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Enhanced response of global wetland methane emissions to the 2015–2016 El Niño-Southern Oscillation event

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Abstract

Wetlands are thought to be the major contributor to interannual variability in the growth rate of atmospheric methane (CH4) with anomalies driven by the influence of the El Niño-Southern Oscillation (ENSO). Yet it remains unclear whether (i) the increase in total global CH4 emissions during El Niño versus La Niña events is from wetlands and (ii) how large the contribution of wetland CH4 emissions is to the interannual variability of atmospheric CH4. We used a terrestrial ecosystem model that includes permafrost and wetland dynamics to estimate CH4 emissions, forced by three separate meteorological reanalyses and one gridded observational climate dataset, to simulate the spatio-temporal dynamics of wetland CH4 emissions from 1980–2016. The simulations show that while wetland CH4 responds with negative annual anomalies during the El Niño events, the instantaneous growth rate of wetland CH4 emissions exhibits complex phase dynamics. We find that wetland CH4 instantaneous growth rates were declined at the onset of the 2015–2016 El Niño event but then increased to a record-high at later stages of the El Niño event (January through May 2016). We also find evidence for a step increase of CH4 emissions by 7.8±1.6 Tg CH4 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 CH4 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, and the complex temporal phasing with ENSO, in driving the variability and trends of atmospheric CH4 concentrations. In addition, the need to account for uncertainty in meteorological forcings is highlighted in addressing the interannual variability and decadal-scale trends of wetland CH4 fluxes.

Introduction

Methane (CH4) is a potent greenhouse gas and has contributed to ~20% of observed warming since pre-industrial times (IPCC 2013). Atmospheric CH4 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 CH4 is strongly related to the climatic sensitivity of biogenic CH4 sources, of which global wetland CH4 comprises 60%–80% of natural emissions (Quiquet et al 2015,
Hopcroft et al. (2017) and this large role is likely to persist into the future (Zhang et al. 2017). Thus, interannual variability in 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 such as the El Niño-Southern Oscillation (ENSO). ENSO is one of the largest climate phenomena that drives carbon dynamics and their anomalies across large portions of the globe (Chatterjee et al. 2017).

El Niño, the positive phase of ENSO, influences water- and carbon- fluxes of tropical terrestrial ecosystems through a change in patterns of atmospheric pressure and sea surface temperature (Philander 1990). These changes 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 comprise 50%–70% of global wetland CH$_4$ emissions (Bousquet et al. 2006), are similarly influenced by the periodic variations of air temperature and precipitation related to ENSO phases (Pison et al. 2013). Atmospheric measurements of CH$_4$ provide evidence that the growth rate of global CH$_4$ concentrations can rise during strong El Niño years (Nisbet et al. 2016, Bousquet et al. 2006), but terrestrial biogeochemical models 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).

At decadal time scales, the relationship between the annual CH$_4$ growth rate and variability in global wetland CH$_4$ emissions is not fully agreed upon, and the observed pause in the growth rate during 2000–2006 and subsequent return of the growth rate since 2007 (Nisbet et al. 2014) is not fully understood. A recent study suggests that global wetlands have played a limited role during the renewed rise of the growth rate through 2012 (Poulter et al. 2017). However, isotopic measurements indicate that the resumed increase in the growth rate could originate either from biogenic sources (Schwietzke et al. 2016) like tropical wetlands (Nisbet et al. 2016), from agricultural sources (Schaefer et al. 2016), or from the combined effect of decreased biomass burning (Worden et al. 2017) and increased fossil-fuel emissions (Helmig et al. 2016). In addition, simple-box models and more complex atmospheric inversion models can attribute the recent CH$_4$ change to varying hydroxyl radical (OH) concentration, the major CH$_4$ sink in the atmosphere (Turner et al. 2017, Rigby et al. 2017). Our poor understanding of wetland CH$_4$ responses at annual to decadal time scales calls for revisiting the role of relationships between climate forcings and wetland CH$_4$ fluxes to help reconcile top-down and bottom-up methodologies.

Previous El Niño anomalies, in years 1982–1983, 1997–1998, and 2015–2016, had significant impacts on terrestrial ecosystems and these events were considered key drivers of the atmospheric CO$_2$ growth rate variability (Liu et al. 2017). The most recent El Niño event (2015–2016) caused unprecedented warming and extreme drought 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 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). The more recent El Niño event may have also contributed to record warming during 2015 and the first third of 2016, with global air temperature at 0.94 °C above the 20th century mean annual average (www.ncdc.noaa.gov/sotc/global/201613, last access in 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 phase and 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 are the major mechanisms that link wetland CH$_4$ emissions to the atmospheric increases observed since 2007?

### Methods

We use a process-based ecosystem model LPJ-wsl (Lund-Potsdam-Jena model, WSL version) forced with four different meteorological forcings to simulate wetland CH$_4$ emissions from 1980–2016. These drivers include one station-based monthly geo-interpolation dataset (CRU) and three meteorological reanalyses products (table 1). We use multiple climate datasets to investigate uncertainty from meteorological forcing driving simulated atmospheric CH$_4$ concentrations, and hence, to better characterize CH$_4$ variation in response to climate variations.

| Run ID | 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-1 Daily                | T, P, SW, LW       | 1980–2016    |
| iv    | ERA-1 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.
LPJ-wsl (Poulter et al 2011) is a process-based dynamic global vegetation model (DGVM) developed for studying terrestrial ecosystems, based on an earlier LPJ core model (Sitch et al 2003). The version of the model applied in this study includes a new hydrology 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\textsubscript{4} emission model (Hodson et al 2011), each of which is incorporated into the LPJ-wsl framework with explicit representation of the effects of snow and freeze/thaw cycles on soil temperature and moisture and thus CH\textsubscript{4} emissions (Zhang et al 2016). We apply an empirical model to estimate CH\textsubscript{4} emissions in the model which is based on soil respiration, inundated area, and a temperature-based ecosystem emission efficiency (Christensen et al 1996). Soil respiration is modelled empirically in response to temperature and soil moisture based on an Arrhenius type equation where varying effective activation energies for respiration and a dampening of the temperature sensitivity (Q\textsubscript{10}) due to acclimation were considered (Sitch et al 2003). The simulated dynamics of wetland area and CH\textsubscript{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\textsubscript{4} emitting factors by scaling simulated global estimates to match 172 Tg CH\textsubscript{4} yr\textsuperscript{-1} in 2004, which was estimated from an independent atmospheric inversion study (Spahni et al 2011), and is in agreement with independent satellite-based methods from Bloom et al (2010). We improved inundation estimates by calibrating the TOPMODEL parameter ‘maximum inundation potential’ (\textit{I}_{\text{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), an inventory-based dataset Global Lakes and Wetlands Database (GLWD) (Lehner and Döll 2004), and 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 our simulated wetland area includes seasonally inundated wetlands, e.g. floodplains, and perennially inundated vegetated wetlands, but excludes rice agriculture, non-vegetated reservoirs, medium to large sized lakes, rivers, and coastal wetlands that are not accounted for by the GLWD.

The climate datasets included the monthly meteorology from the Climate Research Unit (CRU) TS 3.25 (Harris et al 2014) and three state-of-the-art metrological reanalysis products. The reanalysis products were comprised of 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-1) (Dee et al 2011) from the European Centre for Medium-Range Weather Forecasts (ECMWF) data assimilation system and, and lastly, a 6 hourly Japanese 55 year Reanalysis (JRA-55) (Kobayashi et al 2015) from the Japan Meteorological Agency. The reanalysis data (total precipitation, 2 m air temperature, downward shortwave radiation, and downward longwave radiation) were aggregated to a common daily time-step and downscaled to 0.5° spatial resolution grid using first order conservative interpolation. The soils dataset we used was the Harmonized World Soil Database v1.2 (Nachtgeraele et al 2008) and using pedotransfer functions of the surface soil texture (Cosby et al 1984) to estimate volumetric water holding capacity. 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 daily photosynthetically active radiation flux and potential evapotranspiration (Prentice et al 1993). Additional details of the climate datasets and model experiments are in the supplementary material (table S1 available at stacks.iop.org/ERL/13/074009/mmedia). 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) (Hurt et al 2011). Spin-up was done using randomly selected climate inputs from 1901–1930 for CRU and 1980–2000 for reanalysis with fixed atmospheric CO\textsubscript{2} to the 1860 value. After equilibrium, a transient simulation with fire effects and varying land cover was performed for the years 1901–2016 (for CRU) and 1980–2016 (for reanalysis), forced with changing climate conditions and varying atmospheric CO\textsubscript{2} concentration (www.esrl.noaa.gov/ccgg/trends, last access at August 2017). The simulations consider gross land-use transitions (with no wood harvest) with primary and secondary lands treated separately (for details, see Arneth et al 2017), where the soil moisture and soil respiration were calculated by fraction-weighting individual land stands within a grid cell.

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 previous studies (Fang et al 2017, Liu et al 2017) have shown a hysteresis in the Earth systems response to changes in temperature and precipitation patterns, we carried out a cross-correlation analysis to examine possible time-lag effects of wetland CH\textsubscript{4} response to El Niño events.
To test whether annual wetland CH$_4$ 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 (www.esrl.noaa.gov/gmd/ccgg/flask.php, last access at August 2017). We then used the first derivative of spline-smoothed monthly wetland CH$_4$ anomalies to calculate the wetland CH$_4$ instantaneous growth rate. 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 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 an indicator of the strength of CH$_4$ seasonality in the northern tropics, where CH$_4$ amplitude is mainly controlled by OH and fluxes from the land biosphere. Given that wetlands contribute the largest fraction of natural CH$_4$ sources and that the interannual variability of OH is relatively small (Montzka et al 2011), the changing trends in the CH$_4$ amplitude consequently imply that the variation in the trend is largely affected by changing CH$_4$ dynamics in wetland ecosystems. To test whether the shifting spatio-temporal patterns of simulated wetland CH$_4$ dynamics are consistent with observations, we compared the observed MLO CH$_4$ amplitude with simulated wetland CH$_4$ amplitude, which was calculated as the difference between annual maxima and minima in spline-smoothed monthly wetland CH$_4$ anomalies.

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 the Level-3 monthly ‘solutions’, version RL05, from Geo Forschung Zentrum, the University of Texas Center for Space Research, and the Jet Propulsion Laboratory from April 2002 to December 2016 to analyze the temporal variations of water mass 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. We used the ensemble mean of monthly TWS from three different products in the analysis because the ensemble mean was the most effective in reducing the noise in gravity fields solutions from GRACE data (Sakumura et al 2014).

**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 1(a)). We find significant negative correlations ($r_{\text{MERRA2}} = -0.51$, $r_{\text{ERA-40}} = -0.36$, $r_{\text{CRU}} = -0.45$, $r_{\text{JRA-55}} = -0.35$, $p < 0.01$) between the ENSO MEI index and monthly wetland CH$_4$ anomalies, regardless of the climate data used in the simulations. This is consistent with 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 instance, the atmospheric CH$_4$ variations of the mid-troposphere measured by the Infrared Atmospheric Sounding Interferometer aboard METOP satellite, and by the Atmospheric Infrared Sounder aboard NASA’s Aqua satellite, also show higher increases 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 provide 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 to a large increase in flood extent, 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 decreases in flooded area. All of the evidence above suggests a robust negative relationship between annual anomalies of wetland CH$_4$ emissions and ENSO events, i.e. positive anomalies during La Niña and vice versa.

However, negative anomalies of annual wetland CH$_4$ emissions do not necessarily lead to a decrease in the instantaneous growth rate of wetland CH$_4$ emissions during El Niño. We find that the growth rate of wetland CH$_4$ emissions is initially decreased but then is in a rising phase during the later stages of strong El Niño events. Although, the amplitude of the rising varied depending on which meteorological forcing was used in the simulations (figure 1(b)). This is mainly because strong El Niño events drive negative wetland CH$_4$ growth rates at the beginning of the ENSO anomaly, but then the growth rate rapidly recovers to positive values. Despite positive atmospheric methane growth rate correlations with El Niño events, the general decline in wetland area causes declines in wetland CH$_4$ emissions at the beginning of strong
El Niño phases. The high temperatures over the tropics strongly increase the CH₄ growth rate due to higher soil decomposition rates during the later stages of the 2015–2016 El Niño event. Cross-correlation analyses between the monthly growth rate of wetland CH₄ emissions and the MEI index suggest that the peak correlation occurs at a 3 month lag (when ENSO leads ΔCH₄/Δt) 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 Interannual Variability (IAV) of wetland CH₄ emissions is dominated by the tropics (30°S–30°N) with relatively small contributions from the Northern Hemisphere (figures 1(c) and (d)). MERRA2 showed the highest IAV among all four simulations, whereas the CRU-based simulation had the lowest IAV. The rise of wetland CH₄ emission growth rate is consistent with the observed spikes of atmospheric CH₄ growth rates during strong El Niño events (Nisbet et al 2016).
Impact of 2015–2016 El Niño on wetland CH$_4$

The amplitude of instantaneous growth in wetland CH$_4$ emissions during the 2015–2016 El Niño was higher than that in the previous periods 1982–1983 and 1997–1998, suggesting an increased sensitivity of wetland CH$_4$ in response to the recent El Niño (figure 1(b)). Our results captured the magnitude of this large increase in wetland CH$_4$ emissions with an instantaneous growth rate of $\sim 7.6 \pm 1.6$ 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 ($\sim 3$ in 1997–1998 and $\sim 2.5$ 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 $\sim 4.2 \pm 1.4$ 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 the wet season (October 2015–May 2016) (figure 2). There was a widespread increase in CH$_4$ emissions over western Amazonia, mainly attributed to increased soil respiration. 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. Temperature is the primary climatic variable driving the increasing long-term trend 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).

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 3(a)). These simulations suggest that the average annual CH$_4$ emissions from 2007–2014 increased by $\sim 7.8 \pm 1.6$ 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 $\sim 3.5$ ppb CH$_4$ yr$^{-1}$ for the post-2007 period, or about half of the observed increase in concentrations. The CRU-based simulation in this study did not show a strong step-increase between these two periods, suggesting only a marginal contribution from wetlands with a 1.5 Tg CH$_4$ yr$^{-1}$ increase in the post-2007 growth rate. This is consistent with findings from an ensemble modeling experiment using CRU as a forcing dataset, which found no significant increase of global wetland CH$_4$ emissions during 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, likewise suggested that wetlands made only a small contribution to the post-2007 growth at $\sim 1$ ppb yr$^{-1}$ (McNorton et al 2016).

In contrast to the CRU simulations just listed, 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), and mainly due to increases in precipitation across 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 considerable uncertainties in CH$_4$ emissions due to climate drivers (figure 3(a)). The model experiments demonstrated that the discrepancy originates 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 using a daily or monthly temporal resolution, which likely reduced uncertainties from applying the simulated 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 3(b)). MERRA2, ERA-I, and JRA-55 underestimated the peak CH$_4$ emission in

| 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-I   | 142.3                         | 26.6| 1.9 | 170.9|
|                  | JRA-55  | 141.5                         | 29.8| 1.8 | 173.1|
| 2007–2014        | CRU     | 139.1                         | 35.0| 1.7 | 173.8|
|                  | MERRA2  | 145.6                         | 32.8| 1.9 | 180.3|
|                  | ERA-I   | 148.6                         | 27.0| 1.8 | 177.4|
|                  | JRA-55  | 147.7                         | 31.1| 1.8 | 180.6|

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.
Figure 2. Spatial distributions of seasonal ensemble mean anomalies in wetland CH$_4$ emissions (a): (eCH$_4$, Unit: g CH$_4$ 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.

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. To this means we calculated 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 suggests a subtle change in the response of global wetland CH$_4$ emissions to increasing global temperatures. However, the sensitivity of the modeled results strongly increased for the period of 2007–2016 relative to the two previous time periods. The sensitivity in CH$_4$ emissions increased by $\sim$200% in MERRA2, ERA-I, and JRA-55, whereas the CRU run resulted in a lower percent increase (42%) compared to the other model experiments. The concurrent increase in the sensitivity of CH$_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 ($r_{\text{MERRA2}} = 0.59$, $r_{\text{ERA-I}} = 0.59$, $r_{\text{CRU}} = 0.56$, $r_{\text{JRA-55}} = 0.5$, d.f. = 176, $p < 0.01$) with GRACE TWS, and suggest a $\sim 150 \, 10^3 \, \text{km}^2$ increase in inundation over time period of 2007–2014. This also implies that, despite an observed decline in open waters in the tropics (due to the anthropogenic effect from denser populations and impacts from human activities for the period of 1990s and early 2000s (Prigent et al. 2012)), the enhanced precipitation since 2007 (Sun et al. 2017, Rodell et al. 2018) was primarily related to the ENSO phase over tropical land, which has affected wetland patterns and CH$_4$ emissions globally.

**Relationship between wetland CH$_4$ and atmospheric growth rate**

There was a statistically significant ($p < 0.10$) 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 correlated with MLO observations ($r_{\text{MERRA2}} = 0.36$, $r_{\text{ERA-I}} = 0.42$, $r_{\text{CRU}} = 0.29$, $r_{\text{JRA-55}} = 0.37$, d.f. = 30, $p < 0.05$) and only CRU-based simulations showed a weak correlation between
wetland \( \text{CH}_4 \) emissions and enhanced global \( \text{CH}_4 \) seasonality. These significant correlations suggest relationships between atmospheric \( \text{CH}_4 \) seasonality and natural wetland emissions, despite the major role of OH in determining \( \text{CH}_4 \) seasonality. The increasing trends in \( \text{CH}_4 \) amplitude also imply a high likelihood that there is an underlying shift of \( \text{CH}_4 \) 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 \( \text{CH}_4 \) emissions and the annual atmospheric \( \text{CH}_4 \) growth rate in simulations

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**Figure 4.** Sensitivity of (a) wetland \( \text{CH}_4 \) anomalies (unit: Tg \( \text{CH}_4 \) yr MEI\(^{-1} \)) and (b) wetland area anomalies for the tropics (unit: Mkm\(^2\) yr MEI\(^{-1} \); 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 \( \text{CH}_4 \) 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\(^{-1} \) Mkm\(^2\) = \( 10^6 \) km\(^2 \)) for the tropics (30\(^\circ\)S–30\(^\circ\)N) compared to area-weighted average terrestrial water storage (TWS; unit: mm H\(_2\)O) 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.
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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.

forced by the daily meteorological datasets MERRA2 ($r = 0.31$, d.f. = 33, $p < 0.1$), ERA-1 ($r = 0.36$, 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). Recent studies have reported an increase in annual CH$_4$ emissions from global livestock (Wolf et al 2017) and an expansion of agricultural areas for rice paddies in southern Asia (Zhang et al 2017a), a region where precipitation has largely increased since 2007. Thus, we hypothesize that a combination of tropical wetlands and agricultural sources are likely responsible for the resumed growth rate of atmospheric CH$_4$ concentrations, which is consistent with the depletion in the global isotopic signature in $^{13}$CH$_4$ (Schaefer et al 2016) and with regional measurements of $^{13}$CH$_4$ in the tropics (Nisbet 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 sensitivity of wetland CH$_4$ emissions to ENSO oscillation since 2007, which we attribute to increases in the areal extent of tropical wetlands from increased precipitation. Our study also highlights the need to account for uncertainty in the climate forcing for estimating wetland CH$_4$ emissions.

Data availability

The data that support the findings of this study are available upon request, for access please contact Z Zhang (yuisheng@gmail.com). Atmospheric CH$_4$ concentration datasets were obtained from the NOAA ESRL GMD Carbon Cycle Cooperative Global Air Sampling Network (www.esrl.noaa.gov/gmd/ccgg/flask.php, last access at August 2017). The annual
mean global CH4 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) (www.esrl.noaa.gov/psd/enso/mei/, last access at October 2017) as indices for representing ENSO strength.

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