Enhanced methane emissions from tropical wetlands during the 2011 La Niña

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Year-to-year variations in the atmospheric methane (CH₄) growth rate show significant correlation with climatic drivers. The second half of 2010 and the first half of 2011 experienced the strongest La Niña since the early 1980s, when global surface networks started monitoring atmospheric CH₄ mole fractions. We use these surface measurements, retrievals of column-averaged CH₄ mole fractions from GOSAT, new wetland inundation estimates, and atmospheric δ¹³C-CH₄ measurements to estimate the impact of this strong La Niña on the global atmospheric CH₄ budget. By performing atmospheric inversions, we find evidence of an increase in tropical CH₄ emissions of ∼6–9 TgCH₄ yr⁻¹ during this event. Stable isotope data suggest that biogenic sources are the cause of this emission increase. We find a simultaneous expansion of wetland area, driven by the excess precipitation over the Tropical continents during the La Niña. Two process-based wetland models predict increases in wetland area consistent with observationally-constrained values, but substantially smaller per-area CH₄ emissions, highlighting the need for improvements in such models. Overall, tropical wetland emissions during the strong La Niña were at least by 5% larger than the long-term mean.

CH₄ is the second most important anthropogenic greenhouse gas after CO₂, accounting for 20% of direct anthropogenic radiative forcing. CH₄ contributes strongly to anthropogenic climate change, directly through its radiative forcing as well as indirectly through impacts on atmospheric chemistry. With a relatively short atmospheric lifetime of ∼9 years, CH₄ is a primary target for global warming mitigation strategies. Over the past decades, the atmospheric CH₄ growth rate has been highly variable, including an approximate stabilization from 1999 to 2006 followed by a renewed growth since 2007. Among a range of explanations that were proposed, some studies have suggested that more than 70% of the interannual variations of CH₄ can be explained by wetland CH₄ emissions.

Wetland CH₄ emissions are highly sensitive to soil temperature and moisture. Paleo records and studies of contemporary CH₄ suggest a strong positive feedback of wetlands to global warming through CH₄ emissions. Proper quantification of this feedback is important for accurate future climate projections. Therefore, it is crucial to better understand the sensitivity of wetland CH₄ emissions to changes in climatic parameters. The El Niño Southern Oscillation (ENSO) is a major mode of variability of global precipitation and temperature, comprising alternating El Niño and La Niña phases. Hodson et al. estimated the influence of precipitation and temperature change, driven by ENSO, on wetland CH₄ emissions using a process-based wetland model. They found that...
A large fraction of CH₄ variability is correlated with ENSO, with higher tropical wetland CH₄ emission during La Niña periods. However, this pattern has not been verified until now by atmospheric CH₄ measurements during a La Niña. Furthermore, La Niña periods have received less attention in studies of the atmospheric CH₄ budget than El Niño, since continued warming likely favors neutral or El Niño conditions.

The La Niña of 2011 (LN11 hereafter) was the strongest since 1980 (see Fig. 1a) and offers the possibility to investigate the response of the atmospheric CH₄ budget to La Niña conditions. In this study, we investigate this response by combining different measurement dataset and model simulations. A brief overview of them is given in the next section.

**Method and Data**

Atmospheric CH₄ measurements are available during the 2011 La Niña period from ground-based networks (NOAA-ESRL, CSIRO), and space (GOSAT, SCIAMACHY). The Greenhouse Gases Observing Satellite (GOSAT) has been measuring spectra for retrieval of the column average mole fraction of CH₄ (XCH₄) since June 2009. Onboard GOSAT is the Thermal And Near infrared Sensor for carbon Observation-Fourier Transform Spectrometer (TANSO-FTS), from which XCH₄ is obtained with high sensitivity to the lower troposphere, and hence, to surface emissions. We analyze the interannual variability in GOSAT full-physics (FP) XCH₄ obtained using the RemoteC algorithm, and ground-based CH₄ flask-air measurements. Supplementary Material (SM) Section 9 further explains the FP retrieval method and justifies our choice of FP XCH₄ over XCH₄ derived from other retrieval algorithms.
In addition to the surface emissions, changes in atmospheric transport can cause interannual variability in CH$_4$. Large-scale transport patterns, including the strength of inter-hemispheric exchange and atmospheric temperature are influenced by ENSO. To quantify the contribution of these meteorological parameters, we ran the Tracer Transport Model version 5 (TM5) repeating surface emissions of 2008 for every year in 2009–2015. This simulation is referred to as TM5-Meteorology from hereon (see SM Section 1). To quantify the contribution of the surface emissions to XCH$_4$ variability, we look at the difference between GOSAT FP XCH$_4$ and XCH$_4$ sampled from TM5-Meteorology.

Atmospheric inverse modeling systems are well established tools to convert atmospheric CH$_4$ measurements into surface emissions. We use the TM5-4DV AR (TM5-variational data assimilation system) in combination with GOSAT FP XCH$_4$, and surface measurements from NOAA-ESRL and CSIRO to optimize surface CH$_4$ emissions. Note that the inverse model makes use of actual meteorological fields from the ECMWF ERA-interim reanalysis to account for variability in the atmospheric transport of CH$_4$. Earlier studies have established the link between biomass burning CH$_4$ emissions and ENSO. To exclude the influence of biomass burning, fire related CH$_4$ emissions from the Global Fire Emissions Database version 4s (GFED4s) inventory have been subtracted from the TM5-4DV AR emissions.

The origin of an atmospheric CH$_4$ anomaly can be identified using CH$_4$ stable isotope measurements. We look at measurements of $^{13}$C/$^{12}$C in CH$_4$ (expressed in $\delta$-notation as $\delta^{13}$C-CH$_4$) analyzed by INSTAAR in samples from the NOAA-ESRL (ref. 30, see Fig. 2b). $\delta^{13}$C-CH$_4$ of atmospheric CH$_4$ (global average in 2009$=-47.14‰$) is controlled by the relative contribution from different source types with distinct isotopic signatures. The mean isotopic signatures of the biogenic category is $\sim-60‰$ (includes wetlands, agriculture, waste), for the thermogenic category it is $\sim-37‰$ (includes fossil-fuels) and for pyrogenic category it is $\sim-22‰$ (includes biomass burning). To account for impact of meteorological variability on $\delta^{13}$C-CH$_4$, a meteorology simulation of $\delta^{13}$C-CH$_4$ was performed using TM5.

To identify factors which might have altered the wetland emissions, we look at the variability in land precipitation and temperature data in CRU-TS version 3.23 (Climatic Research Unit-time series). We also analyze CH$_4$ emission and surface inundation extent from two process-based wetland models: LPJ-wsl and CLM4.5. Additionally, we derive an independent estimate of inundation extent from remotely sensed Surface Water Microwave Product Series (SWAMPs).

The primary sink of CH$_4$ is the reaction with OH in the troposphere ($\sim454–617$ Tg CH$_4$ yr$^{-1}$), and interannual variations in OH can also contribute to the observed CH$_4$ variability. Tropospheric OH concentrations are influenced by many factors, including temperature, water vapor, O$_3$, NO$_x$, CH$_4$, CO, and the overhead stratospheric ozone column. The TM5-4DVAR inversions performed in this study make use of OH fields from ref. 39, which vary seasonally, but are the same each year. To investigate possible variations caused by the OH sink, we analyze posterior CH$_4$ emissions of LMDz-PYVAR-SACs inversion. In this inversion, the OH fields were optimized simultaneously using methyl chloroform (MCF) measurements (see SM Section 1.3).

Data Analysis. The above mentioned measurements and model outputs have been analyzed by taking their monthly averages and integrating them over three zones over the globe: Tropics (TRO: 30°S to 30°N), Northern Extra Tropics (NET: 30°N to 90°N), Southern Extra Tropics (SET: 90°S to 30°S). The time series of these monthly averages have been detrended and smoothened using a 12 month running mean. The resulting...
Results and Discussion

GOSAT observations. Figure 1b shows detrended and smoothed time series of GOSAT FP XCH₄. During LN11, SET and TRO have increasing XCH₄ (ΔSET = 5.6 ppb and ΔTRO = 2.4) contrasted by a decrease in NET (ΔNET = −2.7 ppb). During LN12, the opposite trends are found: XCH₄ gradually reduced in SET and TRO and increased in NET.

Figure 1c shows the results of TM5-Meteorology simulation. The modeled XCH₄ decreases over NET and increases over SET (ΔSET = 3.7 ppb, ΔNET = −3.9 ppb). These trends can be attributed to the faster inter-hemispheric exchange during La Niña conditions, which transferred additional CH₄ rich air from the Northern Hemisphere to the Southern Hemisphere. Francey et al. found the strongest inter-hemispheric transport of CH₄ during LN11 since 1990. Previous studies have reported such enhancement in inter-hemispheric transport, and consequent increase in CH₄ in the Southern Hemisphere, during the La Niña of 2007–2008 and 1989. During LN12, the strength of anomalies over both regions weakens as inter-hemispheric exchange returns to its normal strength. Modeled XCH₄ over TRO show less variation during LN11. During LN12, the modeled XCH₄ (ΔTRO = −3.3 ppb) explains a major fraction of GOSAT XCH₄ (ΔTRO = −3.6 ppb) variability. It is noteworthy that OH concentrations are not affected in our meteorology simulation as TM5 uses OH fields from Spivakovský et al. Even though these fields don’t vary interannually, temperature variations can still cause variability in the atmospheric CH₄ sink, as the rate constant for reaction with OH is temperature dependent.45

Figure 1d shows the GOSAT FP XCH₄ after correction for variations in atmospheric transport using the TM5-Meteorology simulation, and indicates the fraction of CH₄ variability that can be attributed to variability in CH₄ sources and sinks. An analogous plot showing surface flask-air measurements is given in the SM section 4 and shows similar patterns. During LN11, the largest transport-corrected ΔXCH₄ is seen in TRO (ΔTRO = 2.0 ppb), pointing to higher CH₄ emissions from the tropical continents. As SET does not have large CH₄ surface emissions, it is caused most likely by transport from TRO. This means the transport-corrected anomaly of TRO is transferred to SET.

Emissions and source attribution. Detrended and smoothed time series of the posterior TM5-4DVAR emissions are shown in Fig. 2a. The CH₄ emissions over TRO show a positive anomaly during LN11 (μ₁TRO = 5.9 TgCH₄ yr⁻¹). μ₁TRO is higher by 11.7 TgCH₄ yr⁻¹ in LN11 than in the preceding EN10 (μ₀TRO = −5.8 TgCH₄ yr⁻¹). This can be due to higher CH₄ emissions from tropical wetlands during the La Niña, as suggested by ref. 15. During LN12, the CH₄ emission enhancement over TRO is weaker (μ₁TRO = 3.9

Table 1 summarizes Δ of time series shown in Figs 1 and 2.

| Region | Phase | Δq | µq | ∆q | µq |
|--------|-------|----|----|----|----|
| NET:   | EN10  | −0.85 | −1.60 | 0.74 | 4.58 | −0.05 |
|        | LA11  | −2.66 | −3.86 | 1.20 | 0.01 | −0.03 |
|        | LA12  | 0.31  | 0.38  | −0.08 | −8.91 | 0.03 |
| TRO:   | EN10  | 0.86  | 0.61  | 0.24 | −5.76 | 0.01 |
|        | LA11  | 2.42  | 0.38  | 2.04 | 5.94 | −0.06 |
|        | LA12  | −3.57 | −3.32 | −0.25 | 3.94 | 0.02 |
| SET:   | EN10  | 0.55  | 0.77  | −0.23 | 0.21 | −0.06 |
|        | LA11  | 5.62  | 3.70  | 1.92 | 0.63 | −0.01 |
|        | LA12  | −1.73 | −0.78 | −0.94 | −1.14 | 0.03 |
| GLO:   | EN10  | 0.56  | 1.18  | −0.61 | −0.96 | −0.03 |
|        | LA11  | 0.91  | −0.50 | 1.41 | 7.58 | −0.03 |
|        | LA12  | −1.59 | −1.54 | 0.05 | −6.11 | 0.03 |

Table 1. Δq(i.e. the sum of the derivative) or µq(i.e. mean) of the times series of quantity q, averaged over region r, as shown in Figs 1 and 2 during different ENSO phases. Please note that the GOSAT and TM5-4DVAR time series do not cover the whole EN10 period, as continuous GOSAT measurements are only available since June 2009, and the 12-month smoothing causes data points loss. Only δ₁³C-CH₄ values cover the whole EN10.
TgCH$_4$ yr$^{-1}$). NET has a sharp decrease in CH$_4$ emissions during LN11 ($\Delta$emission$^{-1} = -13$ TgCH$_4$ yr$^{-1}$), which shifts the maximum of the global CH$_4$ emission anomaly towards the beginning of LN11.

Detrended and smoothened time series of $\delta^{13}$C-CH$_4$ is shown in Fig. 2b. During LN11, $\delta^{13}$C-CH$_4$ decreased over each region. Over TRO, we observe a decrease of 0.06‰, which is a larger decrease than the GLO $\delta^{13}$C-CH$_4$ decrease by 0.03‰. An isotope mass balance calculation shows that if the increase in TRO CH$_4$ emissions of 11.7 TgCH$_4$ yr$^{-1}$ (change from EN10 with $\mu_{TRO}^{emission}$ to LN11 with $\mu_{TRO}^{emission}$), is attributed to a biogenic source, it would cause a drop in $\delta^{13}$C-CH$_4$ of similar magnitude. This indicates that the source of the LN11 CH$_4$ anomaly in the Tropics is of biogenic origin. The increase of GLO $\delta^{13}$C-CH$_4$ ($\approx 0.03‰$) over LN12 can be explained by reduced biogenic emissions ($\mu_{GLO}^{emission}$ (LN12) - $\mu_{GLO}^{emission}$ (LN11) = $\sim -14$ TgCH$_4$ yr$^{-1}$) and increased biomass burning emissions ($\mu_{GFED4s}^{emission}$ (LN12) - $\mu_{GFED4s}^{emission}$ (LN11) = 2.2 TgCH$_4$ yr$^{-1}$) in comparison to LN11.

Tropical Biomass burning is strongly influenced by ENSO$^{46}$. Globally, GFED4s biomass burning CH$_4$ emissions indicate a decrease of 0.67 TgCH$_4$ yr$^{-1}$ from EN10 to LN11 (see SM Section 5). The effect of this change on the isotopic composition is only $-0.003‰$, thus much smaller than the observed trend. According to GFED4s, CH$_4$ emissions from biomass burning over TRO during LN11 are close to average over the whole period ($\mu_{TRO}^{GFED4s}$ = $-0.23$ TgCH$_4$ yr$^{-1}$). In LN12, these emissions were higher in NET and TRO ($\mu_{TRO}^{GFED4s}$ = 1.09 TgCH$_4$ yr$^{-1}$ and $\mu_{NET}^{GFED4s}$ = 1.32 TgCH$_4$ yr$^{-1}$). This increase may be explained by higher fuel availability due to enhanced biomass growth during the preceding LN11. Ref. 47 suggested a similar impact of Australian biomass burning on CO$_2$ emissions.

Figure 3a and b show monthly anomalies recorded in climate parameters. A significant redistribution of heat and precipitation is seen during the different phases of ENSO. $\mu_{TRO}^{precipitation}$ was $-1.72$, 4.90, and 0.64 mm during EN10, LN11, and LN12, respectively. During LN11 the precipitation anomaly in TRO (and in GLO) was the highest since the onset of the 21st century (see SM Figure 10). Regions like Australia had six consecutive seasons of increased rainfall over the La Niña of 2011 and 2012$^{48}$. Higher temperatures were observed in NET during LN11 ($\mu_{NET}^{temperature}$ = $-0.18^\circ$C), favoring increased biomass burning, for example, near Moscow during the summer of 2010$^{49,50}$. Mean temperatures during LN11 ($\mu_{TRO}^{temperature}$ = $-0.05^\circ$C) were in between those during EN10 ($\mu_{TRO}^{temperature}$ = $0.15^\circ$C) and LN12 ($\mu_{TRO}^{temperature}$ = $-0.22^\circ$C).

An increase in total inundated area is observed in the remotely sensed SWAMPS data (see Fig. 3c). The total inundated area estimated by the wetland models LPJ-wsl and CLM4.5 also show a similar increase. However, these wetland models estimate a relatively weaker enhancement in CH$_4$ emissions with $\mu_{TRO}^{emission}$ = 1.54 TgCH$_4$ yr$^{-1}$ for LPJ-wsl and $\mu_{TRO}^{emission}$ = 2.38 TgCH$_4$ yr$^{-1}$ for CLM4.5 during LN11 (see SM Section 8).

To further investigate the relation between inversion-estimated CH$_4$ emissions and potential climatic drivers, we examine their correlation coefficients (R) [see SM Figure 11]. CH$_4$ emission anomalies (as shown in

![Figure 3](https://www.nature.com/scientificreports/)
Fig. 2a) correlate stronger with precipitation anomalies than with temperature anomalies (as shown in Fig. 3) in both NET \( R_{\text{precipitation\_emission}} = 0.86 \), \( R_{\text{temperature\_emission}} = -0.52 \) and TRO (\( R_{\text{precipitation\_emission}} = 0.85 \), \( R_{\text{temperature\_emission}} = -0.62 \). This points to precipitation as the more important driver of the \( \text{CH}_4 \) anomaly in TRO during LN11, supported further by the correlation with inundated area (\( R_{\text{inundation\_emission}} = 0.67 \)). This is consistent with the findings of Bloom et al.\(^3\), who show that precipitation plays a more dominant role than temperature in determining anomalous \( \text{CH}_4 \) variability in the Tropics.

To investigate possible variations caused by the OH sink, we analyzed optimized \( \text{CH}_4 \) emissions from a LMDz-PYVAR-SACS inversion, in which OH fields were also optimized. During LN11, the results of this inversion suggest \( \Delta_{\text{TRO}} \text{emission} \) of 9.1 Tg\( \text{CH}_4 \) yr\(^{-1}\), compared to TM5-4DVAR \( \Delta_{\text{TRO}} \text{emission} \) of ~6 Tg\( \text{CH}_4 \) yr\(^{-1}\) (see SM Section 6). The differences in interannual variations of the emission estimates of the two inversions are mainly caused by their different treatment of OH sink. Assuming that the MCF-optimized OH sink of LMDz-PYVAR-SACS is ~3 Tg\( \text{CH}_4 \) yr\(^{-1}\), this is consistent with the hypothesis of an increased \( \text{CH}_4 \) sink during La Niña and a weaker sink during El Niño\(^5\).

Conclusion

Our inversion results, supported by \( \delta^{13}\text{C}-\text{CH}_4 \) measurements, provide strong evidence of enhanced tropical biogenic \( \text{CH}_4 \) emissions by ~6–9 Tg\( \text{CH}_4 \) yr\(^{-1}\), during the La Niña of 2011. Wetlands were the likely cause of this anomaly as a simultaneous increase in total inundated area is shown by remote sensing observations and hydrological models. The increase in inundated area was in response to La Niña induced increase in precipitation. 2011 experienced the strongest La Niña event in the past 4 decades as well as since the onset of modern atmospheric \( \text{CH}_4 \) measurements. It is noteworthy that during this La Niña the increase in global \( \text{CH}_4 \) mole fractions were not as pronounced as a simultaneous decrease in the \( \text{CH}_4 \) emissions in the Northern Extra Tropics. Our analysis presents the first evidence of the large-scale response of wetland \( \text{CH}_4 \) emissions to ENSO variability using satellite retrievals.

Data Availability

We use Level 2 SRFP XCH4 v2.3.7 GOSAT XCH4 retrievals that are publicly available from ESA’s Climate Change Initiative website (www.esa-ghg-cci.org/). NOAA CH4 and INSTAAR \( \delta^{13}\text{C}-\text{CH}_4 \) measurements are freely available from NOAA’s public ftp server (ftp://aftp.cmdl.noaa.gov/data). CSIRO CH4 measurements can be downloaded from the WDCGG (World Data Centre for Green-house Gases) website. GFED4s \( \text{CH}_4 \) emissions can be downloaded from http://daac.ornl.gov.CRUSTS.33). Precipitation and temperature data are held at British Atmospheric Data Centre, BADC, UK (http://badc.nerc.ac.uk/data/cru/). SWAMP wetlands fraction data can be downloaded from http://wetlands.jpl.nasa.gov after a short registration. CLM4.5 and LPJ-wsl \( \text{CH}_4 \) emissions and wetlands fractions can be obtained by contacting William J. Riley and B. Poulter, respectively.

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Author Contributions
S.P., S.H., T.R., I.A. and M.C.K. conceived the research. P.B., S.P., N.B., G.M., W.J.R., X.X., B.P. and Z.Z. developed and ran the computations models. J.W.C.W., E.J.D., R.D., I.A., K.C.M. and O.T. provided data. S.P. and M.C.K.
analyses the data and model outputs. S.P., S.H., M.C.K. and T.R. wrote the manuscript with suggestion from all the authors.

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