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Interannual variation in methane emissions from tropical wetlands triggered by repeated El Niño Southern Oscillation

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Abstract

Methane (CH_4) emissions from tropical wetlands contribute 60%–80% of global natural wetland CH_4 emissions. Decreased wetland CH_4 emissions can act as a negative feedback mechanism for future climate warming and vice versa. The impact of the El Niño–Southern Oscillation (ENSO) on CH_4 emissions from wetlands remains poorly quantified at both regional and global scales, and El Niño events are expected to become more severe based on climate models' projections. We use a process-based model of global wetland CH_4 emissions to investigate the impacts of the ENSO on CH_4 emissions in tropical wetlands for the period from 1950 to 2012. The results show that CH_4 emissions from tropical wetlands respond strongly to repeated ENSO events, with negative anomalies occurring during El Niño periods and with positive anomalies occurring during La Niña periods. An approximately 8-month time lag was detected between tropical wetland CH_4 emissions and ENSO events, which was caused by the combined time lag effects of ENSO events on precipitation and temperature over tropical wetlands. The ENSO can explain 49% of interannual variations for tropical wetland CH_4 emissions. Furthermore, relative to neutral years, changes in temperature have much stronger effects on tropical wetland CH_4 emissions than the changes in precipitation during ENSO periods. The occurrence of several El Niño events contributed to a lower decadal mean growth rate in atmospheric CH_4 concentrations throughout the 1980s and 1990s and to stable atmospheric CH_4 concentrations from 1999 to 2006, resulting in negative feedback to global warming.

KEYWORDS
atmospheric methane, El Niño–Southern Oscillation, methane emission, tropical wetlands

1 | INTRODUCTION

Methane (CH_4) is an important greenhouse gas that is directly responsible for approximately 20% of climatic warming caused by greenhouse gases in the industrial era (IPCC, 2013). Indeed, the global atmospheric CH_4 burden has more than doubled since the industrial era. The growth rate of atmospheric CH_4 has decreased, however, from approximately 13 ppb/year during the early 1980s to near zero between 1999 and 2006. Since 2007, the growth rate of atmospheric CH_4 has risen again (Dlugokencky et al., 2009; Nisbet, Dlugokencky, & Bousquet, 2014; Saunois et al., 2016; Schaefer et al., 2016). The factors that contribute to the period of near-stable atmospheric CH_4 levels (1999–2006) and the subsequent period of resumed growth (since 2007) remain poorly understood (Kirschke et al., 2013; Nisbet et al., 2014). The attribution of atmospheric CH_4 growth rates to decadal-scale changes in anthropogenic or natural sources is difficult not only because current networks of ecosystem and atmospheric measurements are insufficient for characterizing emissions by regions and source and sink processes but also because vegetation and atmospheric inversion models are associated with significant uncertainties.

In addition to decadal changes, global measurements of CH_4 concentrations show large year-to-year interannual variations (IAVs). Both bottom-up (ecosystem modeling) and top-down (atmospheric inversion modeling) approaches agree that natural wetlands, a climate-sensitive CH_4 source, and the largest natural source of the global methane budget dominate year-to-year changes in CH_4 emissions with the tropical maximum IAV occurring between 30°S and 30°N (Bousquet et al., 2006; Kirschke et al., 2013). Wetland methane emissions typically reach maximum levels in tropical regions (30°S and 30°N) with a secondary maximum in the summer at high latitudes (Matthews & Fung, 1987; Melton et al., 2013). Recent studies have shown that CH_4 emissions from tropical regions contribute 25% of global CH_4 emissions and approximately 50% of global IAV (Bousquet et al., 2006; IPCC, 2013; Kirschke et al., 2013; Melton et al., 2013; Saunois et al., 2016). Thus, climate-induced changes in tropical wetland emissions can have a significant impact on future atmospheric CH_4 levels.

Locally, tropical wetland emissions are sensitive to variations in temperature, precipitation, and water table depth as well as to biotic variables, such as the volume of carbon substrates available for methanogenesis. Wetland methane emissions are sensitive to temperature and precipitation levels (Gedney, Cox, & Huntingford, 2004; Westermann, 1993); for example, they have been observed to respond to warmth and flooding (Bridgham, Cadillo-Quiroz, Keller, & Zhuang, 2013). Particularly for tropical wetland, between 2007 and 2014, increased tropical wetland CH_4 emissions reflected their responses to meteorological change (Nisbet et al., 2016). The El Niño–Southern Oscillation (ENSO) is the dominant mode of interannual climate variability affecting the tropics, and El Niño events are associated with decreased rainfall levels and warmer temperatures (Mcphaden, Zebiak, & Glantz, 2006). Previous studies (Fiore, Horowitz, Dlugokencky, & West, 2006; Hodson, Poulter, Zimmermann, Prigent, & Kaplan, 2011; Warwick, Bekki, Law, Nisbet, & Pyle, 2002) have shown that the IAV in global atmospheric CH_4 concentration is affected by ENSO patterns. Consequently, future changes in ENSO frequency and intensity may significantly affect atmospheric CH_4 concentrations and climate change trends (Cai et al., 2014). Here, we use a process-based model for natural wetland CH_4 emissions—TRIPLEX-GHG (Zhu et al., 2014)—to simulate the impact of the ENSO on tropical wetland CH_4 emissions between 1950 and 2012 and to assess how the ENSO has contributed to CH_4 wetland emissions IAV. We emphasize the effects of climate variability on tropical wetland CH_4 emissions, which should be considered when considering scenarios of future CH_4 emissions.

2 | MATERIALS AND METHODS

2.1 | TRIPLEX-GHG model

The TRIPLEX-GHG (Zhu et al., 2014), which is a new process-based dynamic global wetland CH_4 model that integrates biogeochemical-based methanogenic processes into an existing dynamic global vegetation model (DGVM [Integrated BIosphere Simulator, IBIS]) (Foley et al., 1996), includes explicit descriptions of processes related to CH_4 production, oxidation, and transportation for interactions among hydrology (e.g., the water table), vegetation (e.g., specific wetland plant function types and primary production), and soil biogeochemistry. Factors controlling CH_4 emission processes, such as soil temperature, redox potential, and pH, were incorporated into the model. A water table module was also integrated into the model to improve hydrological processes for wetland simulation. The wetland CH_4 emission modeling performance of TRIPLEX-GHG was evaluated using global field measurements from previous studies, and the corresponding results suggest that the model can be used to simulate magnitudes and capture reasonable temporal patterns in CH_4 emissions from global natural wetlands that underlie varying conditions, including in tropical areas (Zhu et al., 2014, 2015, 2016) (Figure S1).

2.2 | Model forcing data

The driving and initial data used to perform the simulations included global datasets of climate, vegetation, soil properties (i.e., texture, pH, and soil carbon), topographical features, and wetland distributions. All data layers had a consistent 0.25°×0.25° spatial resolution. The global vegetation map used for the model initialization was generated from the GlobCover 2009 land cover map (Bontemps et al., 2011) and World Wildlife Fund (WWF) terrestrial ecoregions database (Olson et al., 2001). The soil classification map was generated from the Digital Soil Map of the World (DSMW), and DSMW attributes were linked to the soil properties dataset of Batjes (2006) to generate soil texture (i.e., the clay, sand, and silt fraction in soil) and soil pH maps. A global soil dataset (IGBP-DIS, 2000) was used to generate soil carbon data for model initialization. The model was run using the CRU TS 3.21 climate dataset and which provided monthly input data on surface air temperatures, total precipitation, cloud cover percentages, and relative humidity for the model, and a simple nearest-neighbor method was used to downscale the original spatial resolution from 0.5° to 0.25° for consistency with the other finer-resolution input data. Tropical wetland distribution data were extracted from the GLWD Level 3 dataset of Lehner and Döll (2004). It was assumed that inundated parts within the grid remained unchanged throughout the year. Rice paddies were not included in the model runs, and only the natural wetland classes described by Lehner and Döll (2004) were used to calculate CH_4 emissions. ENSO events occurring between 1950 and 2012 were collected to investigate the relationships between wetland CH_4 emissions and the ENSO. Such events (El Niño and La Niña) were defined according to Climate Prediction Center (http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml) described as Southern Oscillation Index (SOI) and NINO3.4 Index, as well as the Multivariate ENSO Index (MEI) raised by Wolter and Timlin (1998). Between 1950 and 2012, strong El Niño events occurred in 1952, 1958, 1964, 1966, 1969, 1973, 1983, 1987–1988, 1992, 1995, 1998, 2003, and 2010, whereas strong La Niña events occurred in 1956, 1971, 1974, 1976, 1989, 1999–2000, 2008, and 2011.

2.3 | Simulation performance

To quantify the effects of climate variability (temperature and precipitation) alone, the potential effects of land cover change (because of anthropogenic activity) and ecosystem disturbances (e.g., fire) were excluded from the model simulations. To evaluate the contributions of precipitation and temperature to tropical wetland CH_4 emissions, two simulations forced with constant precipitation or constant temperature were conducted using 1950 levels. The differences were then separately calculated to normal simulation. To evaluate the effects of precipitation and temperature changes caused by ENSO events on tropical wetland CH_4 emissions at the decadal scale, three simulations of the TRIPLEX-GHG model were conducted (Table S1), and emission differences between the pseudo- and normal simulations were calculated for 1951 to 2012 (divided into six decadal periods: 1951–1960, 1961–1970, 1971–1980, 1981–1990, 1991–2000, 2001–2012). To isolate the effects of changes in wetland areas caused by climate change, wetland areas were fixed and kept constant across the pre-established model simulation time frame (1950–2012).

3 | RESULTS

According to the correlation analysis of modeled tropical wetland CH_4 emissions and ENSO indices, most detrended modeling tropical wetland CH_4 emissions variability patterns match the phasing and amplitude of detrended ENSO indices with maximum coefficients of determination of 0.45 and 0.48 for SOI and negative NINO3.4 Index (Nino3.4) with an 8-month time lag, respectively ($p < .05$). A maximum coefficient of determination of 0.54 was found for the negative MEI with a 7-month time lag ($p < .05$) (Figure 1). We found no time lag between ENSO indices and tropical wetland precipitation, whereas an 8-month time lag was observed between tropical wetland precipitation and tropical wetland CH_4 emissions. In addition, a time lag of approximately 3–4 months was detected between ENSO indices and tropical wetland temperatures, and a 3-month time lag was found between tropical wetland temperature and tropical wetland CH_4 emissions. Precipitation and temperature levels affect wetland CH_4 emissions directly, and ENSO events influence temporal patterns of precipitation and temperature, which could induce a combination time lag (~8 months) between ENSO events and tropical wetland CH_4 emissions (Table S2). On average, our results indicate that the ENSO has a pronounced effect on tropical wetland CH_4 emissions (e.g., explaining 49% of IAV).

The simulated tropical wetland CH_4 emissions show negative anomalies during El Niño periods and positive anomalies during La Niña periods (Figure 2a). The model simulation results show a systematic decrease in CH_4 emissions at the start of strong to moderate El Niño events (e.g., 1982/1983, 1987/1988, and 1997/1998) and an increase in CH_4 emissions during most La Niña events (e.g., 1956, 1971, 1974–1976, 1989, 1999–2000, 2008, and 2011) and at the end of El Niño events (Figure 2a).

In addition to the ENSO, two of the strongest Atlantic Multidecadal Oscillations (AMOs) related to drought events recorded in tropical regions (2005 and 2010) yielded the lowest of all the estimated tropical wetland CH_4 emissions throughout the simulated years (Figure 2a). One notable exception is the increase in tropical wetland CH_4 emissions observed between 1991 and 1992 that was mainly a result of cooling (by 0.5°C) and rainfall changes following the Mount Pinatubo volcanic eruption (Kirschke et al., 2013). Between 1991 and 1992, simulated CH_4 emissions increased in tropical wetlands, even when El Niño conditions prevailed (Figure 2a). When La Niña and El Niño events occur for two consecutive years, and when an El Niño event is followed by a La Niña event, wetland CH_4 emissions show a net increase in the tropical zone (e.g., 1973–1974, 1988–1989, 1998–1999, and 2010–2011),

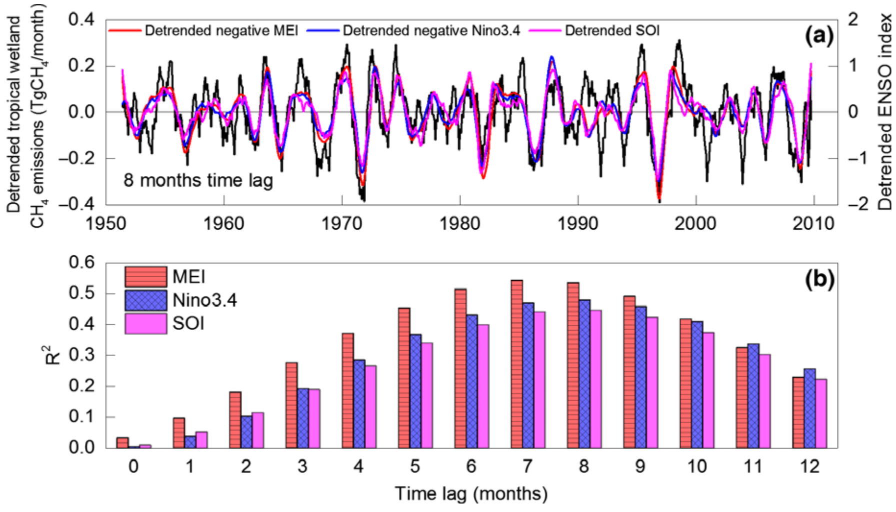

FIGURE 1 Correlations between detrended tropical wetland CH_4 emissions (Tg CH_4 per month) and three detrended key ENSO indices (Southern Oscillation Index (SOI), NINO3.4 Index (Nino3.4), and Multivariate ENSO Index (MEI)): (a) time series compared at an 8-month time lag and (b) coefficients of determination (R^2) of time series comparisons at different time lags (zero to 12 months)

whereas a net decrease is nearly always observed when a La Niña event is followed by an El Niño event (e.g., 1956–1958, 1971–1973, and 2008–2010).

On average, El Niño events are associated with a larger absolute emission anomaly than La Niña events because of their differing frequencies (Figure 2a). In the early 1970s, when more La Niña events occurred, tropical wetland CH_4 emissions showed a significant increasing trend (Figure 2a). However, from the latter half of the 1970s to 2005, when more El Niño events occurred, the amount of CH_4 released from tropical wetlands decreased gradually (0.41 Tg CH_4 per year from 1976 to 2005, $R^2 = .72$, $p < .001$), despite emissions being enhanced by two La Niña events in 1989 and 1999–2000 (Figure 2a). Tropical wetland CH_4 emissions seem to increase due to the frequency of La Niña events being higher than that of El Niño events from 2006 to 2012, which of course must be substantiated with long-term data, including data on long-term future predictions (Figure 2a).

The observed atmospheric methane concentration growth rate slowed in the 1990s, was nearly zero with constant mole fractions from 1999 to 2006, and resumed beginning in 2007 (Nisbet et al., 2014) (Figure 2a,b), following the simulated tropical wetland CH_4 emission growth rate to some extent (Figure 2b). Previous study has shown that the simulated tropical wetland CH_4 emissions can explain 25% of the variation in atmospheric methane growth rates (Zhu et al., 2015). Decreasing tropical wetland CH_4 emission trends were also detected in the three periods mentioned above and were particularly significant for the period from 1999 to 2006, during which the atmospheric methane showed constant mole fractions (Figure 2c). Our results also show that CH_4 emissions from tropical wetlands increased by 5–6 Tg CH_4 between 2005 and 2012, when two La Niña events (2007/2009 and 2010/2012) occurred (Figure 2).

The remotely sensed Net Primary Productivity (NPP) (Zhao & Running, 2010) of tropical wetlands is reduced (enhanced) during El Niño (La Niña) events (Figure 2c) and is significantly positively correlated with simulated tropical wetland CH_4 emissions ($R^2 = .5$, $p < .01$). For tropical wetlands, a long-term remotely sensed monthly Normalized Difference Vegetation Index (NDVI, which is an effective representation of ecosystem productivity) is positively correlated with tropical wetland CH_4 emissions, and both the NDVI and tropical wetland CH_4 emissions exhibited similar temporal patterns (Figure 2d,e). Such relationships are more significant in South-East Asia (SEA) and Africa (AF) than they are in South America (SA) (Figure S2).

The results showed that precipitation has a slight but positive effect, whereas temperature has a significantly negative effect on CH_4 emissions from tropical wetlands (Figure 3). Temperature is an essential contributing factor to CH_4 emissions from tropical wetlands, and its contribution to the decrease in CH_4 emissions increases over time, particularly beginning in the 1980s, when the effect becomes more pronounced (Figure 3a). The contribution of precipitation and temperature was investigated at a decadal scale for 1951–2012 (six decadal periods, Figure 4). Compared to neutral years, precipitation is always enhanced during La Niña events and can increase or decrease during El Niño events across tropical wetland areas (Figure 4a). By contrast, La Niña and El Niño events always (except in 1992) exert negative and positive effects, respectively, on temperature (Figure 4b). This phenomenon for temperature is also found at the long annual scale throughout the study period (Figure 2a) and is consistent with fluctuations in tropical wetland CH_4 emissions (except in 1992) (Figure 2a).

At the decadal scale, changes in precipitation did not exert consistent effects on tropical wetland CH_4 emissions according to ENSO events (Figures 4c and S3a,c). However, changes in temperature have significantly negative effects on tropical wetland CH_4 emissions (Figure S3b,d) that reflect the occurrence of ENSO events, except in 1999/2000 and 2011; before each of these years, an extreme El Niño event and an extreme drought event occurred (Figure 4d). When considering the combined effects of precipitation and temperature changes caused by ENSO events on CH_4 emissions for tropical wetlands (Figure 4e), the impacts induced by precipitation enhance or offset the effects of temperature when the effects of precipitation and temperature changes caused by ENSO events occur in the same or opposite directions (Figure 4c–e).

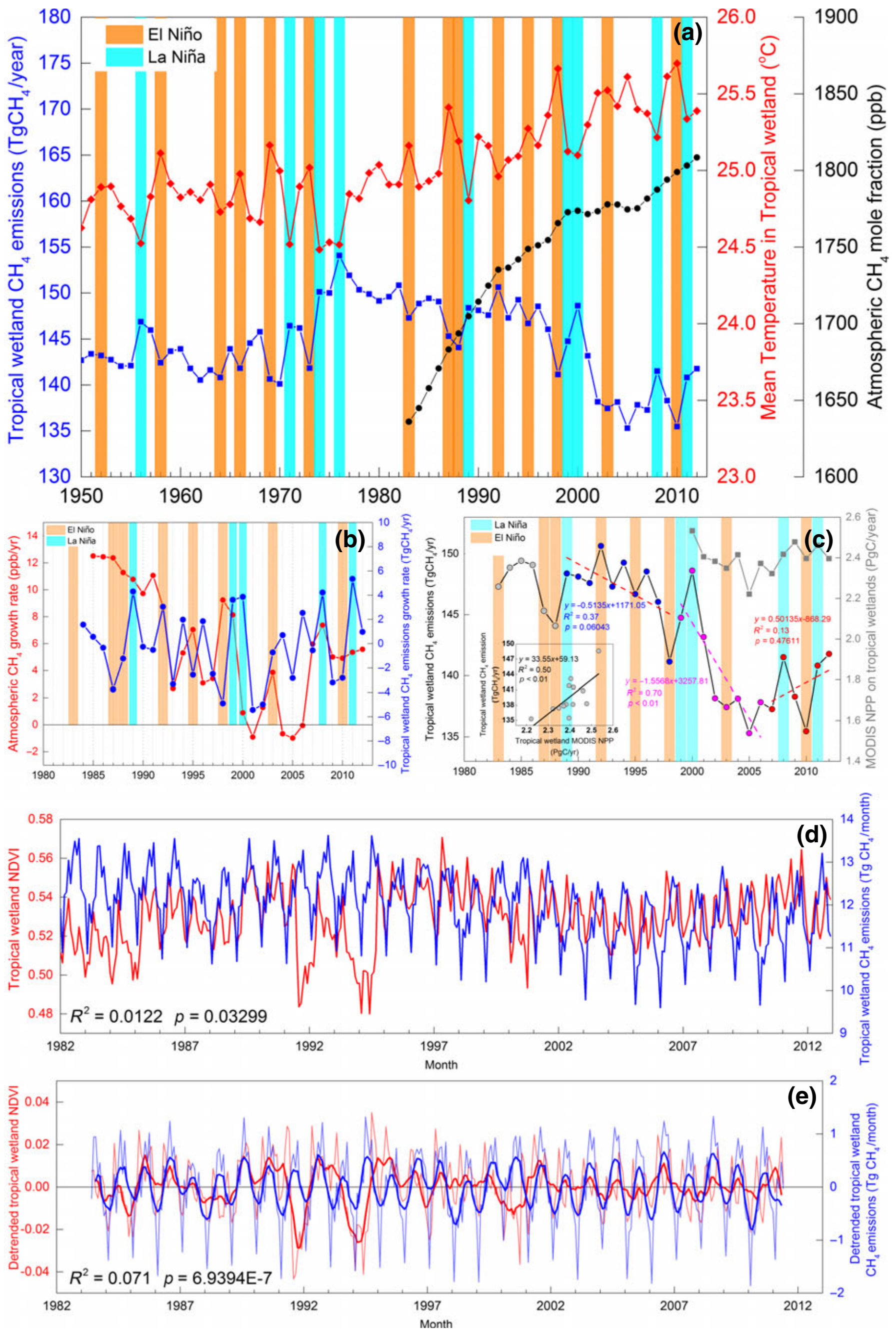

FIGURE 2 (a) Annual variation in CH_4 emissions (Tg CH_4 per year) from tropical wetlands (1950–2012), the mean annual temperature (°C) in tropical wetlands (1950–2012), and atmospheric CH_4 concentrations (ppb) (1983–2012). El Niño events: orange bars; La Niña events: blue bars. (b) atmospheric CH_4 growth rate (ppb/year) and tropical wetland CH_4 emission growth rate (Tg CH_4 per year) (1980–2012); (c) The relationship between moderate-resolution imaging spectroradiometer (MODIS)-based Net Primary Productivity (NPP) and CH_4 emissions in tropical wetlands (R^2 = .5, p < .01) and tropical wetland CH_4 emissions and corresponding dynamics from 1983. Tropical wetland CH_4 emissions were divided into three periods: 1989–1998 (R^2 = .37, p = .06), 1999–2006 (R^2 = .70, p < .01), 2007–2012 (R^2 = .13, p = .48); (d) The relationship between monthly NDVI and CH_4 emissions over tropical wetlands (R^2 = .0122, p < .05); and (e) The relationship between detrended monthly NDVI and CH_4 emissions over tropical wetlands (R^2 = .071, p < .01)

Tropical wetland CH_4 emissions decreased by −0.9 Tg CH_4 per year (compared with the 1980s decadal mean) during the 1982/1983 extreme El Niño event and by approximately −6 Tg CH_4 per year (compared with the 1990s decadal mean) during the 1997/1998 extreme El Niño event (Figure 5, Table S3). CH_4 emission rates were significantly depressed in most tropical wetland areas during these two extreme events (Figure 5). During another remarkable El Niño event that occurred in the 1980s (1987/1988), tropical wetland CH_4 emissions were also significantly lower (Table S3).

During 1999–2006, the 1997/1998 strong El Niño event and the weak El Niño conditions prevailing in the early 2000s drove a negative trend in tropical methane emissions of ~1.6 Tg CH_4 year (Figure 2c, Table S3). Conversely, the reverse trend was observed from 2007–2012 and was dominated by the occurrence of La Niña events in 2007–2009 and 2010–2012 (i.e., emissions increased) (Figure 2, Table S3).

Between 2000 and 2012, particularly in the Amazon Basin, wetland CH_4 emissions were relatively high in 2000 but decreased significantly in 2005 and 2010 (Figure S4). Our model simulations show that the CH_4 emission rate for more than 70% of all wetlands in the Amazon Basin decreased (ranging from 1.2 to 24.7 g CH_4 m^{-2} $year^{-1}$) during the 2005 and 2010 extreme drought events (compared with the 2000–2012 CH_4 emission rate average). By contrast, a more pronounced increase of 0.67 to 29.2 g CH_4 m^{-2} $year^{-1}$ occurred in over 90% of all wetlands during La Niña events (Figure S4).

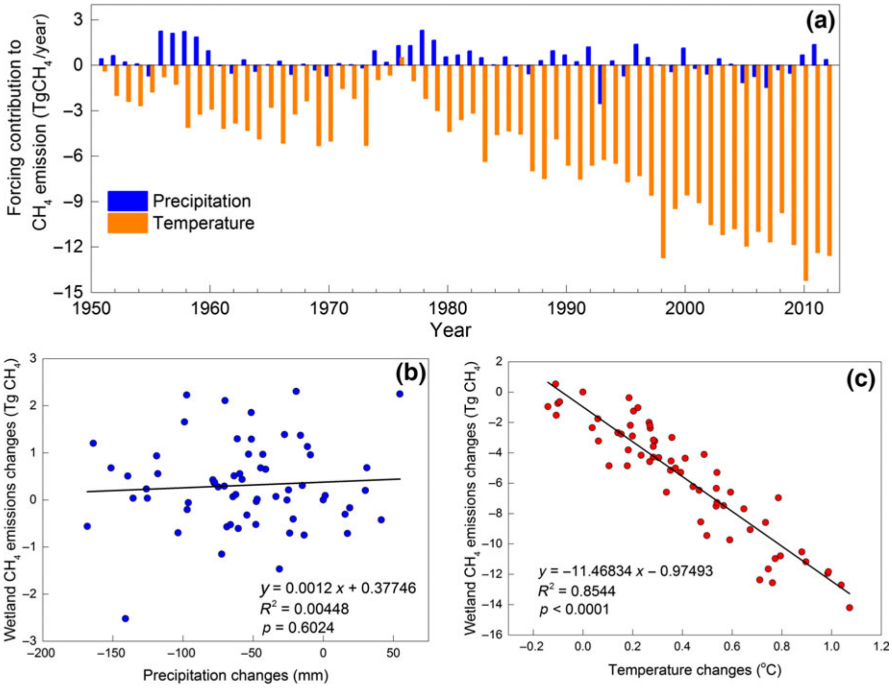

FIGURE 3 (a) The asymmetric effects of temperature (orange) and precipitation (blue) on tropical wetland CH_4 emissions from 1950; (b) Correlation between precipitation changes and CH_4 emission changes in tropical wetlands (1950–2012); and (c) Correlation between temperature changes and CH_4 emission changes in tropical wetlands (1950–2012)

4 | DISCUSSION

Large fluctuations in atmospheric methane growth rates, which decreased during the 1980s and 1990s, stabilized during the stagnation period of 1999–2006, and resumed beginning in 2007, are quantitatively observed (Nisbet et al., 2014). However, the causes underlying these observed changes remain poorly understood (Bousquet et al., 2006; Kirschke et al., 2013).

Focusing on the last 15 years, several possible scenarios have been proposed to explain the slowdown growth rate for atmospheric CH_4 concentration during 1999–2006, even with great debate (Dlugokencky et al., 2009). The patterns could be caused by decreased natural source emissions (Bousquet et al., 2006; Li et al., 2002; Worthy et al., 2009), or decreasing-to-stable fossil fuel emissions and stable-to-increasing microbial emissions (Kirschke et al., 2013) or steady-state microbial and thermogenic emissions (Levin et al., 2012) instead of decreased Northern Hemisphere microbial sources (Kai, Tyler, Randerson, & Blake, 2011). Although OH decrease was observed, which could alter CH_4 sink processes (Rigby et al., 2008), the change in OH is believed not to be the key factor (Bousquet et al., 2011; Pison, Ringeval, Bousquet, Prigent, & Papa, 2013; Sussmann, Forster, Rettinger, & Bousquet, 2012). A number of studies (Karion et al., 2013; Ohara et al., 2007) have suggested that anthropogenic CH_4 emissions (e.g., fossil fuels) have also increased since 2000 and have likely also contributed to the increase in the atmospheric CH_4 level observed from 2007 (Bergamaschi et al., 2009). However, the increase in atmospheric methane concentrations since 2007 is coincident with a decrease in $^{13}CH_4$ (IPCC, 2013; Nisbet et al., 2014; Schaefer et al., 2016), which is not consistent with an increase driven by ^{13}C-enriched anthropogenic sources, such as natural gas leaks. Increased microbial anthropogenic emissions (agriculture and waste) and increases from high-latitude wetland emissions could complement the 25% contribution to the atmospheric CH_4 concentration increase in natural wetlands found here, to reconcile ^{12}C and ^{13}C atmospheric signals observed from 2007. One isotopic shifting analysis suggested that the rising atmospheric CH_4 levels have been dominated by biogenic methane emissions, particularly in the tropics, rather than by fossil fuel emissions or methane removal by the OH radical, indicating that tropical wetland CH_4 emission responses to meteorological changes could be a major factor (Nisbet et al., 2016). In this study, the possible causes and mechanisms for the reduction in methane emissions triggered by repeated ENSO events in tropical wetlands are striking for several reasons. First, relative to neutral years, changes in temperature have much stronger effects on tropical wetland CH_4 emissions than changes in precipitation during ENSO years. Second, El Niño and La Niña events have a nonsymmetrical effect on CH_4 wetland emission anomalies during 1950–2012. The average increase in wetland emissions of 5–6 Tg CH_4 found in this study explains more than 25% of the increase in global emissions estimated by inverse modeling (IM) between 2005 and 2010 (Kirschke et al., 2013), which amounts to 20 ± 3 Tg CH_4 per year. The results of this study suggest that the stronger impacts of El Niño events relative to those of La Niña events on tropical wetland CH_4 emissions from the 1980s to the early 2000s are partially responsible for the slowdown in the increase in atmospheric CH_4 concentrations occurring during this period. After 2006 (from 2007 to 2012), this nonsymmetrical effect on tropical wetland CH_4 emissions caused by La Niña events being more frequent than El Niño events may partly contribute to the renewed increase in atmospheric CH_4 concentrations.

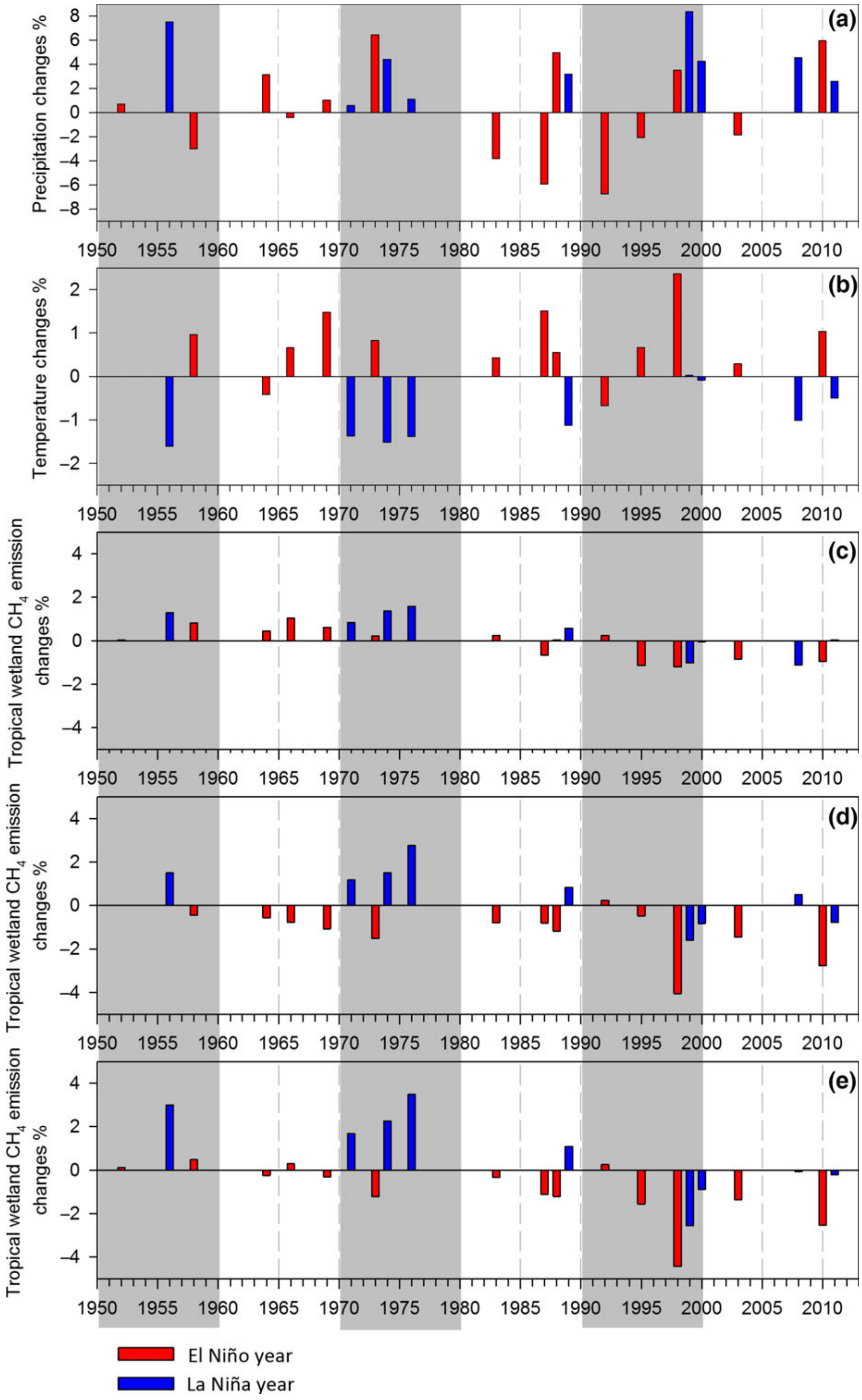

FIGURE 4 The effects of ENSO events on tropical wetland CH_4 emissions from 1951 to 2012 (divided into six decadal periods: 1951–1960, 1961–1970, 1971–1980, 1981–1990, 1991–2000, and 2001–2012). (a) Precipitation changes (related to the decadal mean of precipitation for neutral years) caused by ENSO events in each decade in tropical wetlands; (b) Temperature changes (related to the decadal mean of temperature for neutral years) caused by ENSO events in each decade in tropical wetlands; (c) The effects of precipitation changes caused by ENSO events on CH_4 emissions from tropical wetlands; (d) The effects of temperature changes caused by ENSO events on CH_4 emissions from tropical wetlands; and (e) The combined effects of precipitation and temperature changes caused by ENSO events on CH_4 emissions from tropical wetlands

Two main mechanisms can help explain the impact of El Niño events on the reduction in CH_4 emissions from tropical wetlands (Figure 6): The availability of carbon substrates for methanogenesis decreases because of decreased productivity and lower water tables. These two aspects could be reflected by the phasing delay between ENSO indices and tropical wetland CH_4 emissions. On the one hand, the phasing delay for temperature caused by ENSO events could affect the plant growth and then change the temporal pattern of availability of carbon substrates for methanogenesis. On the other hand, the water table will change with the water absence or flood conditions; that is, the water level is high and wetlands will be filled quickly if previous period has been wet while the wetlands will be filled relatively late if previous period has been drought.

We observed that during El Niño (La Niña) periods, NPP is reduced (enhanced) in tropical wetlands and that tropical wetland CH_4 emissions are closely correlated with NPP. As a good representation of terrestrial ecosystem productivity, the NDVI presents reasonable temporal tropical wetland CH_4 emission trends, particularly

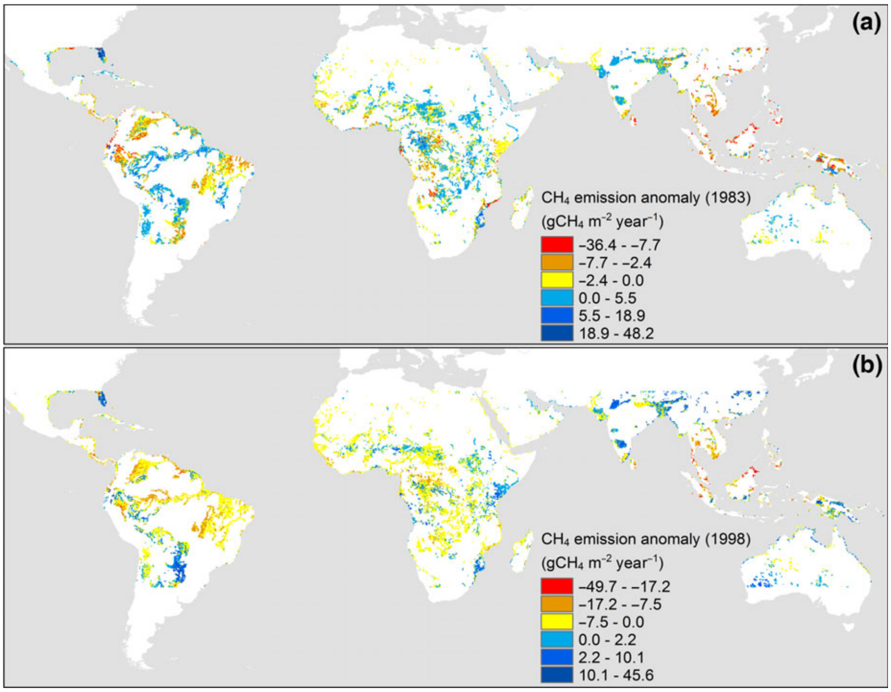

FIGURE 5 Spatial impacts of extreme El Niño events on tropical wetland CH_4 emissions (g CH_4 m^{-2} $year^{-1}$): (a) 1982/1983 (compared with the 1980s decadal mean) and (b) 1997/1998 (compared with the 1990s decadal mean)

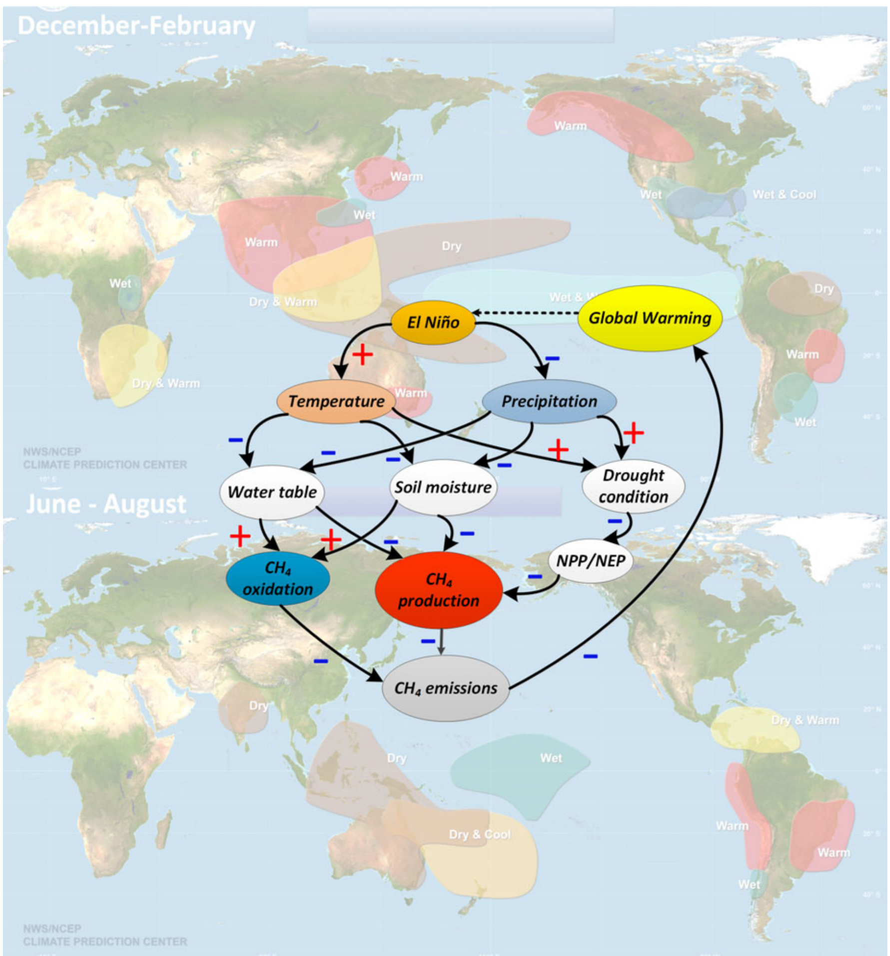

FIGURE 6 Schematic diagram of the main ENSO impacts on tropical wetland CH_4 emissions. An El Niño event, prompting high temperatures and low precipitation, can trigger water table reduction, decreased soil moisture levels, decreased NPP and net ecosystem productivity (NEP) values, and increased CH_4 soil consumption, leading to a reduction in CH_4 emissions from tropical wetlands and thus generating negative feedback against the global warming observed in recent years. The reverse is the case for La Niña events. It should be noted that such ENSO impacts on CH_4 emissions from tropical wetlands may operate at different timescales (IPCC, 2013). Background picture source: NWS/NCEP Climate Prediction Center

for Africa (AF) and South-East Asia (SEA), although this relationship is relatively weak for South America (SA), as NDVI production was constrained by cloud contamination and sensitivities to seasonally variable atmosphere water vapor and aerosol conditions, especially in the Amazon region (Huete et al., 2006; Kobayashi & Dye, 2005; Samanta et al., 2011).

A number of studies have shown that CH_4 wetland emissions are positively correlated with NEP, which is an ecosystem variable that integrates several factors that control CH_4 emissions in vegetated wetlands (Sjögersten et al., 2014; Whiting & Chanton, 1993) and biomass CO_2 fixation (Christensen et al., 2000; Joabsson & Christensen, 2001). Based on data collected from simultaneous measurements of CO_2 and CH_4 exchange in wetlands extending from subarctic peatlands to subtropical marshes, Whiting and Chanton (1993) found a positive correlation between CH_4 emissions and NEP, suggesting that NEP is a master variable that integrates many factors that control CH_4 emissions in vegetated wetlands. This carbon substrate limitation mechanism shows that recent assimilates contribute the most labile carbon substrates to methanogenic habitats, resulting in higher CH_4 emissions with increases in NPP (or NEP) (Figure 6).

Zhao and Running (2010) reported that the NPP over large regions of lower latitude and altitude is negatively correlated with temperature, mostly because of warming-related increases in water stress and autotrophic respiration, especially in the Southern Hemisphere. One modeling study by Tian et al. (1998) showed that annual variations in NPP and NEP in Amazonian ecosystems are closed related to shifts in ENSO periods, resulting in a negative annual NEP (ecosystem carbon source) in El Niño years and a positive annual NEP (ecosystem carbon sink) in non-El Niño years in most areas of the Amazon Basin, which indicated that ENSO significantly affects ecosystem productivity in tropical Amazon regions. ENSO events influence temperature and rainfall patterns worldwide and alter temporal variations in tropical productivity, including over wetlands, thereby changing substrates for methanogenic habitats. Subsequently, CH_4 emissions from tropical wetlands fluctuate according to the frequency and intensity of ENSO events.

The water table depth for tropical wetlands, which is affected by both temperature and precipitation, appears to be an important control factor for tropical wetland CH_4 emissions. During El Niño events, for example, lower water tables result in decreasing soil moisture levels and increasing soil temperature, whereas the opposite occurs during La Niña events. Decreased soil moisture levels caused by climate-induced droughts likely lead to reduced CH_4 emissions (Ferretti et al., 2005). ENSO events can greatly affect the spatial and temporal patterns of temperature and precipitation across tropical areas. Decreased precipitation and increased temperature and drought condition will lower the water table, which could in turn reduce the production of methane and enhance the oxidation of methane due to the change in wetland anaerobic conditions. Variations in temperature and moisture have been suggested to influence natural methane emissions from wetlands, which decrease during warm-dry periods and increase in response to cooling temperatures and increasing moisture levels (Ferretti et al., 2005). Simulated drought experiments have demonstrated that the soil consumption of methane could increase (Wood & Silver, 2012). The change in anaerobic conditions will alter the oxygen availability levels, and in turn influence CH_4 oxidation to a greater extent than methanogenesis. Consequently, a greater fraction of total CH_4 production will be oxidized by methanotrophic bacteria as the concentration of O_2 increases in the soil profile (Teh, Silver, & Conrad, 2005).

The lowest estimated CH_4 emissions were simulated in 2005 and 2010 and could be primarily attributed to serious drought periods occurring in the Amazon area during these 2 years, particularly in 2010 (Lewis, Brando, Phillips, Van Der Heijden, & Nepstad, 2011). The 2009–2010 drought in the Amazon region was one of the most severe in recent history, and water levels in rivers across the basin reached record low levels by October of 2010 (Xu et al., 2011). Combined with the effects of the relatively low NPP, which were also caused by drought (Potter, Klooster, Hiatt, Genovese, & Castilla-Rubio, 2011), the wetland CH_4 emissions declined significantly in the Amazon Basin and result in a drop in total wetland CH_4 emissions from the entire tropical area.

In this study, the tropical wetland distribution was retrieved from a static global wetland map, and we assumed that inundated sections within the grid remained unchanged throughout the year. We focused on the effects of ENSO events under changing climatic conditions and compared tropical wetland CH_4 emissions across constant and dynamic wetland area distributions (retrieved from the Surface Water Microwave Product Series [SWAMPS] dataset) for 2000–2012 (Figure S5). The correlation between simulated tropical wetland CH_4 emissions for constant and dynamic wetland area distributions is roughly 0.45 (Figure S3b). Thus, dynamic wetland areas may affect the quantity of the CH_4 emissions but did not significantly change the dynamic trends of CH_4 emissions from tropical wetlands between 2000 and 2012. Although wetland area variations exert slight effects on tropical wetland annual CH_4 emission trends, they have been shown to considerably influence seasonal total emissions patterns (Ringeval et al., 2010). Nevertheless, to accurately evaluate the methane budget of tropical or even global wetlands, it is critically important to improve wetland mapping by considering seasonal and IAVs in wetland distributions because the wetland extent could contribute 30%–40% to the estimated range of total wetland emissions (Saunois et al., 2016). Wetland CH_4 emission modeling could be improved not only by quantifying the impacts of climate IAV on wetland CH_4 emissions but also by improving representations of wetland area, wetland biogeochemistry, hydrology, and permafrost dynamics in Earth systems and global climate models. Furthermore, the intensification of CH_4 flux measurements could generate useful information for validating the responses of tropical wetland CH_4 emissions to ENSO events and constraining the behavior of the processed model. Predicting future atmospheric CH_4 concentrations and global methane budgets without considering the feedbacks triggered by repeated ENSO events in tropical wetlands would be difficult. The Wetland and Wetland CH_4 Inter-comparison of Models Project (WETCHIMP), which was conducted to evaluate large-scale wetland characteristics and corresponding CH_4 emissions by using ten wetland models, indicated that large uncertainties still exist in wetland CH_4 emission estimation due to model structure, complexity, and spatiotemporal resolutions (Wania et al., 2013). Further model development for peatlands and tropical flood plains in hydrological models and the consideration of extreme climatic events, such as the ENSO, in global wetland models will improve predictions of future CH_4 emissions under changing climatic conditions. Additional work to isolate the interactions of other CH_4 sources and sinks affected by ENSO variability, namely, biomass burning and OH variability, is critically needed.

Global warming may also increase the intensity of ENSO events (Hansen et al., 2006), which may subsequently result in severe and prolonged drought conditions (Alencar, Nepstad, & Diaz, 2006; Lewis et al., 2011; Nepstad et al., 2004). A comprehensive understanding of ENSO effects on tropical wetlands and possible feedback effects on climate change (via CH_4 emissions) remains a distant goal. Given the predicted increase in ENSO events frequency under conditions of future global warming (Cai et al., 2014; Power, Delage, Chung, Kociuba, & Keay, 2013), such profound impacts on global wetland ecosystems and contributions to the global CH_4 cycle (sinks and sources) warrant a substantial increase in the research performed on this topic.

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REFERENCES

Alencar, A., Nepstad, D., & Diaz, M. C. V. (2006). Forest understory fire in the Brazilian Amazon in ENSO and non-ENSO years: Area burned and committed carbon emissions. *Earth Interactions*, *10*, 1–17.

Batjes, N. H. (2006). ISRIC-WISE derived soil properties on a 5 by 5 arc-minutes global grid. Report 2006/02. Retrieved from http://www.isric.org, ISRIC – World Soil Information, Wageningen (with data set).

Bergamaschi, P., Frankenberg, C., Meirink, J. F., Krol, M., Villani, M. G., Houweling, S., ... Ingeborg, L. (2009). Inverse modeling of global and regional CH_4 emissions using SCIAMACHY satellite retrievals. *Journal of Geophysical Research: Atmospheres*, *114*, D22301.

Bontemps, S., Defourny, P., Bogaert, E. V., Arino, O., Kalogirou, V., & Perez, J. R. (2011). GLOBCOVER 2009: Product description and validation report. UCLouvain & ESA Team.

Bousquet, P., Ciais, P., Miller, J., Dlugokencky, E., Hauglustaine, D., Prigent, C., ... Carouge, C. (2006). Contribution of anthropogenic and natural sources to atmospheric methane variability. *Nature*, *443*, 439–443.

Bousquet, P., Ringeval, B., Pison, I., Dlugokencky, E., Brunke, E.-G., Carouge, C., ... Hauglustaine, D. (2011). Source attribution of the changes in atmospheric methane for 2006–2008. *Atmospheric Chemistry and Physics*, *11*, 3689–3700.

Bridgham, S. D., Cadillo-Quiroz, H., Keller, J. K., & Zhuang, Q. (2013). Methane emissions from wetlands: Biogeochemical, microbial, and modeling perspectives from local to global scales. *Global Change Biology*, *19*, 1325–1346.

Cai, W., Borlace, S., Lengaigne, M., Van Rensch, P., Collins, M., Vecchi, G., ... Jin, F.-F. (2014). Increasing frequency of extreme El Nino events due to greenhouse warming. *Nature Climate Change*, *4*, 111–116.

Christensen, T., Friborg, T., Sommerkorn, M., Kaplan, J., Illeris, L., Soegaard, H., ... Jonasson, S. (2000). Trace gas exchange in a high-Arctic valley: 1. Variationsin CO2 and CH4 Flux between tundra vegetation types. *Global biogeochemical cycles*, *14*, 701–713.

Dlugokencky, E., Bruhwiler, L., White, J., Emmons, L., Novelli, P. C., Montzka, S. A., ... Miller, J. B. (2009). Observational constraints on recent increases in the atmospheric CH_4 burden. *Geophysical Research Letters*, *36*, L18803.

Ferretti, D. F., Miller, J., White, J., Etheridge, D., Lassey, K., Lowe, D., ... Van Ommen, T. (2005). Unexpected changes to the global methane budget over the past 2000 years. *Science*, *309*, 1714–1717.

Fiore, A. M., Horowitz, L. W., Dlugokencky, E. J., & West, J. J. (2006). Impact of meteorology and emissions on methane trends, 1990–2004. *Geophysical Research Letters*, *33*, L12809.

Foley, J. A., Prentice, I. C., Ramankutty, N., Levis, S., Pollard, D., Sitch, S., & Haxeltine, A. (1996). An integrated biosphere model of land surface processes, terrestrial carbon balance, and vegetation dynamics. *Global biogeochemical cycles*, *10*, 603–628.

Gedney, N., Cox, P. M., & Huntingford, C. (2004). Climate feedback from wetland methane emissions. *Geophysical Research Letters*, *31*, L20503.

Hansen, J., Sato, M., Ruedy, R., Lo, K., Lea, D. W., & Medina-Elizade, M. (2006). Global temperature change. *Proceedings of the National Academy of Sciences*, *103*, 14288–14293.

Hodson, E., Poulter, B., Zimmermann, N., Prigent, C., & Kaplan, J. O. (2011). The El Niño-Southern Oscillation and wetland methane interannual variability. *Geophysical Research Letters*, *38*, L08810.

Huete, A. R., Didan, K., Shimabukuro, Y. E., Ratana, P., Saleska, S. R., Hutyra, L. R., ... Myneni, R. (2006). Amazon rainforests green-up with sunlight in dry season. *Geophysical Research Letters*, *33*, L06405.

IGBP-DIS (2000). Global Soil Data Task. Global Soil Data Products CD-ROM (IGBP-DIS). International Geosphere-Biosphere Programme, Data and Information System, Potsdam, Germany. Available from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A. Retrieved from http://www.daac.ornl.gov

IPCC (2013). Carbon and other biogeochemical cycles. In T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex & P. M. Midgley (Eds.), *Climate change 2013: The physical science basis* (pp. 465–570). Cambridge, UK and New York, NY: Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.

Joabsson, A., & Christensen, T. R. (2001). Methane emissions from wetlands and their relationship with vascular plants: An Arctic example. *Global Change Biology*, *7*, 919–932.

Kai, F. M., Tyler, S. C., Randerson, J. T., & Blake, D. R. (2011). Reduced methane growth rate explained by decreased Northern Hemisphere microbial sources. *Nature*, *476*, 194–197.

Karion, A., Sweeney, C., Pétron, G., Frost, G., Michael Hardesty, R., Kofler, J., ... Banta, R. (2013). Methane emissions estimate from airborne measurements over a western United States natural gas field. *Geophysical Research Letters*, *40*, 4393–4397.

Kirschke, S., Bousquet, P., Ciais, P., Saunois, M., Canadell, J. G., Dlugokencky, E. J., ... Zeng, G. (2013). Three decades of global methane sources and sinks. *Nature Geoscience*, *6*, 813–823.

Kobayashi, H., & Dye, D. G. (2005). Atmospheric conditions for monitoring the long-term vegetation dynamics in the Amazon using normalized difference vegetation index. *Remote Sensing of Environment*, *97*, 519–525.

Lehner, B., & Döll, P. (2004). Development and validation of a global database of lakes, reservoirs and wetlands. *Journal of Hydrology*, *296*, 1–22.

Levin, I., Veidt, C., Vaughn, B., Brailsford, G., Bromley, T., Heinz, R., ... White, J. (2012). No inter-hemispheric $^{13}CH_4$ trend observed. *Nature*, *486*, E3–E4.

Lewis, S. L., Brando, P. M., Phillips, O. L., Van Der Heijden, G. M., & Nepstad, D. (2011). The 2010 amazon drought. *Science*, *331*, 554.

Li, C., Qiu, J., Frolking, S., Xiao, X., Salas, W., Moore, B., . . . Sass, R. (2002). Reduced methane emissions from large-scale changes in water management of China's rice paddies during 1980–2000. *Geophysical Research Letters*, *29*, 33-1–33-4.

Matthews, E., & Fung, I. (1987). Methane emission from natural wetlands: Global distribution, area, and environmental characteristics of sources. *Global biogeochemical cycles*, *1*, 61–86.

Mcphaden, M. J., Zebiak, S. E., & Glantz, M. H. (2006). ENSO as an integrating concept in earth science. *Science*, *314*, 1740–1745.

Melton, J., Wania, R., Hodson, E., Poulter, B., Ringeval, B., Spahni, R., . . . Chen, G. (2013). Present state of global wetland extent and wetland methane modelling: Conclusions from a model intercomparison project (WETCHIMP). *Biogeosciences*, *10*, 753–788.

Nepstad, D., Lefebvre, P., Lopes Da Silva, U., Tomasella, J., Schlesinger, P., Solorzano, L., . . . Guerreira Benito, J. (2004). Amazon drought and its implications for forest flammability and tree growth: A basin-wide analysis. *Global Change Biology*, *10*, 704–717.

Nisbet, E. G., Dlugokencky, E. J., & Bousquet, P. (2014). Methane on the rise—again. *Science*, *343*, 493–495.

Nisbet, E. G., Dlugokencky, E. J., Manning, M. R., Lowry, D., Fisher, R. E., France, J. L., . . . Ganesan, A. L. (2016). Rising atmospheric methane: 2007-2014 growth and isotopic shift. *Global biogeochemical cycles*, *30*, 1356–1370.

Ohara, T., Akimoto, H., Kurokawa, J.-I., Horii, N., Yamaji, K., Yan, X., & Hayasaka, T. (2007). An Asian emission inventory of anthropogenic emission sources for the period 1980–2020. *Atmospheric Chemistry and Physics*, *7*, 4419–4444.

Olson, D. M., Dinerstein, E., Wikramanayake, E. D., Burgess, N. D., Powell, G. V. N., Underwood, E. C., . . . Kassem, K. R. (2001). Terrestrial ecoregions of the world: A new map of life on earth. *BioScience*, *51*, 933–938.

Pison, I., Ringeval, B., Bousquet, P., Prigent, C., & Papa, F. (2013). Stable atmospheric methane in the 2000s: Key-role of emissions from natural wetlands. *Atmospheric Chemistry and Physics*, *13*, 11609–11623.

Potter, C., Klooster, S., Hiatt, C., Genovese, V., & Castilla-Rubio, J. C. (2011). Changes in the carbon cycle of Amazon ecosystems during the 2010 drought. *Environmental Research Letters*, *6*, 034024.

Power, S., Delage, F., Chung, C., Kociuba, G., & Keay, K. (2013). Robust twenty-first-century projections of El Nino and related precipitation variability. *Nature*, *502*, 541–545.

Rigby, M., Prinn, R. G., Fraser, P. J., Simmonds, P. G., Langenfelds, R., Huang, J., . . . Weiss, R. F. (2008). Renewed growth of atmospheric methane. *Geophysical Research Letters*, *35*, L22805.

Ringeval, B., Noblet-Ducoudré, N. D., Ciais, P., Bousquet, P., Prigent, C., Papa, F., & Rossow, W. B. (2010). An attempt to quantify the impact of changes in wetland extent on methane emissions on the seasonal and interannual time scales. *Global Biogeochemical cycles*, *24*, GB2003.

Samanta, A., Costa, M. H., Nunes, E. L., Vieira, S. A., Xu, L., & Myneni, R. B. (2011). Comment on "drought-induced reduction in global terrestrial net primary production from 2000 through 2009". *Science*, *333*, 1093.

Saunois, M., Bousquet, P., Poulter, B., Peregon, A., Ciais, P., Canadell, J. G., . . . Zhu, Q. (2016). The global methane budget 2000–2012. *Earth System Science Data*, *8*, 697–751.

Schaefer, H., Fletcher, S. E. M., Veidt, C., Lassey, K. R., Brailsford, G. W., Bromley, T. M., . . . White, J. W. C. (2016). A 21st-century shift from fossil-fuel to biogenic methane emissions indicated by $^{13}CH_4$. *Science*, *352*, 80–84.

Sjögersten, S., Black, C. R., Evers, S., Hoyos-Santillan, J., Wright, E. L., & Turner, B. L. (2014). Tropical wetlands: A missing link in the global carbon cycle? *Global biogeochemical cycles*, *28*, 1371–1386.

Sussmann, R., Forster, F., Rettinger, M., & Bousquet, P. (2012). Renewed methane increase for five years (2007–2011) observed by solar FTIR spectrometry. *Atmospheric Chemistry and Physics*, *12*, 4885–4891.

Teh, Y. A., Silver, W. L., & Conrad, M. E. (2005). Oxygen effects on methane production and oxidation in humid tropical forest soils. *Global Change Biology*, *11*, 1283–1297.

Tian, H., Melillo, J. M., Kicklighter, D. W., Mcguire, A. D., Helfrich, J. V. K., Moore, B., & Vörösmarty, C. J. (1998). Effect of interannual climate variability on carbon storage in Amazonian ecosystems. *Nature*, *396*, 664–667.

Wania, R., Melton, J. R., Hodson, E. L., Poulter, B., Ringeval, B., Spahni, R., . . . Kaplan, J. O. (2013). Present state of global wetland extent and wetland methane modelling: Methodology of a model inter-comparison project (WETCHIMP). *Geoscientific Model Development*, *6*, 617–641.

Warwick, N., Bekki, S., Law, K., Nisbet, E., & Pyle, J. (2002). The impact of meteorology on the interannual growth rate of atmospheric methane. *Geophysical Research Letters*, *29*, 1947.

Westermann, P. (1993). Temperature regulation of methanogenesis in wetlands. *Chemosphere*, *26*, 321–328.

Whiting, G. J., & Chanton, J. P. (1993). Primary production control of methane emission from wetlands. *Nature*, *364*, 794–795.

Wolter, K., & Timlin, M. S. (1998). Measuring the strength of ENSO events: How does 1997/98 rank? *Weather*, *53*, 315–324.

Wood, T. E., & Silver, W. L. (2012). Strong spatial variability in trace gasdynamics following experimental drought in a humid tropical forest. *Global Biogeochemical Cycles*, *26*, GB3005.

Worthy, D. E., Chan, E., Ishizawa, M., Chan, D., Poss, C., Dlugokencky, E. J., . . . Levin, I. (2009). Decreasing anthropogenic methane emissions in Europe and Siberia inferred from continuous carbon dioxide and methane observations at Alert, Canada. *Journal of Geophysical Research: Atmospheres*, *114*, D10301.

Xu, L., Samanta, A., Costa, M. H., Ganguly, S., Nemani, R. R., & Myneni, R. B. (2011). Widespread decline in greenness of Amazonian vegetation due to the 2010 drought. *Geophysical Research Letters*, *38*, L07402.

Zhao, M., & Running, S. W. (2010). Drought-induced reduction in global terrestrial net primary production from 2000 through 2009. *Science*, *329*, 940–943.

Zhu, Q., Liu, J., Peng, C., Chen, H., Fang, X., Jiang, H., . . . Zhou, X. (2014). Modelling methane emissions from natural wetlands by development and application of the TRIPLEX-GHG model. *Geoscientific Model Development*, *7*, 981–999.

Zhu, Q., Peng, C., Chen, H., Fang, X., Liu, J., Jiang, H., . . . Yang, G. (2015). Estimating global natural wetland methane emissions using process modelling: Spatio-temporal patterns and contributions to atmospheric methane fluctuations. *Global Ecology and Biogeography*, *24*, 959–972.

Zhu, Q., Peng, C., Liu, J., Jiang, H., Fang, X., Chen, H., . . . He, J.-S. (2016). Climate-driven increase of natural wetland methane emissions offset by human-induced wetland reduction in China over the past three decades. *Scientific Reports*, *6*, 38020.

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