Enhanced response of global wetland methane emissions to recent El Niño-Southern Oscillation events

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Abstract: Wetlands are thought to be the major contributor to interannual variability in the growth rate of atmospheric methane (CH_4) with anomalies driven by the influence of the El Niño-Southern Oscillation (ENSO). However, it remains unclear whether the increase in total global CH_4 emissions during El Niño versus La Niña events is from wetlands and how large the contribution of wetland CH_4 emissions is to the interannual variability of atmospheric CH_4. Here, we use a terrestrial ecosystem model that includes permafrost and wetland dynamics to estimate CH_4 emissions, forced by three separate meteorological reanalyses and one gridded observational climate dataset, to simulate the spatio-temporal dynamics of wetland CH_4 emissions from 1980-2016. The results show that, although wetland CH_4 responds to El Niño events with negative anomalies during the El Niño periods, the instantaneous growth rate of wetland CH_4 emissions exhibits complex phase dynamics. All of our simulations suggest that a record-high wetland CH_4 growth rate was reached in the beginning of the 2015-2016 El Niño event. We also find evidence for a step increase of CH_4 emissions by 7.8±1.6 Tg CH_4 yr^{-1} during 2007-2014 compared to the average of 2000-2006 from simulations using meteorological reanalyses, which is equivalent to a ~3.5 ppb yr^{-1} rise in CH_4 concentrations. The step increase is mainly caused by the expansion of wetland area in the tropics (30°S-30°N) due to an enhancement of tropical precipitation as indicated by the suite of the meteorological reanalyses. Our study highlights the role of wetlands in driving the variability and trends of atmospheric CH_4 concentrations and stresses the need to account for uncertainty in climate forcings in addressing the interannual variability and decadal-scale trends of wetland CH_4 fluxes.

Introduction

Methane (CH_4) is a potent greenhouse gas contributing to about 20% of the warming induced by long-lived greenhouse gases since pre-industrial times (IPCC, 2013). Atmospheric CH_4 concentrations have risen from preindustrial levels of 715 parts per billion (ppb) since the 1800s (Etheridge *et al.*, 1998; MacFarling Meure *et al.*, 2006) to current global concentration of ~1847 ppb, a 2.5-fold increase, primarily driven by anthropogenic activities (Kirschke *et al.*, 2013), e.g. fossil fuel activities, agriculture, and also by the biogeochemical feedbacks of natural processes to climate change (Arneth *et al.*, 2010; Tian *et al.*, 2016; Saunois *et al.*, 2016). However, the variability in the annual growth rate of atmospheric CH_4 is considered to be strongly associated with the response of biogenic CH_4 sources to climate variability, in which global wetlands contributes 60-80% of biogenic emissions during the past (Quiquet *et al.*, 2015; Hopcroft *et al.*, 2017) and likely into the projected future (Zhang *et al.*, 2017b). Thus, the growth rate of atmospheric CH_4 is largely affected by the response of global wetland CH_4 emissions to the year-to-year mode of global climate variability like the El Niño-Southern Oscillation (ENSO), one of the largest climate phenomena that drives carbon fluxes and their anomalies across large portions of the globe (Chatterjee *et al.*, 2017).

El Niño, the positive phase of ENSO, influences the hydrologic and carbon cycle of tropical terrestrial ecosystems through a change in atmospheric pressure patterns and sea surface temperatures that induce strong warming and reduced precipitation patterns by shifting the Intertropical Convergence Zone southward, causing amplified wildfires (Worden *et al.*, 2013) and reduced wetland areal extent and CH_4 emissions (Hodson *et al.*, 2011). Tropical wetlands, which contribute 50-70% of the global wetland CH_4 emissions (Bousquet *et al.*, 2006), are largely affected by the periodic variations of air temperature and precipitation induced by ENSO phases (Pison *et al.*, 2013). However, in contrast to the findings from forward models, e.g. terrestrial biogeochemical models, which suggest that tropical and global wetland CH_4 emissions are usually found to decrease during El Niño (Hodson *et al.*, 2011; Zhu *et al.*, 2017; Ringeval *et al.*, 2014), atmospheric measurements show that the growth rate of global CH_4 concentration can rise during strong El Niño years (Nisbet *et al.*, 2016). In addition, the link between the annual CH_4 growth rate and the variability in global wetland CH_4 emissions has been challenged by the observed pause in the growth during 2000-2006, but following which, in 2007, a strong growth rate resumed (Nisbet *et al.*, 2014). Recent studies suggest that global wetlands played a limited role during the renewed rise through 2012 (Poulter *et al.*, 2017; Turner *et al.*, 2017; Rigby *et al.*, 2017). Meanwhile, isotopic measurements appear to indicate that the resumed increase in the growth rate rather originates from biogenic sources than from fossil-fuels (Schwietzke *et al.*, 2016), suggesting an increased influence of tropical wetlands (Nisbet *et al.*, 2016) or agricultural sources (Schaefer *et al.*, 2016). This calls for revisiting the role of teleconnections, and their timing, on wetlands and land-atmosphere CH_4 fluxes to help reconcile top-down and bottom-up methodologies.

Previous extreme El Niño events, in years 1982-1983, 1997-1998, and 2015-2016, had significant impacts on terrestrial ecosystems and are considered key drivers of the atmospheric CO_2 growth rate variability (Liu *et al.*, 2017). It has been reported that the latest El Niño event (2015-2016) was one of the strongest on record, causing unprecedented warming and extreme droughts over most of the Amazonia regions (Jiménez-Muñoz *et al.*, 2016; L'Heureux *et al.*, 2016; Lim *et al.*, 2017; Chatterjee *et al.*, 2017). The occurrence of this extreme El Niño event severely disrupted regional ecosystems, causing sharp increases in atmospheric CO_2 concentrations (Betts *et al.*, 2016) and a doubling of fire-induced emissions in Southeast Asia (Whitburn *et al.*, 2016). El Niño may have also contributed to record warming during 2015 and the first third of 2016, at 0.98°C above the 20th century mean monthly average (http://www.ncdc.noaa.gov/sotc/global/201613, last access at August 2017). Exactly how much the 2015-2016 ENSO phenomenon has impacted global wetland CH_4 emissions and to what extent it has affected the annual growth rate of atmospheric CH_4 concentration remains unknown due to challenges in monitoring and modeling.

Here, we analyze the relationship between ENSO phases and annual wetland CH_4 emissions by addressing two main questions. First, how does ENSO, with particular attention to the ENSO event in 2015-2016, affect the interannual variability of CH_4 emissions from global wetlands? Second, what is the relationship between the interannual variability of the growth in atmospheric CH_4 and wetland CH_4 emissions over the recent decade, and what are the major mechanisms linking wetland CH_4 emissions to the increases since 2007?

Methods

We use a process-based ecosystem model LPJ-wsl (Lund-Potsdam-Jena model, *WSL* version) forced with four different atmospheric forcings to simulate wetland CH_4 emissions from 1980 to 2016. The four climate products include one station-based monthly geo-interpolation dataset (CRU) and three meteorological reanalyses products. The reason for using multiple forcings is to investigate the uncertainty from meteorological forcings in driving the simulated atmospheric CH_4 concentrations, and hence to better characterizes the CH_4 variations in response to climate variability.

LPJ-wsl (Poulter *et al.*, 2011) is a process-based dynamic global vegetation model (DGVM) developed for studying terrestrial ecosystems, which is based on an earlier LPJ core model (Sitch *et al.*, 2003). The version of the model applied in this study includes a new hydrologic model TOPMODEL to determine wetland area and its inter- and intra-annual dynamics (Zhang et al., 2016), a permafrost and dynamic snow model (Wania et al., 2009), and a prognostic wetland CH_4 emission model (Hodson et al., 2011), each of which is incorporated into the LPJ-wsl framework with consideration of the effects of snow and freeze/thaw cycles on CH_4 emissions

(Zhang *et al.*, 2016). The estimation of CH_4 emissions is based on an empirical model that considers soil respiration, inundated area, and a temperature-based ecosystem emission efficiency (Christensen *et al.*, 1996). The simulated variations in wetland areas and CH_4 emissions have been evaluated against large-scale observations in previous studies (Hodson *et al.*, 2011; Zhang *et al.*, 2016; Zhang *et al.*, 2017b). Here, we calibrated temperature-modified CH_4 emitting factors by scaling simulated global estimates to match 172 Tg CH_4 yr^{-1} in 2004, which was estimated from an independent atmospheric inversion study (Spahni et al., 2011), and in agreement with independent satellite-based methods from Bloom *et al.* (2010). We improved inundation estimates by calibrating the TOPMODEL parameter 'maximum inundation potential' (F_{max}) (Zhang et al., 2016) using an independent inundation dataset (Poulter *et al.*, 2017) that was derived from a satellite-based Surface Water Microwave Product Series (SWAMPS) (Schroeder *et al.*, 2015) and inventory-based dataset Global Lakes and Wetlands Database (GLWD) (Lehner and Döll, 2004), as well as from a regional wetland map derived from satellite retrievals for Amazonia (Hess et al., 2015). To avoid confusion regarding double counting (Thornton *et al.*, 2016), we clarify that in this study simulated wetland area explicitly includes both permanently inundated vegetated wetlands and seasonally inundated wetlands, e.g. floodplains, but excludes reservoirs, large and small lakes and rivers, as well as coastal wetlands that are defined and constrained by GLWD, and rice agriculture.

The climate datasets included the monthly meteorology from the Climate Research Unit (CRU) TS 3.25 (Harris *et al.*, 2014), three state-of-the-art metrological reanalysis products, including 1-hourly reanalysis Modern-Era Retrospective analysis for Research and Applications Version 2 (MERRA2) (Gelaro *et al.*, 2017) from the NASA Global Modeling and Assimilation Office (GMAO), 6-hourly ERA-Interim (ERA-I) (Dee *et al.*, 2011) from the European Centre for Medium-Range Weather Forecasts (ECMWF) data assimilation system and 6-hourly Japanese 55-year Reanalysis (JRA-55) (Kobayashi *et al.*, 2015) from the Japan Meteorological Agency (JMA). To generate these three forcing datasets, four output products (total precipitation, 2m air temperature, downward shortwave radiation, and surface longwave radiation) were aggregated to a daily time-step and downscaled to a common 0.5° spatial resolution grid using bilinear interpolation to match the gridded soils input. For the monthly CRU data, LPJ-wsl was set up to use a wet-day frequency dataset, a weather generator (Geng *et al.*, 1986) to generate daily precipitations, and a set of simplified equations with monthly cloud cover as input to calculate mid-month daily photosynthetically active radiation flux and potential evapotranspiration (Prentice *et al.*, 1993). Additional details of the climate forcing datasets and model experiments are in Supplementary Material (Table S1). The LPJ-wsl state variables (i.e., carbon in vegetation, litter, and soils) were simulated to reach equilibrium by using a 1000-year spinup, with fire dynamics, and a 398-year spinup for land use change using Land-Use Harmonization dataset (LUHv2) (Hurtt *et al.*). After equilibrium, a transient simulation with fire effects included was performed for the years 1901-2016 (for CRU) and 1980-2016 (for reanalysis), forced with changing climate conditions as prescribed. For the reanalysis

simulations, CO_2 concentrations were gradually increased starting from the spinup and recycling the meteorological information.

We used the Multivariate ENSO index (MEI) for representing the ENSO strength (Wolter and Timlin, 1998). The MEI index represents the first unrotated principal component of the combined, normalized fields of the primary climate variables observed over the tropical Pacific, reflecting a global signal of climate-land-atmosphere interaction for both El Niño and La Niña events; Given that studies on progressions of carbon fluxes during El Niño (Yuanyuan *et al.*, 2017; Liu *et al.*, 2017) have shown a hysteresis in the Earth system's response to changes in temperature and precipitation patterns, we carried out a cross-correlation analysis to examine possible time-lag effects of wetland CH_4 response to El Niño events.

To test whether annual wetland anomalies contributed to the growth rate of atmospheric CH_4, we compared our results against the annual mean global CH_4 growth rate and monthly CH_4 trend derived from NOAA/ESRL (Dlugokencky *et al.*, 1994). We then used the first derivative of spline-smoothed monthly wetland CH_4 anomalies as a metric for quantifying the growth rate of month wetland CH_4 emissions. The time series of CH_4 concentration measurements, derived from NOAA cooperative air sampling network, were processed with a curve fitting method (Thoning *et al.*, 1989) that decomposes the full signal into a long-term growth rate fit by a polynomial function, seasonal oscillations by a harmonic function and a low pass digital filter to retain interannual and short-term variations. From the decomposed signal, we derived the component signals such as trend, growth rate, and annual amplitude. The CH_4 amplitude of the seasonal cycle from Mauna Loa surface site (MLO: 19.53°N, 155.58°W) in NOAA/ESRL was applied to the analysis as a reflection of the strength of CH_4 seasonality, which is mainly controlled by CH_4 uptake and release processes of the land biosphere. Given that the wetlands contribute to the largest portion of natural CH_4 sources and the interannual variability of the major CH_4 sink, hydroxyl radical (OH) is relatively small (Montzka *et al.*, 2011), the changing trends in CH_4 amplitude consequently imply that they are largely affected by changing CH_4 dynamics in the wetland ecosystems. We compared the observed MLO CH_4 amplitude with simulated wetland CH_4 amplitude, which is calculated as the difference between maxima and minima in spline-smoothed monthly wetland CH_4 anomalies within one year, to test whether the simulated shifting patterns of wetland CH_4 dynamics is consistent with observations.

For evaluation of wetland areal changes we used terrestrial water storage (TWS) anomalies, observed by the Gravity Recovery and Climate Experiment (GRACE) satellite measurement, as a proxy for groundwater storage and surface inundation (Bloom *et al.*, 2012; Boening *et al.*, 2012). We used Level-3 monthly solutions from Geo Forschung Zentrum (GFZ), the University of Texas Center for Space Research (CSR), and the Jet Propulsion Laboratory (JPL) from April 2002 to December 2016 to analyze the time variations of the water mass changes in the tropics. The monthly TWS was multiplied by a spatial grid of scaling coefficients derived from post-processing of GRACE observations (Landerer and Swenson, 2012) to restore the

signals attenuated in the processing at small spatial scales. Given the ensemble mean was the most effective in reducing the noise in the gravity fields solutions (Sakumura *et al.*, 2014), we applied the ensemble mean of monthly TWS from three different products in the analysis.

Results and Discussion

Long-term response of wetland CH_4 to ENSO

The ensemble climate simulations indicate a strong link between ENSO and wetland CH_4 emissions, with higher emissions during La Niña and lower emissions during El Niño (Figure 1a). We find a significant negative correlation (d.f. = 443, $p < 0.01$) between the ENSO MEI index and monthly wetland CH_4 anomalies, regardless of the climate data used in the simulations. This is consistent with the findings from bottom-up modeling estimates (Hodson *et al.*, 2011; McNorton *et al.*, 2016; Zhu *et al.*, 2017), atmospheric modeling (Pison *et al.*, 2013; Chen and Prinn, 2006) and satellite observations. For example, the atmospheric CH_4 observations from the Infrared Atmospheric Sounding Interferometer (IASI) aboard METOP and the Atmospheric Infrared Sounder (AIRS) aboard NASA's Aqua satellite also suggest similar findings in that column-averaged dry-air mole fractions of CH_4 (XCH_4) show higher increase in 2007-2008 and 2010-2011 when strong La Niña events occurred (Xiong *et al.*, 2016). Airborne-based estimates of the interannual variability of CH_4 fluxes for eastern Amazon Basin also provides ancillary evidence that the CH_4 emissions are greatest in 2008, a year of La Niña phase (Basso *et al.*, 2016). Recent satellite observations from the Greenhouse gases Observing SATellite (GOSAT) also suggest large-scale fluctuations in atmospheric CH_4 during ENSO events, indicating that wetland CH_4 emissions are ~5% higher during La Niña events (Pandey *et al.*, 2017). The increase in CH_4 emissions from wetlands during La Niña can be attributed predominantly to a large increase in flood extents, primarily over tropical areas (including SE Australia, northern South America, and Southeast Asia) (Boening *et al.*, 2012), whereas the decreases during El Niño are possibly due to drought-induced shrinking of flooded areas. All of the evidence above suggests a robust negative relationship between anomalies of wetland CH_4 emissions and ENSO events, i.e., positive anomalies during La Niña and vice versa.

However, negative anomalies of wetland CH_4 emissions do not necessarily lead to a decrease in the growth rate of wetland CH_4 emissions during El Niño. We find that the growth rate of wetland CH_4 emissions is in a rising phase during strong El Niño events with the amplitudes of the growth rate varied, with the strength dependent on which meteorological forcing was used in the simulations (Figure 1b). This is mainly because strong El Niño events exhibit negative CH_4 growth rates at the beginning of the ENSO anomaly, but then the growth rate rapidly recovers to positive values. Despite that the largely decreased inundations caused declines in CH_4 emissions at the beginning of strong El Niño phases, the extremely high temperatures over the tropics strongly increase the CH_4 growth rate due to higher

soil decomposition rates. Cross-correlation analyses between the monthly growth rate of wetland CH_4 emissions and the MEI index suggest that the peak correlation occurs at a 3-month lag (when ENSO leads $\Delta CH_4/\Delta t$) for the globe. As expected, the timing of wetland response to ENSO varies regionally, where Tropical Asia and Tropical South America exhibit a ~4 month lag and no lag, respectively (Figure S1). The IAV of wetland CH_4 emissions is dominated by the Tropics (30°S-30°N) with relatively small contributions from the Northern Hemisphere (Figures 1c, 1d). MERRA2 showed the highest IAV among all four simulations, whereas the CRU-based simulation had the lowest IAV. The rise of wetland CH_4 emission growth rate is consistent with the observed spikes of atmospheric CH_4 growth rates during strong El Niño events (Dlugokencky *et al.*, 1998).

Impact of 2015-2016 El Niño on wetland CH_4

Annual growth in CH_4 emissions from global wetlands during the 2015-2016 El Niño surpassed any growth rate previously observed, including the growth rate observed during two strong El Niño events, in 1982-1983 and 1997-1998. Our simulations captured the magnitude of this large increase in wetland CH_4 emissions with an instantaneous growth rate of ~7.6±1.6 Tg CH_4 yr^{-1} during 2015-2016 El Niño. The meteorological datasets drove instantaneous growth rates that ranged between 9.2 Tg CH_4 $month^{-1}$, 8.6 Tg CH_4 yr^{-1}, 7.2 Tg CH_4 yr^{-1}, and 5.5 Tg CH_4 yr^{-1} using MERRA2, JRA-55, CRU, and ERA-I, respectively. Although the 2015-2016 El Niño was not as strong as the 1997-1998 El Niño according to the MEI index (~3 in 1997-1998 and ~2.5 in 2015-2016), the combined effect of rising CO_2 concentrations and high temperatures most likely amplified the impact, causing 1.8 times the maximum growth rate of CH_4 of the 1997-1998 El Niño event (mean growth rate of ~4.2±1.4 Tg CH_4 yr^{-1} for the respective time period).

The spatial distribution of wetland CH_4 anomalies demonstrated that the large increases in soil respiration drove the strong growth rate and occurred during the March-April-May (MAM) season in 2016 as a consequence of warming and droughts in this summer (October 2015 - May 2016) (Figure 2). There was a widespread increase in CH_4 emissions over western Amazonia, mainly attributed to increased soil respiration resulting from drought-induced mortality. Despite a large decline in wetland extent due to severe drought, significant positive anomalies in CH_4 emission peaked across the western Amazonian basin, likely due to high temperatures. A number of studies reported that hot and dry conditions during El Niño caused tree mortality and declines in biomass growth and resulted in increased litter and carbon release (Jones and Cox, 2005; Keeling *et al.*, 1995), which is consistent with LPJ-wsl simulated results. Temperature is the primary climatic variable driving the long-term trend and resulting increase in CH_4 emissions (Zhang *et al.*, 2017b). However, precipitation is the dominant climatic variable regulating interannual variability in CH_4 emissions by altering the inundation extent and creating anaerobic conditions suitable for methanogenesis in the tropics (Zhang *et al.*, 2017b). In addition, the higher CO_2 concentrations in 2016 compared to levels during the 1997-1998 El Niño have enhanced the impact of temperature on CH_4 IAV through a

positive feedback on primary production from CO_2 fertilization effects. This has led to increased soil carbon substrate availability for microbial decomposition and a positive feedback is therefore modeled in LPJ-wsl and in most of the land surface models (Wania *et al.*, 2013).

Wetland CH_4 trends between 2000-2006 and post-2007

Using the meteorological reanalysis data, we find evidence for a step increase in global annual wetland emissions between the periods of 2007-2014 relative to that of 2000-2006 (Figure 3a). These simulations suggest that the average annual CH_4 emissions from 2007-2014 increased by ~7.8±1.6 Tg CH_4 yr^{-1} compared to the average of 2000-2006, which is equivalent to an increase in the growth rate of up to ~ 3.5 ppb CH_4 yr^{-1} for the post-2007 period, or about half of the observed increase in concentrations. Interestingly, CRU-based simulation in this study did not show a strong step-increase between these two periods, suggesting an insignificant contribution only from wetlands with a 1.5 Tg CH_4 yr^{-1} increase in the post-2007 resume of the growth rate. This is consistent with the findings from an ensemble modeling experiment using CRU as forcing dataset, which did not result in a significant increase of global wetland CH_4 emissions to the period of renewed atmospheric CH_4 growth (Poulter *et al.*, 2017). Another recent atmospheric modeling study, also using CRU as forcing for their prior inputs, suggested likewise that wetlands made only a small contribution to the post-2007 growth with ~1ppb/yr (McNorton *et al.*, 2016). In contrast, all our simulations using meteorological reanalysis data suggest that more than 90% of the increase in the growth rate of wetland CH_4 is from the Tropics (Table 2), mainly due to increases in precipitation across the South America, Tropical Africa, and Southeast Asia since 2007. MERRA2-based simulations suggest that the post-2007 rise in global CH_4 concentrations primarily comes from South America and Tropical Africa, whereas ERA-I and JRA-55 identify South America as the largest contributor to the CH_4 growth rate (Figure S2).

The different IAV patterns of CH_4 emissions among these simulations suggest that the uncertainties in climate drivers in estimation of CH_4 emissions (Figure 3a). The model experiments demonstrated that the discrepancy is mainly from different model behavior when using products like CRU and meteorological reanalyses like MERRA2, ERA-I, and JRA-55, regardless of the temporal resolution of climate inputs used (Figure S3). We found only minor differences between using daily and monthly temporal resolution, which likely reduced uncertainties from applying the weather generator and thus show that the weather generator covered the internal climatic variability at monthly scale. The importance of considering uncertainty of climate forcing was also reflected in the representation of the seasonal cycle of CH_4 emissions. The comparison of simulated CH_4 emissions with independent estimates using an atmospheric model STILT based on CARVE airborne experiments (Zona *et al.*, 2016) suggested a dominant role of climate forcings in capturing CH_4 seasonality in arctic regions (Figure 3b). MERRA2, ERA-Interim, and JRA-55 underestimated the peak CH_4 emission in growing season but were able to capture the general seasonal

cycle in CH_4 emissions for the North Slope of Alaska, while CRU-based estimates failed to reproduce a similar pattern. The seasonal cycle of CH_4 emissions was also generally underestimated by most bottom-up models that used CRU climate data in a synthesis modeling experiment (Melton *et al.*, 2013), highlighting the need to better constrain the CH_4 emissions by taking into account several datasets that represent climate forcing uncertainty.

Sensitivity of wetland CH_4 emissions to ENSO

To further investigate whether the influence of ENSO on global wetland CH_4 fluctuation was strengthening, we evaluated the average sensitivity of simulated wetland CH_4 emissions and wetland areas in the tropics to ENSO events by calculating the ratio of the annual anomaly of CH_4 emission/wetland area to the annual MEI index for three different time periods, 1980-1999, 2000-2006, and 2007-2016 (Figure 4). We observed a minor change in the sensitivity of CH_4 emissions and wetland areas between 1980-1999 and 2000-2006, which suggest a dampened feedback of global wetland CH_4 emissions to increasing global temperatures. However, the sensitivity became enhancing post-2007. The sensitivity of the modeled results was strongly increased for the period of 2007-2016 relative to the two previous time periods. The sensitivity in CH_4 emissions was increased by ~200% in MERRA2, ERA-I, and JRA-55, whereas the CRU run resulted in a lower percent increase (42%) compared to the other model experiments. The concurrent increase in the sensitivity of CH_4 emissions and wetland areas indicates that the increase of CH_4 emissions since 2007 can mainly be attributed to an increased sensitivity of wetland areas, which was driven by the changing precipitation patterns found in meteorological reanalysis products. The GRACE measurement for relative equivalent water storage confirms the large increase for the period of 2007-2014 compared to earlier periods (Figure 5), suggesting that our simulated increases in tropical wetland areas are robust. All of the modeled wetland areas have significant correlations (d.f.=176, $p < 0.01$) with GRACE TWS, and suggest a ~0.15 Mkm^2 increase in inundation over time period of 2007-2014. This also implies that, despite an observed decline in open water in the tropics (due to the anthropogenic effect from denser population and impact of human activities for the period of 1990s and early 2000s (Prigent *et al.*, 2012)), an increase in precipitation since 2007 was primarily related to La Niña induced precipitation anomalies over Australia, Southeast Asia, and northern South America, which possibly affected wetland patterns and CH_4 emissions globally.

Relationship between wetland CH_4 and atmospheric growth rate

There was a statistically significant (90%-level) positive trend in the simulated annual amplitude of wetland CH_4 emissions, suggesting an increasingly enhanced sensitivity of wetland CH_4 emissions to climate change in recent decades (Figure 6). All model simulations indicated positive trends of the annual amplitude of wetland CH_4 emissions with small differences depending on climate forcings. These simulated positive trends are consistent with observed trends in CH_4 amplitude at

the MLO site, for which MERRA2, ERA-I, and JRA-55 runs were well correlated with MLO observations (d.f. = 30, $p < 0.05$) and only CRU-based simulations showed a weak correlation between wetland CH_4 emissions and enhanced global CH_4 seasonality. These significant correlations suggest that the seasonal amplitude of atmospheric CH_4 concentrations are largely driven by the seasonal cycle of natural wetland emissions. The increasing trends in CH_4 amplitude also imply a high likelihood that there is an underlying shift of CH_4 seasonality in wetland ecosystems and this shift in seasonality is likely greatest in tropical regions.

We found a small, but significant, positive correlation between annual wetland CH_4 emissions and the annual atmospheric CH_4 growth rate in simulations forced by the daily meteorological datasets MERRA2 ($R= 0.31$, d.f.= 33, $p < 0.1$), ERA ($R= 0.36$, d.f.=33, $p < 0.1$), and JRA-55 ($R=0.38$, d.f.=33, $p< 0.05$) for the period of 2000-2015, whereas no significant correlation was found in CRU-based runs ($R=0.07$, d.f.= 33, $p>0.75$). For the period of 1980-1999, none of the simulations showed a significant correlation with the annual atmospheric CH_4 growth rate. The atmospheric CH_4 growth rate is not exclusively a result of changes in wetland emissions, but rather due to a combined influence of anthropogenic and natural sources, and also due to a hydroxyl radical sink (Turner *et al.*, 2017; Rigby *et al.*, 2017). Combined with recent studies reporting the estimated increase in annual CH_4 emissions from global livestock (Wolf *et al.*, 2017) and observed expansion of agricultural areas for rice paddies in Southern Asia (Zhang *et al.*, 2017a), where precipitation has largely increased since 2007, we hypothesize that a combination of tropical wetlands and agricultural sources have most strongly contributed to the resumption in growth rate of atmospheric CH_4 concentrations, which is consistent with the depletion in isotopic signature $^{13}CH_4$ (Schaefer *et al.*, 2016).

Conclusions

We demonstrate that global wetland CH_4 emission anomalies are strongly related to ENSO variability using an extended, multi-meteorological ensemble. At sub-annual time-scales, we also found that the instantaneous growth rate of wetland CH_4 anomalies was positively correlated with ENSO strengths, which provides an explanation for the observed rise of atmospheric CH_4 growth rate during strong El Niño events. The ongoing warming trend, as well as the shifting patterns of global precipitation, has likely had a significant impact on increasing global CH_4 interannual variability. The strong El Niño event in 2015-2016, associated with extreme heat and drought over the Amazonian regions, caused record-high growth rates of wetland CH_4 emissions compared to the previous three decades. We also found an increasing wetland sensitivity to ENSO oscillation since 2007, which we attribute to increased precipitations in the tropics as is visible from three meteorological reanalysis datasets, MERRA2, ERA-Interim, and JRA-55. Our study highlights the need to accurately account for uncertainties in the climate forcing in CH_4 estimations.

Acknowledgements

This study is funded in part by the Gordon and Betty Moore Foundation through Grant GBMF5439 "Quantifying Sources and Sinks in the Global Methane Cycle" to Zhen Zhang, George Hurtt, and Benjamin Poulter. We thank the Competence Center Environment and Sustainability (CCES) project Modeling and Experiments on Land-Surface Interactions with Atmospheric Chemistry and Climate Phase 2 (MAIOLICA2) #42-01, and the National Natural Science Foundation of China (T411391009) for additional funding. We further thank NASA for preparing the MERRA2 dataset, the European Centre for Medium-Range Weather Forecasts for preparing the ERA-Interim dataset, the Japan Meteorological Agency for preparing the Japanese 55-year Reanalysis (JRA-55) dataset, and the Climate Research Unit at the University of East Anglia for providing the CRU dataset. We finally thank the NOAA ESRL Global Monitoring Division for providing CH_4 measurements. We thank Sara H. Knox for constructive comments on the manuscript.

Data availability

The global wetland areal dynamics and CH_4 emissions in this study are available upon request from the corresponding author. Atmospheric CH_4 concentration datasets were obtained from the NOAA ESRL GMD Carbon Cycle Cooperative Global Air Sampling Network (https://www.esrl.noaa.gov/gmd/ccgg/flask.php, last access at August 2017). The annual mean global CH_4 growth rate and monthly trend were derived from NOAA/ESRL ((www.esrl.noaa.gov/gmd/ccgg/trends_ch4/). Terrestrial Water Storage products were derived from the GRACE website (https://grace.jpl.nasa.gov/data/get-data/, last accessed on October 2017). We used the multivariate ENSO index (MEI) (https://www.esrl.noaa.gov/psd/enso/mei/) as indices for representing ENSO strength.

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Figures:

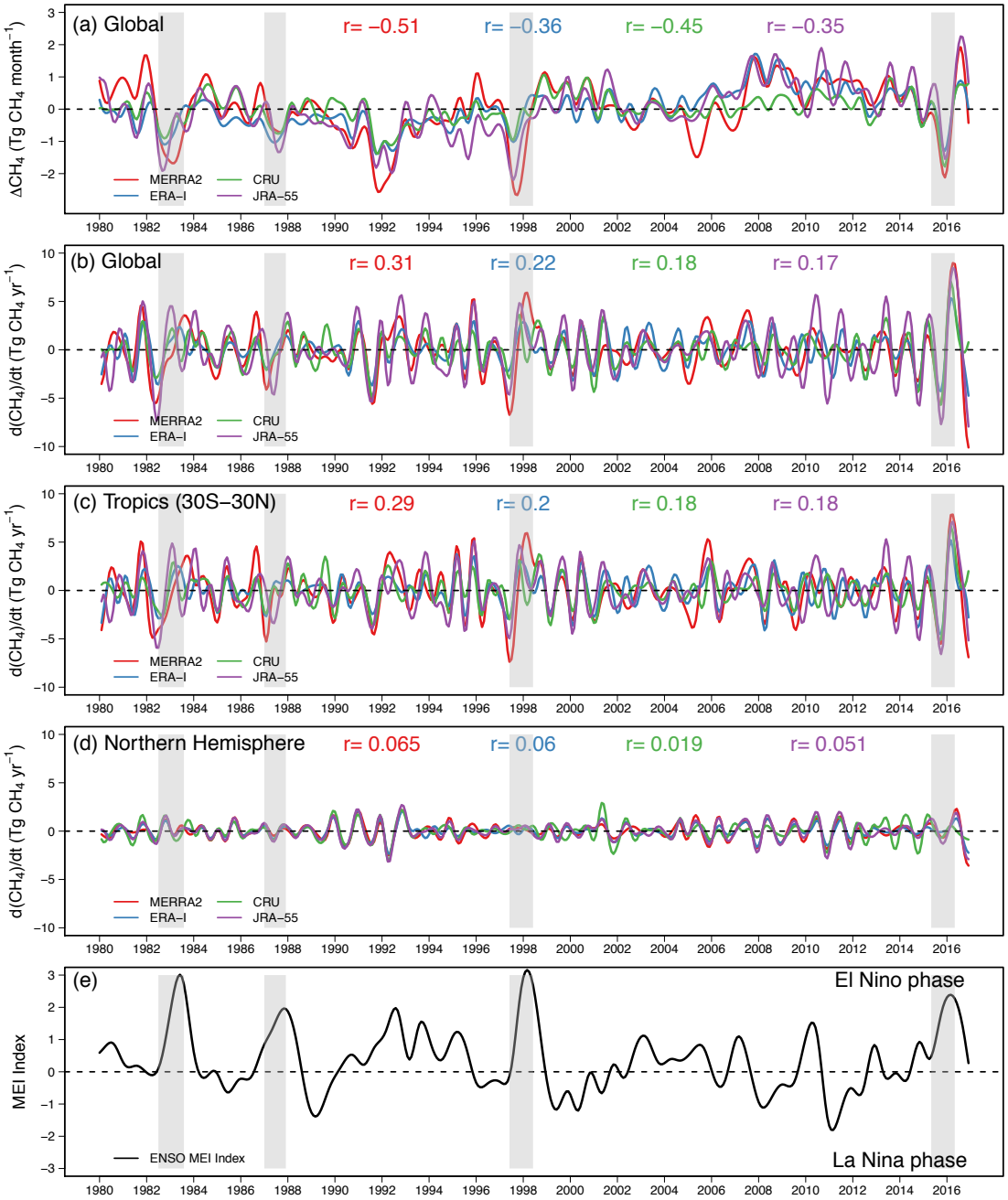

Figure 1. Global anomalies of monthly wetland CH_4 emissions (a) and instantaneous growth rates of wetland CH_4 emission anomalies from 1980 to 2016 for the Global (b), Tropics (middle, 30°S-30°N) (c), and Northern Hemisphere (bottom, >30°N) (d). The global anomalies of wetland CH_4 emissions were calculated relative to monthly average from 1980-2016. The instantaneous growth rate for each simulation is a time derivative of the smoothed monthly CH_4 anomalies using spline functions. The Spearman rank correlation coefficients between the multivariate ENSO index (MEI) and monthly wetland anomalies were derived from cross correlation analyses

(Figure S1) at 3 month lags (Lag= -3), with different colors corresponding to specific runs. Shaded grey areas represent the strong El Niño phases with MEI strength > 60 according to MEI ranks (https://www.esrl.noaa.gov/psd/enso/mei/rank.html, last access at January 2018).

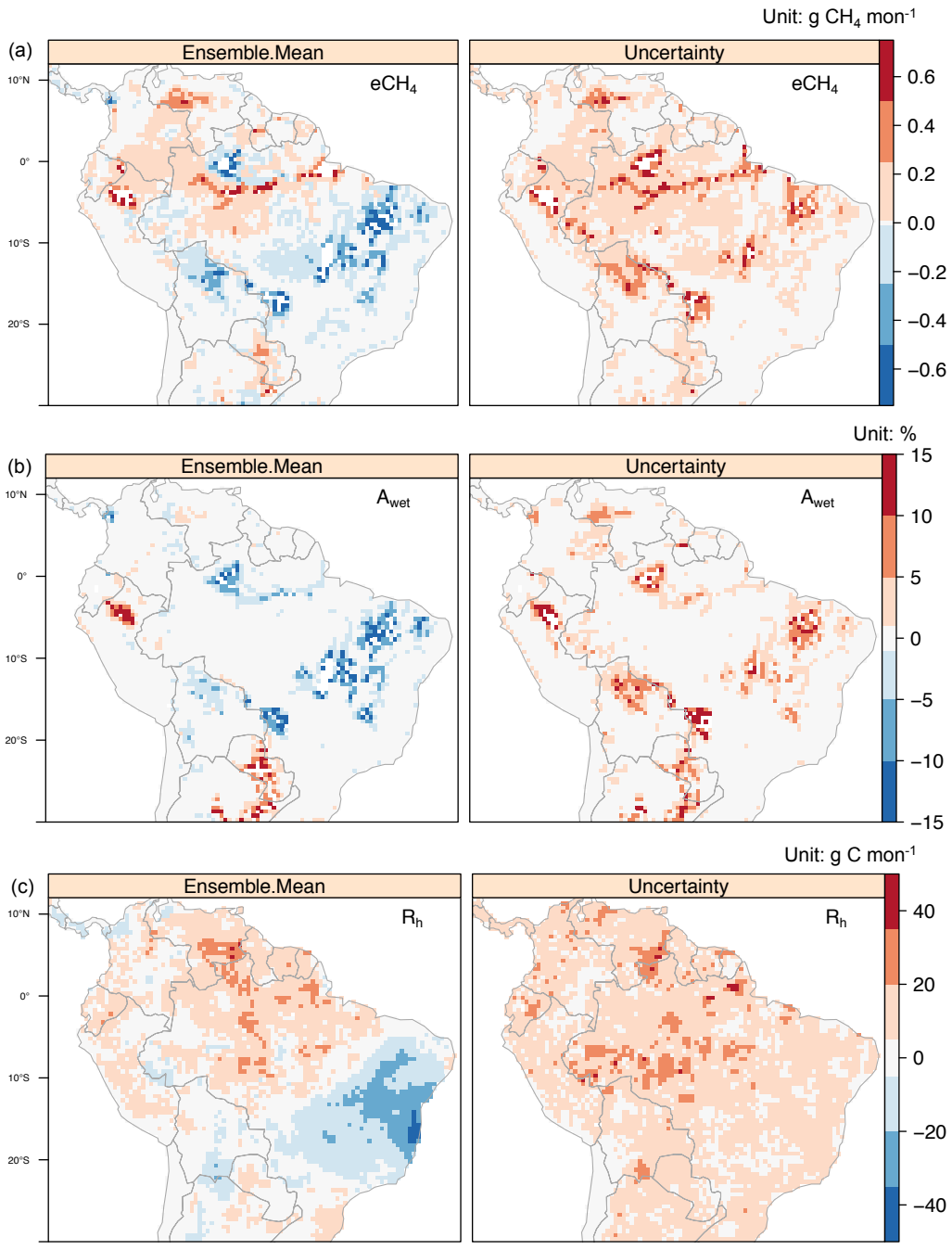

Figure 2. Spatial distributions of seasonal ensemble mean anomalies in wetland CH_4 emissions (a: eCH_4, Unit: g CH_4 m^{-2} mon^{-1}), inundated areas (b: A_{wet}, Unit: %), and heterotrophic respiration (c: R_h, Unit: g C m^{-2} mon^{-1}) of the greater Amazonia region for the March-April-May season, 2016, where eCH_4 shows the highest growth rate during the 2015-2016 ENSO event. The anomalies are calculated as seasonal means during the MAM season of 2016 relative to average over the period of 1980-2016 level, with the uncertainty calculated as one-standard deviation from the four simulations forced by each meteorological dataset.

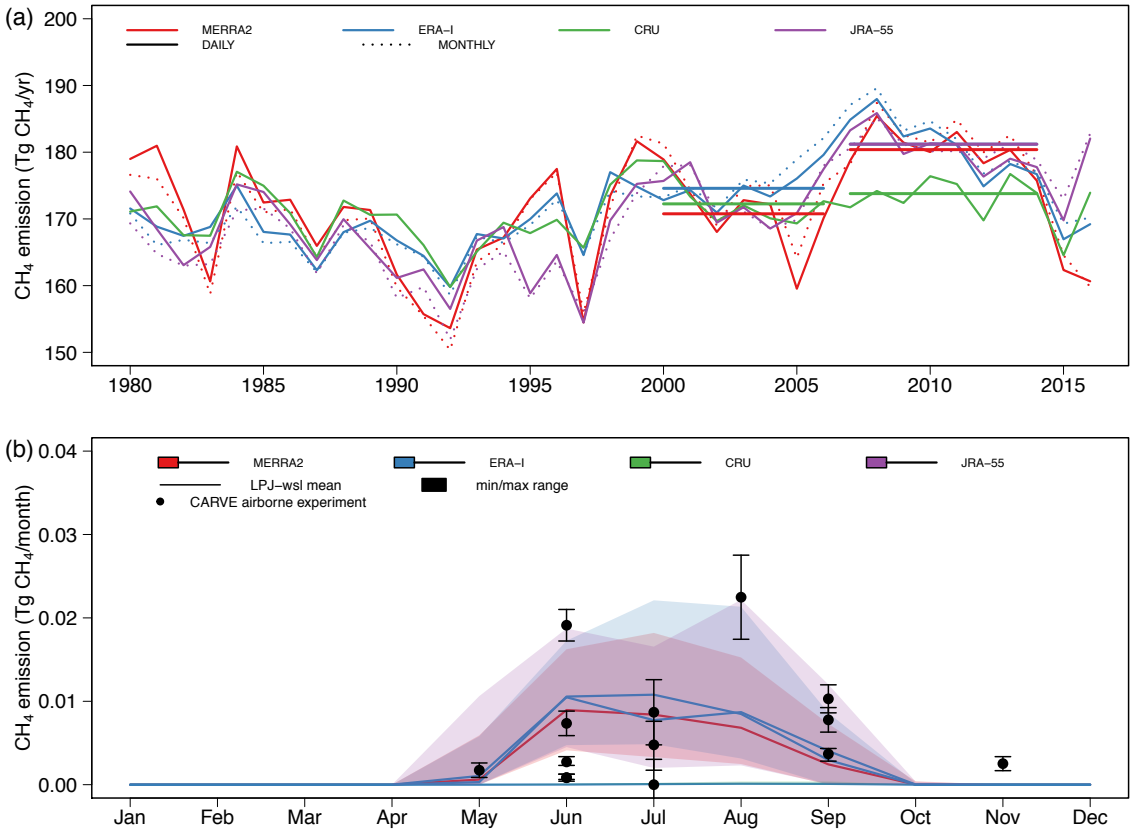

Figure 3. Simulated temporal patterns of CH_4 from all model experiments (see details in Table 1). (a) Time series of annual CH_4 emissions using climate forcings with daily and monthly temporal resolution. The daily forcings were aggregated to monthly values to evaluate the influence of daily variations of climate variables on CH_4 estimations. Solid and dotted lines represent daily and monthly inputs, respectively. The horizontal lines represent averaged annual CH_4 emissions for two time periods, 2000-2006 and 2007-2014, with the different colors representing different climate forcings. (b) Seasonal cycle between LPJ-wsl simulated monthly CH_4 fluxes (black line) using different climate forcings, with min/maximum range (areal shaded) over the Northern Slope of Alaska for 2012-2014 in comparison to the observed regional CH_4 fluxes (dots) estimated from analysis of 15 aircraft flights by the National Aeronautics and Space Administration's Carbon in Arctic Vulnerability Experiment (CARVE).

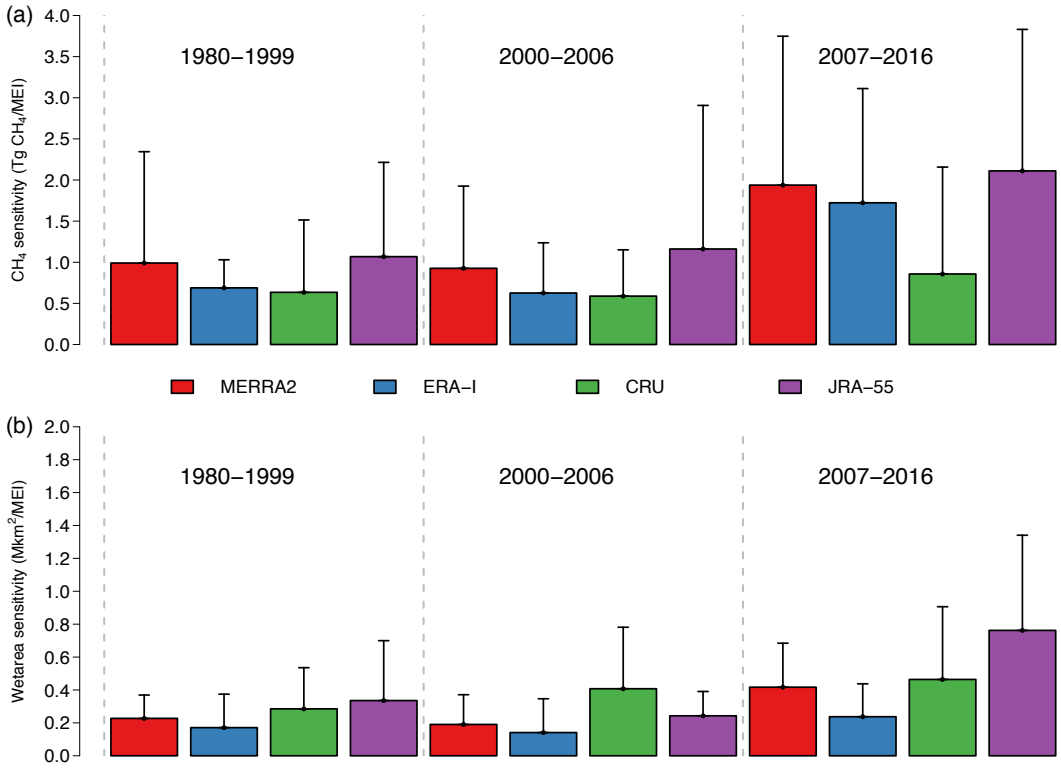

Figure 4. Sensitivity of (a) wetland CH_4 anomalies (Unit: Tg CH_4 /yr/MEI) and (b) wetland area anomalies for the tropics (Unit: Mkm^2/yr/MEI; $Mkm^2 = 10^6\ km^2$) to global ENSO strength for the period of 1980-1999, 2000-2006, and 2007-2016. The sensitivity metric is calculated as the ratio of averaged annual cumulative anomalies of wetland CH_4 emissions and wetland areas to the MEI index. Bars represent the modeled sensitivity from experiments with different forcing datasets, and the error bars represent one standard deviation.

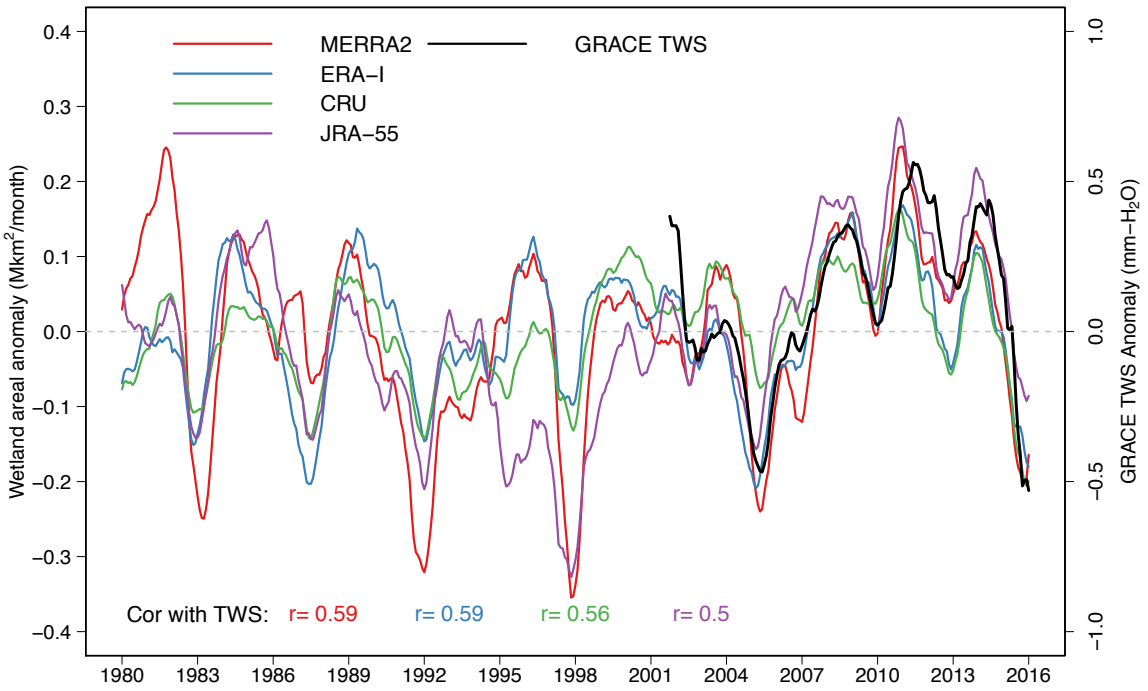

Figure 5. Trends of simulated wetland areal anomalies (Unit: Mkm^2/month; $Mkm^2=10^6\ km^2$) for the tropics (30°S-30°N) compared to area-weighted average terrestrial water storage (TWS; Unit: mm-H_2O) from the ensemble mean of GRACE satellite measurement. The wetland anomalies were calculated relative to the monthly mean of 1980-2016, while TWS anomalies were relative to means of the 2004-2009 period. The fitted trends were calculated by smoothing the monthly anomalies with a 12-month moving average. The Spearman rank correlation coefficients between model and TWS are given for each simulation with different climate forcings in corresponding colors.

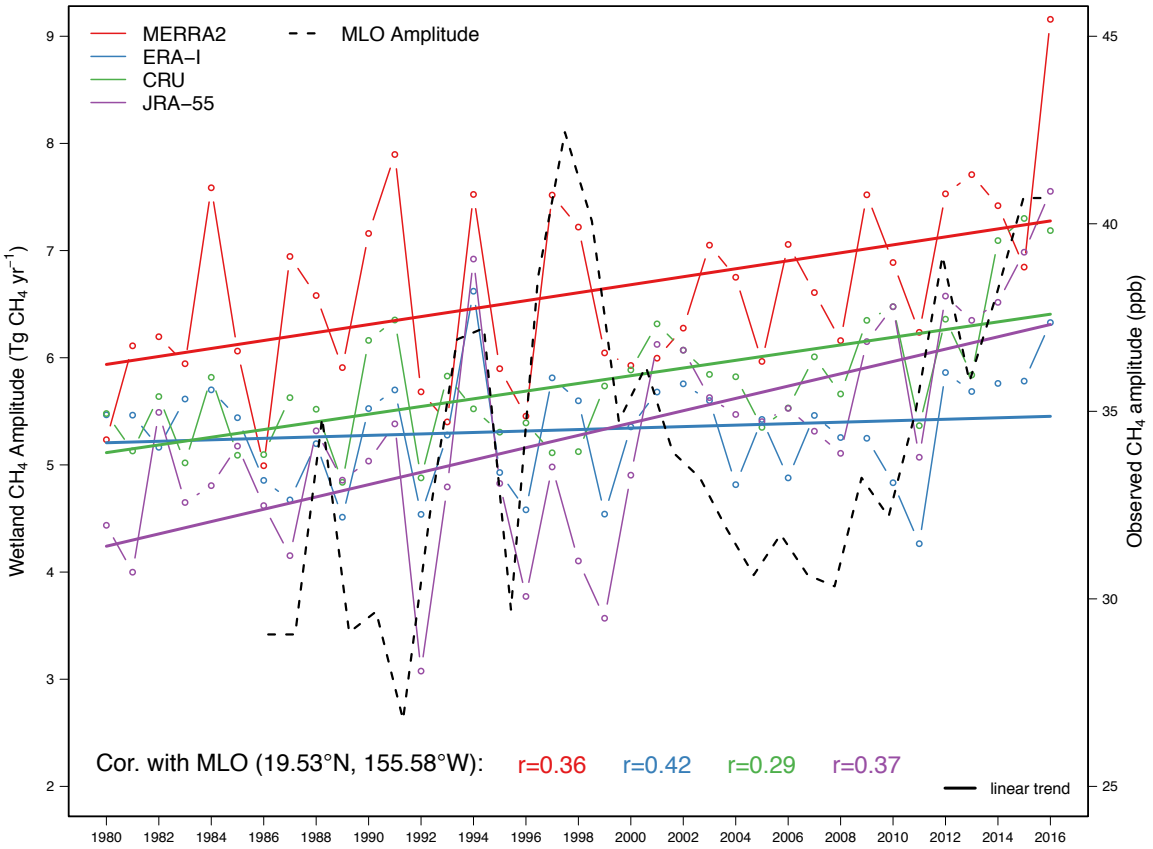

Figure 6. Time series of the seasonal amplitudes of global CH_4 fluxes. The seasonal amplitude of CH_4 fluxes (dashed dotted line) is calculated as the difference between maxima and minima of simulated monthly CH_4 emissions. The dashed black line represents observed peak-to-through seasonal amplitude of atmospheric CH_4 concentration at Mauna Loa observational station. The solid lines represent linear fitted long-term trends of the seasonal CH_4 cycle with Spearman rank correlation coefficients between models and observed amplitudes listed for each model runs in corresponding colors.

Tables:

Table 1. Model experiment descriptions. Climatic variables T, P, SW, LW, CLD, and WETD represent temperature, precipitation, shortwave radiation, longwave radiation, cloud cover, and wet days respectively.

Run ID number	Forcing	Temporal Resolution	Climatic Variables	Time periods
i	MERRA2	Daily	T, P, SW, LW	1980-2016
ii	MERRA2	Monthly	T, P, SW, LW*	1980-2016
iii	ERA-Interim	Daily	T, P, SW, LW	1980-2016
iv	ERA-Interim	Monthly	T, P, SW, LW	1980-2016
v	JRA-55	Daily	T, P, SW, LW	1980-2016
vi	JRA-55	Monthly	T, P, SW, LW*	1980-2016
vii	CRU	Monthly	T, P, CLD, WETD	1901-2016

*CLD and WETD are from CRU for comparison

Table 2. Summary of mean annual CH_4 emissions of the Tropics (30°S-30°N, denoted as TRO), the Northern Extratropics (denoted as NET), and the Southern Extratropics (denoted SET) for 2000-2006, and 2007-2014 from simulations with daily meteorological forcings MERRA2, ERA-I, and JRA-55 and with a spatial-interpolated climate dataset CRU that is based on interpolations from meteorological stations.

Time period	Forcing	eCH_4 (Tg CH_4 yr^{-1})			
		TRO	NET	SET	Global
2000-2006	CRU	138.1	32.3	1.8	172.2
	MERRA2	136.1	32.5	2.1	170.7
	ERA-Interim	142.3	26.6	1.9	170.9
	JRA-55	141.5	29.8	1.8	173.1
2007-2014	CRU	139.1	33.0	1.7	173.8
	MERRA2	145.6	32.8	1.9	180.3
	ERA-Interim	148.6	27.0	1.8	177.4
	JRA-55	147.7	31.1	1.8	180.6

Supplementary Information:

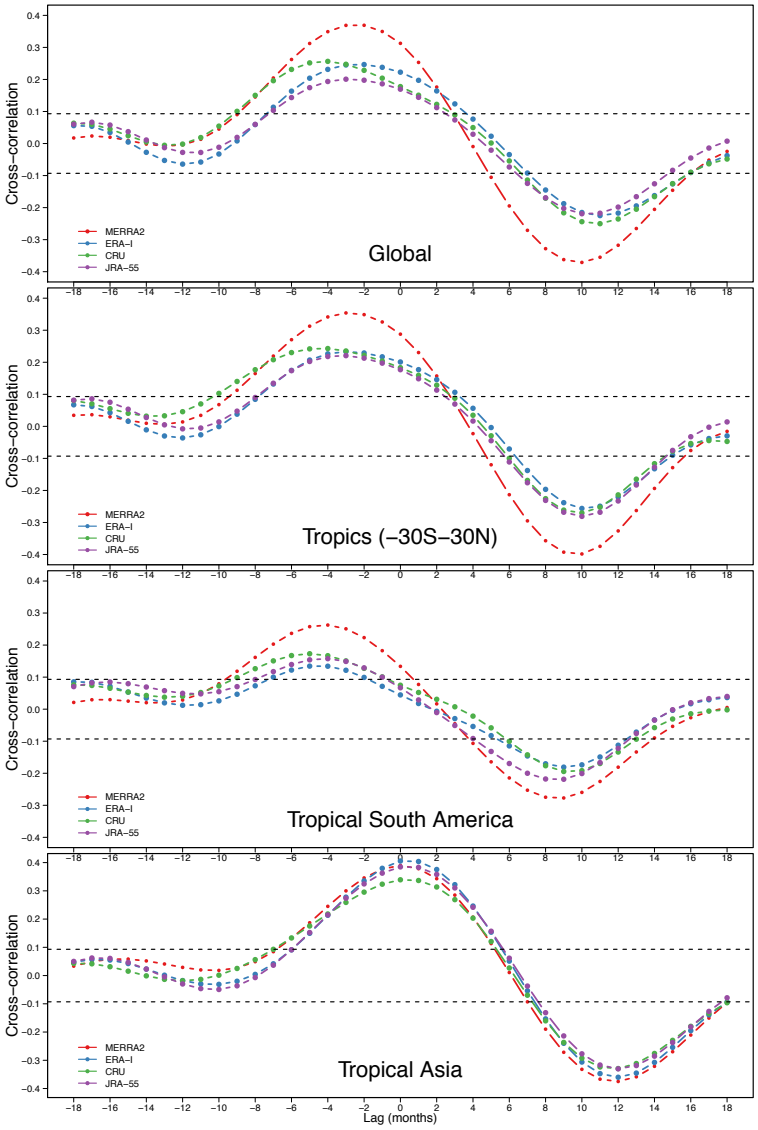

Figure S1. Cross-correlation analysis between ENSO MEI index and instantaneous growth rate of wetland CH_4 anomalies (calculated as time derivative of deseasonalized monthly wetland CH_4 emissions) from four simulations with different forcings (MERRA2, ERA-I, CRU, JRA-55). Dashed horizontal blue lines in all panels represent the 95% confidence interval.

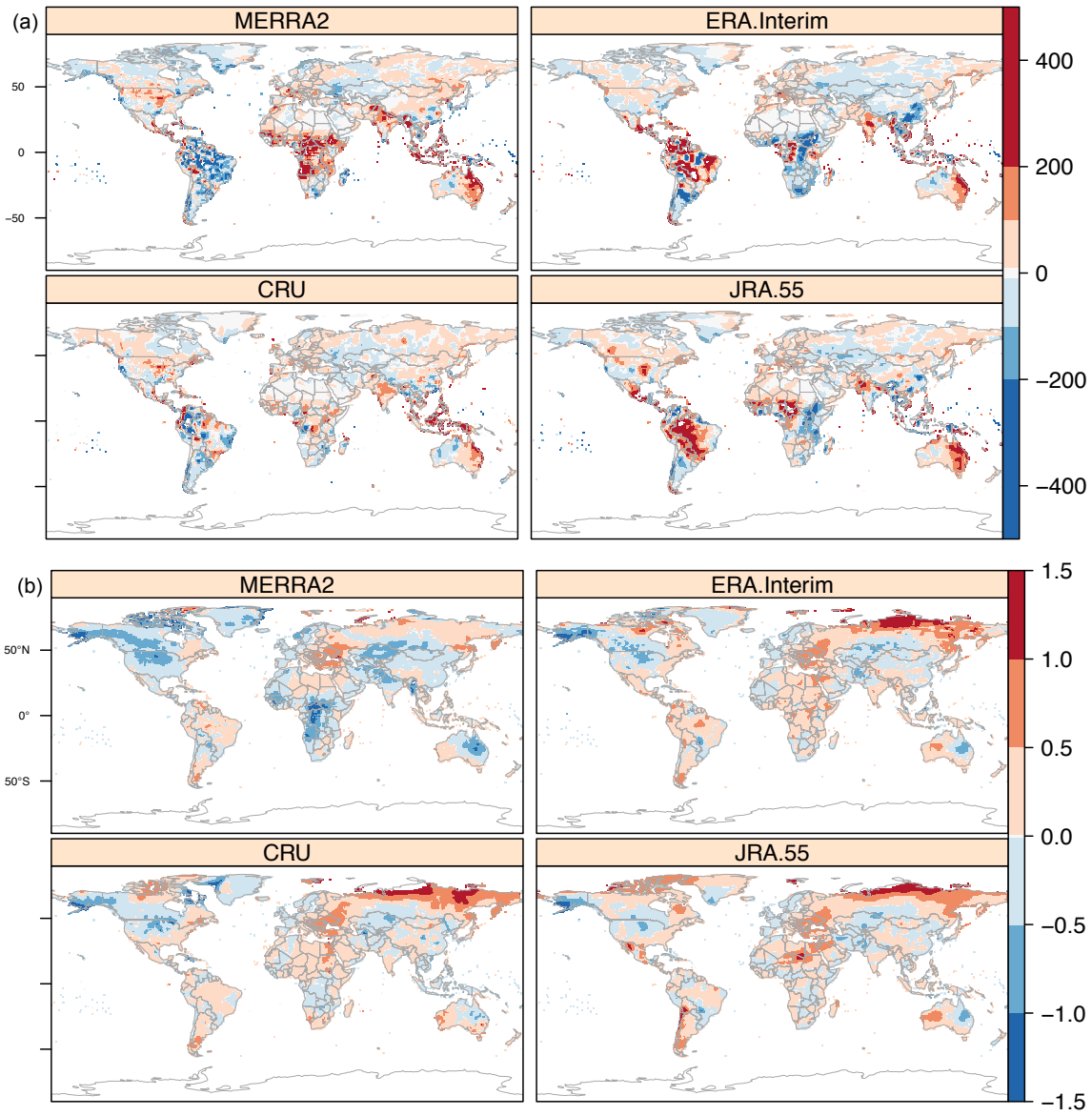

Figure S2. Spatial distribution of the mean difference in (a) precipitation (Unit: mm yr^{-1}) and (b) temperature (Unit: °C yr^{-1}) between 2007-2014 and 2000-2006 for MERRA2 and ERA-Interim.

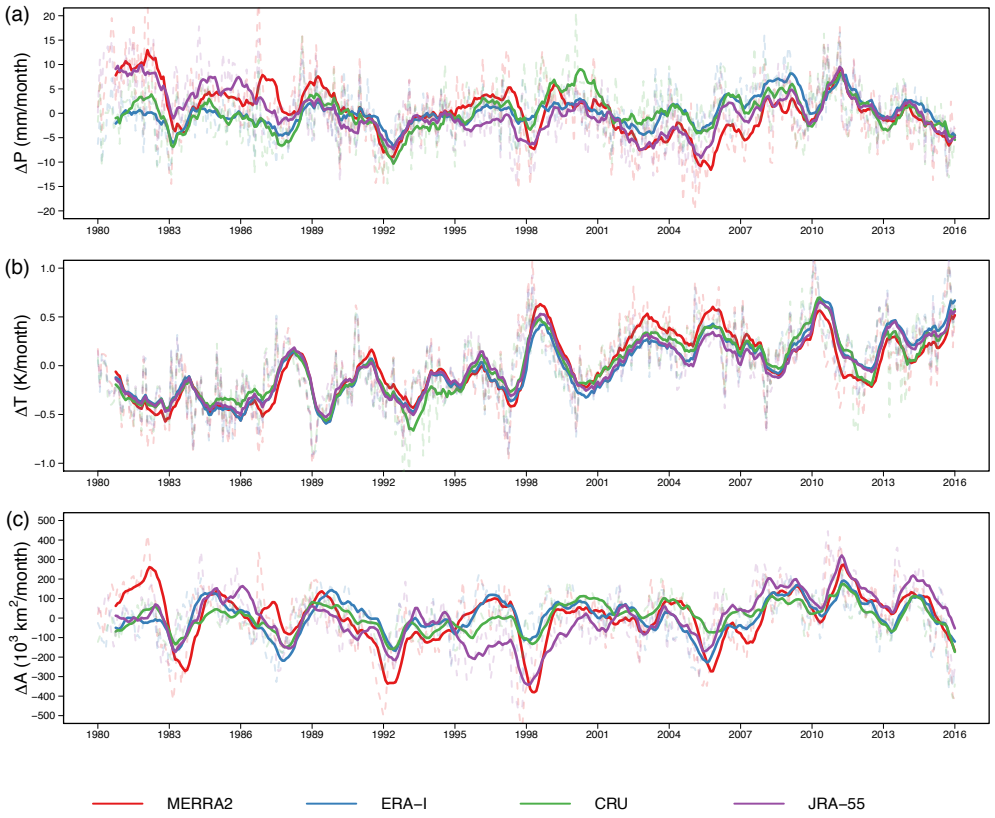

Figure S3. Time series of climate variables and simulated wetland area for the monthly anomalies of (a) precipitation (ΔP), (b) temperature (ΔT), and (c) wetland area (ΔA) in the tropics (30°S-30°N). Monthly anomalies were estimated relative to corresponding long-term monthly mean (1980-2016). Dashed and solid lines represent the monthly anomaly and 12-month moving average respectively.