emissions (2%).

The most important factor in the change in methane wetland fluxes from the preindustrial is due to conversion of wetlands to drylands by humans. We find the present-day emissions would be 33% higher without the conversion of wetlands to drylands. Most of the conversion of wetlands occurs in northern temperate zone (Chappellaz *et al* 1993, Dugan 1993). We find the largest change in wetland emissions from the preindustrial occurs in the northern temperate zone (−79%) with smaller changes in the high latitudes (+9%).

While the importance of changes in inundation to the wetland methane fluxes are well established (e.g., Ringeval *et al* 2010), we consider how other climatic and environmental factors impact the methane fluxes. More than half (54%) of the year–year IAV in methane emissions is explained by the variation in substrate production, with stronger relationships in the tropics than other regions. The relationship between IAV in inundated wetland extent and IAV in methane emissions is high (statistically significant at 95% level of Student's *t* test) in the tropics but weak in the northern

temperate zone and high latitudes. We find that the long-term change in methane fluxes from the various forcing agents (changes in CO_2, nitrogen deposition, climate, and land-use and land-cover change) is mostly mediated through changes in long-term substrate production in determining the long-term change in wetland methane emissions between the various simulations.

There are many uncertainties in quantifying the effects of the controlling factors on methane emissions. These uncertainties may arise from several factors, including: (1) CLM4.5-BGC does not simulate wetland plant functional types and a separate carbon cycle submodel for wetlands (Oleson *et al* 2013) which could potentially impact the CO_2 fertilization effect and other methane transport processes through plant aerenchyma, (2) there is substantial uncertainty in the methane fluxes predicted in the methane module based on uncertainties in the choice of parameter values (Riley *et al* 2011), (3) methane emission is dependent on the temporal variability predicted in the carbon and land model, especially on the substrate production rate, therefore errors associated with the carbon model component could propagate to the methane model and affect emissions (Meng *et al* 2015). Finally, the estimation of inundation area, both as a function of climate and through human modification, is difficult. Despite these uncertainties, our findings have implications for understanding of the evolution of wetland emissions, the attribution of historic methane changes and predicting methane changes more accurately in the future in response to changes in climatic and environmental conditions. Improved understanding of the attribution of radiatively important gases is important for understanding past climate change (e.g., Ciais *et al* 2013) and projecting future feedbacks.

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