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nature climate change

Brief Communication

https://doi.org/10.1038/s41558-023-01629-0

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Received: 7 September 2022

Accepted: 10 February 2023

Published online: 20 March 2023

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The positive response of wetland methane (CH_4) emissions to climate change is an important yet uncertain Earth-system feedback that amplifies atmospheric CH_4 concentrations. Here, using a wetland model, we report intensified wetland CH_4 emissions during 2000–2021, corresponding with 2020 and 2021 being exceptional years of growth. Our results highlight the need for sustained monitoring and observations of global wetland CH_4 fluxes to document emerging trends, variability and underlying drivers.

Methane (CH_4) is a potent greenhouse gas with a warming potential that is 84 times stronger than CO_2 on a 20-year horizon[1]. Because of its relatively short lifetime (~10 years) in the atmosphere, anthropogenic methane emission reductions are an important mitigation option for limiting near-term warming well below a 1.5 °C or 2 °C increase in global temperature[2,3]. The rapidly rising atmospheric methane concentrations in recent decades in addition to the record-high growth rates in 2020 and 2021 (hereafter, 2020/2021) raise concerns, however, that climate change is amplifying natural CH_4 emissions. The reason for the recent rise of methane is still unclear because of the limited understanding of the interplay between methane sources and sinks. However, the continuously depleting trend of atmospheric ^{13}C-CH_4 suggest probably strong contributions from increasing biogenic sources[4–8], pointing to either constant increases from agricultural and waste sectors or wetland CH_4 feedback, or both. Here we report synergies between climate change and the rapid increase in global wetland CH_4 emissions in recent years.

Paleoclimate records suggest that positive warming–wetland CH_4 feedbacks can increase atmospheric methane during rapid, decadal, time scales[9,10]. The wetland CH_4 feedback to global warming is mainly hypothesized to be a result of (1) the effect of rising temperatures on microbial activities (for example, methanogenesis) and on thawing permafrost and (2) the expansion of wetlands with increased total precipitation, to the first order due to the physical relationship (that is, the Clausius–Clapeyron relationship) between rising temperatures and atmospheric water content[11]. Future climate projections[12,13] suggest that wetland emissions will increase by 30–50 $TgCH_4\,yr^{-1}$ globally by 2050 with respect to the 2010 level in the Representative Concentration Pathway (RCP8.5) scenario, in which warming follows emissions trajectories that exceed 3–5 °C. Assuming that anthropogenic methane emissions must decline by 30–60%[14] (~122 $TgCH_4\,yr^{-1}$) for warming to stay below 1.5 °C, this projected increase of wetland emissions could offset 25–40% of the reduction. Recent observational studies suggest that the tropical hydrological cycle has already intensified due to strengthened Walker circulation[15]. In higher latitudes, long-term warming[16] appears to be driving increases in growing-season emissions of wetland methane[17]. Satellite-based observations suggest increases in tropical biogenic CH_4 emissions may already be driving the atmospheric CH_4 upward[18–20] due to intensified rainfall and rising temperature.

Despite the potential for positive methane–climate feedbacks from global wetlands, most Earth System Models (ESMs) and Integrated Assessment Models (IAMs) that informed the last Assessment Report of the IPCC do not directly incorporate this process. These models focus on long-term atmospheric methane concentration increases coming from human activities such as industry and agriculture. From a modelling perspective, wetland emissions are considered to impact mainly the interannual variability (IAV) in the atmospheric CH_4 growth rate (except for years with severe fire events when biomass burning emissions play a larger role), which is regulated by climate phenomena such as the El Niño-Southern Oscillation[21].

Here we apply a wetland methane model developed to represent tropical and permafrost wetlands with two different climate datasets, one based on ground meteorological stations and one from reanalysis, to evaluate climate-change-driven wetland CH_4 emissions from

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https://doi.org/10.1038/s41558-023-01629-0

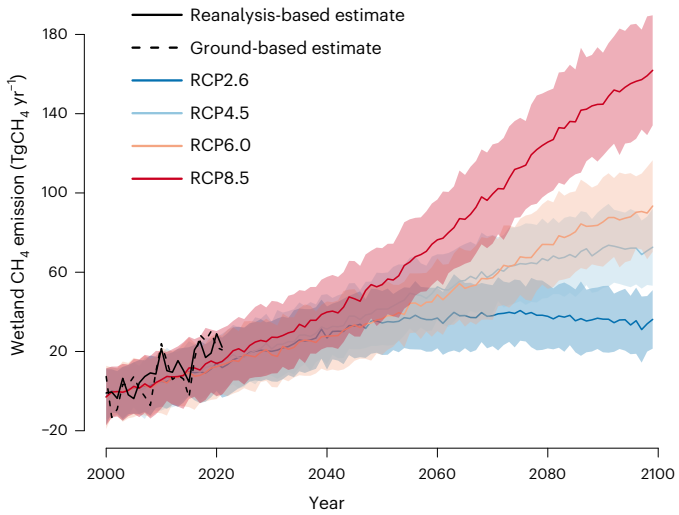

Fig. 1 | Temporal trends and variations in wetland CH_4 emissions during 2000–2021 relative to the baseline of 2000–2006 level in comparison to future projections[12]. Shaded areas present 1σ range of the estimates from each future RCP. Annual total emissions from two estimates based on two climate forcing datasets, a ground-based dataset from the CRU at the University of East Anglia and a reanalysis-based MERRA2. Coloured lines represent ensemble mean of each future projection scenario.

2000 to 2021. The CH_4 emission parameterizations are calibrated against a benchmark dataset of wetland fluxes from an independent atmospheric inversion[22] and thus differ with the two climate datasets (Methods). This treatment is for consistency with the setup of a previous future projection study[12], which used the same land surface model driven by a full ensemble of bias-corrected Coupled Model Intercomparison Project Phase 5 (CMIP5) climate datasets.

We estimate that the wetland CH_4 emissions from simulations based on ground-based and reanalysis-based climate forcing significantly increased ($P < 0.01$; linear regression) at a rate of 1.3–1.4 $TgCH_4\,yr^{-1}$ from 2000 to 2021 (Fig. 1). The estimated increase is higher than the ensemble average under the high warming climate scenario RCP8.5 (at 0.9 $TgCH_4\,yr^{-1}$)[12]. The larger wetland CH_4 increases from the observational-based simulations are probably due to the differences in temperature and precipitation between the CMIP5 models and observation-based climate datasets for the wetland regions. This indicates that global wetlands in high-latitude and tropical regions are experiencing stronger impacts of climate change than predicted in the most intensive climate warming in the CMIP5 models. The simulated wetland dynamics based on a prognostic hydrologic approach shows a good agreement with the land-water mass anomalies from the Gravity Recovery and Climate Experiment satellite (Supplementary Fig. 1).

Global mean annual emissions for 2007–2021 due to climate change impacts on wetlands increased by 5–6% (8–10 $TgCH_4\,yr^{-1}$) relative to the 2000–2006 baseline (Fig. 2a). The positive anomalies

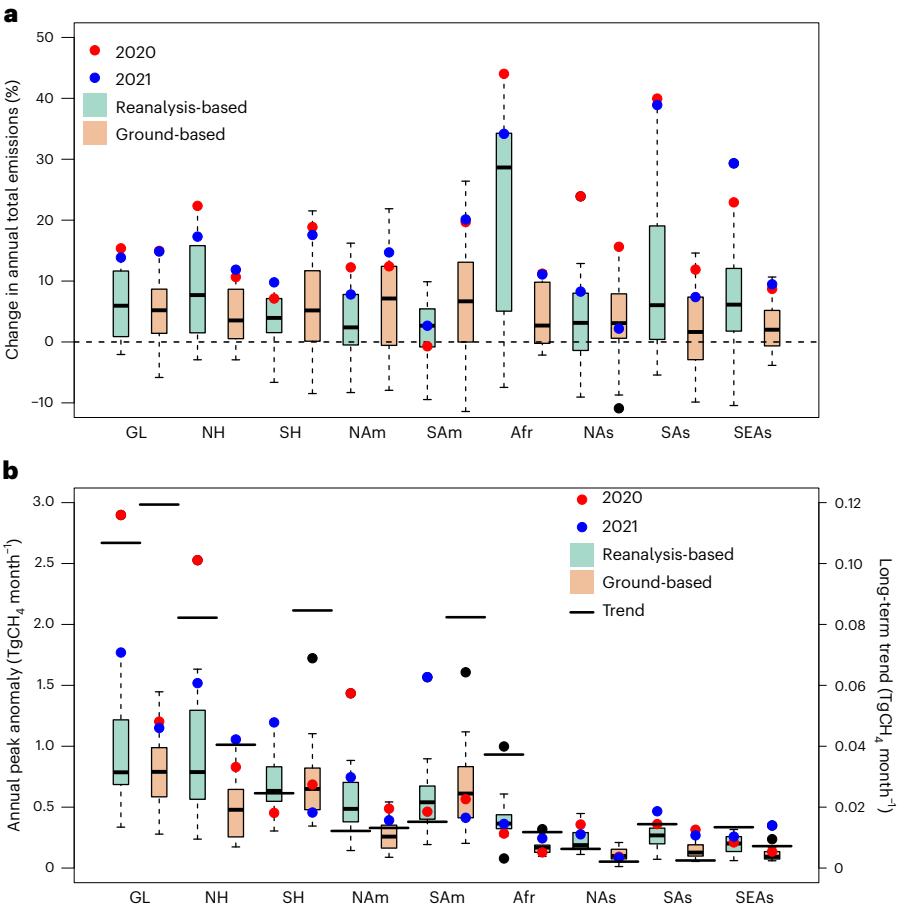

Fig. 2 | Regional changes in wetland CH_4 emissions. a, Anomaly of annual emissions (%) from 2000–2021 ($n = 22$) relative to the mean of its 2000–2006 level for major regions. **b**, Detrended and deseasonalized annual emission anomaly and linear fitted trends for 2000–2021 ($n = 22$). The spread of data represents IAV of corresponding metrics. The central mark and the bottom and top edges of the box indicate the median, and the 25th and 75th percentiles, respectively. The black whiskers extend to the most extreme data points not considered outliers, which are denoted as dots. The black dots are outliers for individual years that are not 2020/2021. The region mask is defined in Supplementary Fig. 2. GL, Global; NH, Northern Hemisphere; SH, Southern Hemisphere; NAm, North America; SAm, South America; Afr, Africa; NAs, North Asia; SAs, South Asia; SEAs, Southeast Asia.

are 14–26 $TgCH_4\,yr^{-1}$ in 2020 and 13–23 $TgCH_4\,yr^{-1}$ in 2021, each of which has a 5% probability of occurring in the 20-year horizon when excluding the positive trend. The uncertainties of annual estimates reflect different IAV across regions, with reanalysis-based estimates generally giving a higher variability than observational-based estimates. Both simulations suggest that tropical wetlands dominate the increase, although with diverse regional differences (Extended Data Fig. 1), mainly due to uncertainty in spatiotemporal patterns of precipitation between the two climate forcing datasets (Extended Data Fig. 2). The simulations driven by the ground-based climate forcing data indicate trends over South America as the single largest contributor, while the reanalysis-based simulations suggest that trends over Africa, South Asia and Southeast Asia are also responsible for high emissions. Despite the difference in estimated emissions magnitudes and regional changes, both simulations agree that tropical wetlands are emerging hotspots, with 2020 and 2021 being highly anomalous years. This finding is in line with recent atmospheric inversions[18,20,23], which suggest that tropical methane emissions contributed to a large portion of the atmospheric methane growth rate in 2020 and 2021.

The detrended and deseasonalized time series (Fig. 2b) shows that the global annual anomalies in 2020 and 2021 are larger than 1σ for the period of 2000–2021 in the reanalysis-based simulation. Even though no strong peak anomalies are detected by the ground-based run, the positive trends are higher than those of the reanalysis-based run (Extended Data Fig. 3). This is mainly due to different parameterization schemes against the different climatic forcings, which results in higher temperature sensitivity and lower wetland extent in the ground-based run compared to the reanalysis-based run (Supplementary Table 3). The reanalysis-based simulation suggests that Africa has a 3σ anomalous peak CH_4 emission in 2019 due to extremely large rainfall events, which coincides with strong XCH_4 (that is, column-averaged CH_4 concentration) enhancement during 2019 over East Africa recorded by two satellite datasets[24]. This pattern is not captured by the ground-based run, highlighting the influence of precipitation inputs on CH_4 estimation for regions with sparse measurements (see Methods for the descriptions about climatic inputs).

Our results suggest the probable emergence of a strong positive wetland CH_4 feedback under current climate-change-driven warming and changes in precipitation. With the uncertainty in climate datasets, it is unclear whether rising temperature or strengthened precipitation plays a more prominent role in the rise of wetland CH_4. Further evidence of intensified wetland CH_4 emissions from top-down inversions would help constrain the representation of processes and parameter uncertainties in the land surface models. Sustained and enhanced multiscale monitoring and observations will also help track sources and changes of methane emissions, particularly in remote areas[25,26] that have sparse measurement coverage and strong potential for climate feedbacks, like many tropical wetlands. While the high-latitude wetlands appear to have only moderate CH_4 increases, the climate–permafrost thaw feedback on future CH_4 emissions remains a concern[12]. The emergence of a wetland–climate feedback emphasizes that coordination between the scientific community on integrating rapidly changing biospheric processes within remaining carbon budgets is a priority for staying below 1.5 °C and 2.0 °C.

Online content

Any methods, additional references, Nature Portfolio reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41558-023-01629-0.

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Methods

LPJ-wsl model

The Lund–Potsdam–Jena-Wald, Schnee and Landschaft (LPJ-wsl) model applied in this study is a process-based dynamic global vegetation model developed for carbon cycle applications. This study extends the Zhang et al.[27] analysis, which ended in 2016, through to 2021. The LPJ-wsl model accounts for the major global processes controlling wetland CH_4 emissions such as soil permafrost, the rate of microbial decomposition and wetland extent dynamics. The version of the LPJ-wsl model applied in this study includes a hydrology model, TOPMODEL, to determine the wetland area and its inter- and intra-annual dynamics[28], a permafrost and dynamic snow model[29], and a wetland CH_4 emission model[30], 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_4 emissions. The permafrost module simulates the freeze–thaw cycle for eight discrete layers of soil thickness, where the soil heat capacity and its thermal conductivity are affected by the volumetric fractions of the soil physical components, such as the water–ice fraction, mineral soil or peat.

Wetland CH_4 module

Generally, wetland CH_4 emissions are modelled as a function of the CH_4 emitting factor, soil temperature at the upper soil depth (0–50 cm), ecosystem heterotrophic respiration and wetland extent. The CH_4 emitting factor (F) for grid cell X is calculated as a combination of latitudinal scaling factors and surface temperature using the equation:

$$F(X) = \sigma(X) F_{\mathrm{T}} + (1 - \sigma(X)) F_{\mathrm{B}} \quad (1)$$

where $\sigma(X)$ is $\exp(T(X) - T_{\max})$, $T(X)$ is the mean soil temperature between 1960 and 1990 at 0–50 cm depth, and maximum temperature $T_{\max}$ = 303.35 K. F_{T} and F_{B} are two latitudinal factors representing typical tropical and boreal wetlands, respectively. F_{T} and F_{B} were fit to match a benchmark of wetland CH_4 fluxes from an independent atmospheric inversion study[22] for consistency with the magnitude of the future projection study[12], which estimated global wetland emissions at ~172 $TgCH_4\,yr^{-1}$ in 2004. For Climatic Research Unit (CRU) runs, monthly climatic inputs for temperature, precipitation, number of wet days and cloud cover are used, while for Modern-Era Retrospective analysis for Research and Applications Version 2 (MERRA2) runs, daily climatic inputs for temperature, precipitation, shortwave radiation and longwave radiation are used. The calibrated F_{T} and F_{B} are 0.0851 and 0.0333, respectively, for MERRA2 runs and 0.1281 and 0.0109, respectively, for CRU runs. The modelled coefficient Q10 that represents the soil temperature dependency of the net CH_4 flux was compared with the values that are extracted from the FLUXNET-CH4, a global database of 47 eddy-covariance measurements[31–33] covering global wetlands, to evaluate the effect of temperature on CH_4 emission predictions. The Q10 metric is extracted from the exponential fit of CH_4 emissions to soil temperature at a 0–50 cm depth using the following equation:

$$Q10 = (R_2/R_1)^{\left(\frac{10}{T_2 - T_1}\right)} \quad (2)$$

where R_1 and R_2 are the CH_4 flux at temperatures T_1 and T_2, respectively. The results suggest that the LPJ-modelled temperature dependence for each season (Supplementary Fig. 3) is generally comparable with the observational estimates and is slightly lower than the measurements during spring (March, April, May), summer (June, July, August) and autumn (September, October, November). The LPJ-wsl model is shown to have relatively low weighted root mean square error compared to satellite-constrained top-down wetland CH_4 estimates among process-based wetland CH_4 models when compared with atmospheric measurements[34]. Notably, recent studies show that process-based wetland models underestimate the magnitude of annual total emissions for some of the underrepresented tropical wetland hotspots, such as African wetlands[25] and South American wetlands[26].

Model simulations

Two gridded meteorological datasets were used for the simulations. The ground-based input dataset was a monthly climatic observation (denoted as CRU) based on meteorological stations that was developed by the CRU at the University of East Anglia. The reanalysis-based climate dataset was a daily climatic dataset from one-hourly reanalysis MERRA2 from the National Aeronautics and Space Administration Global Modeling and Assimilation Office. The CRU dataset is formed by interpolation of site-level measurements to cover land worldwide, while the MERRA2 reanalysis relies on atmospheric models that assimilate multiple sources from satellite observations and ground measurements. The difference in methodology between these two types of climatic inputs results in different spatiotemporal variability in climate variables, especially for precipitation which determines the spatiotemporal patterns of wetland inundation dynamics. Two sets of factorial runs for the period of 2007–2021 were conducted with the climatology data of CRU and MERRA2 to disentangle the drivers of post-2007 wetland methane emissions on CH_4 emissions (Supplementary Table 2). Each set of factorial runs included four runs forced with climatological values (average monthly and/or daily fields for 2000–2006) for air temperature, precipitation and CO_2 concentration. The difference between the baseline simulation and factorial runs provides the individual contributions of climate variables to the anomaly of CH_4 emissions in the post-2007 period.

Decomposition of the time series

The changes in wetland emissions were due to a combination of long-term trends, seasonal cycles and anomalies (IAV, peak emission of a year is especially notable). The components were calculated using equation (3):

$$\mathrm{Y}[\mathrm{t}] = \mathrm{T}[\mathrm{t}] + \mathrm{S}[\mathrm{t}] + \mathrm{r}[\mathrm{t}] \quad (3)$$

The function first determines the trend component $T[t]$ for time t using a 12-month moving average with equal weights. The seasonal component $S[t]$ is then centred. The residual $r[t]$ is the anomaly that is determined by removing trends and seasonal cycles from the original time series.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

All the wetland CH_4 emission data[35] and regional masks used in this study are available in the publicly accessible Zenodo repository (https://doi.org/10.5281/zenodo.7595223).

Code availability

Code and documentation for the LPJ-wsl model[36] is publicly available at https://github.com/ben-poulter/LPJ-wsl_v2.0.git.

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Acknowledgements

This research was funded by National Natural Science Foundation of China Basic Science Center for Tibetan Plateau Earth System project (NSFC BSCTPES No. 41988101), the NASA CYGNSS grant no. 20-CYGNSS20-0038, and Woodwell Climate Research Center Subaward no. #WOODWELL-3PAU01-01. We acknowledge support from NASA's Terrestrial Ecology Program and Carbon Monitoring System. A.F.F. was supported by an appointment to the NASA Postdoctoral Program at the NASA Goddard Space Flight Center, administered by Oak Ridge Associated Universities under contract with NASA. Correspondence and request for materials should be addressed to Z.Z. (email: yuisheng@gmail.com).

Author contributions

Z.Z. and B.P. designed the study. Z.Z. performed the simulations and analysed the data. Z.Z., B.P., A.F.F., Q.Y., P.C., S.P. and X.L. wrote the paper.

Competing interests

The authors declare no competing interests.

Additional information

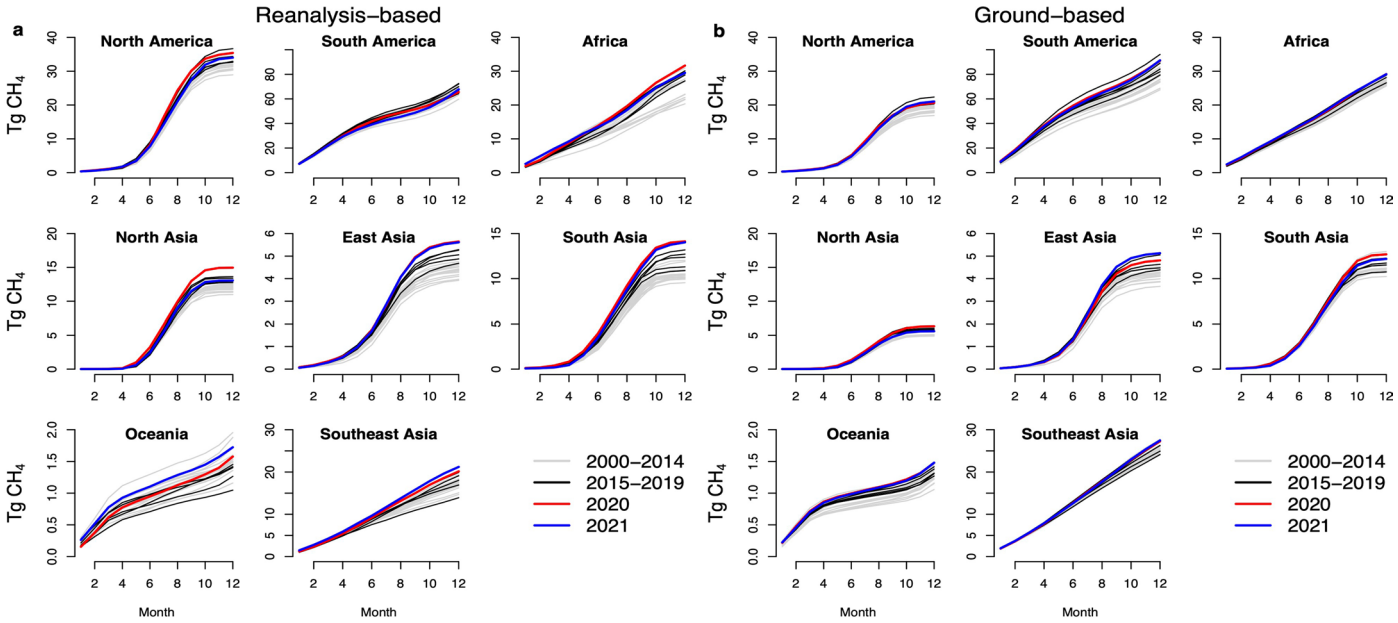
Extended data is available for this paper at https://doi.org/10.1038/s41558-023-01629-0.

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s41558-023-01629-0.

Correspondence and requests for materials should be addressed to Zhen Zhang.

Peer review information *Nature Climate Change* thanks Xin Lan, Jacob Shaw and the other, anonymous, reviewer(s) for their contribution to the peer review of this work.

https://doi.org/10.1038/s41558-023-01629-0



Extended Data Fig. 1 | Cumulative monthly wetland CH_4 emissions for individual years by region. (**a**) the reanalysis-based estimate forced by MERRA2 and (**b**) the ground-based estimate forced by CRU.

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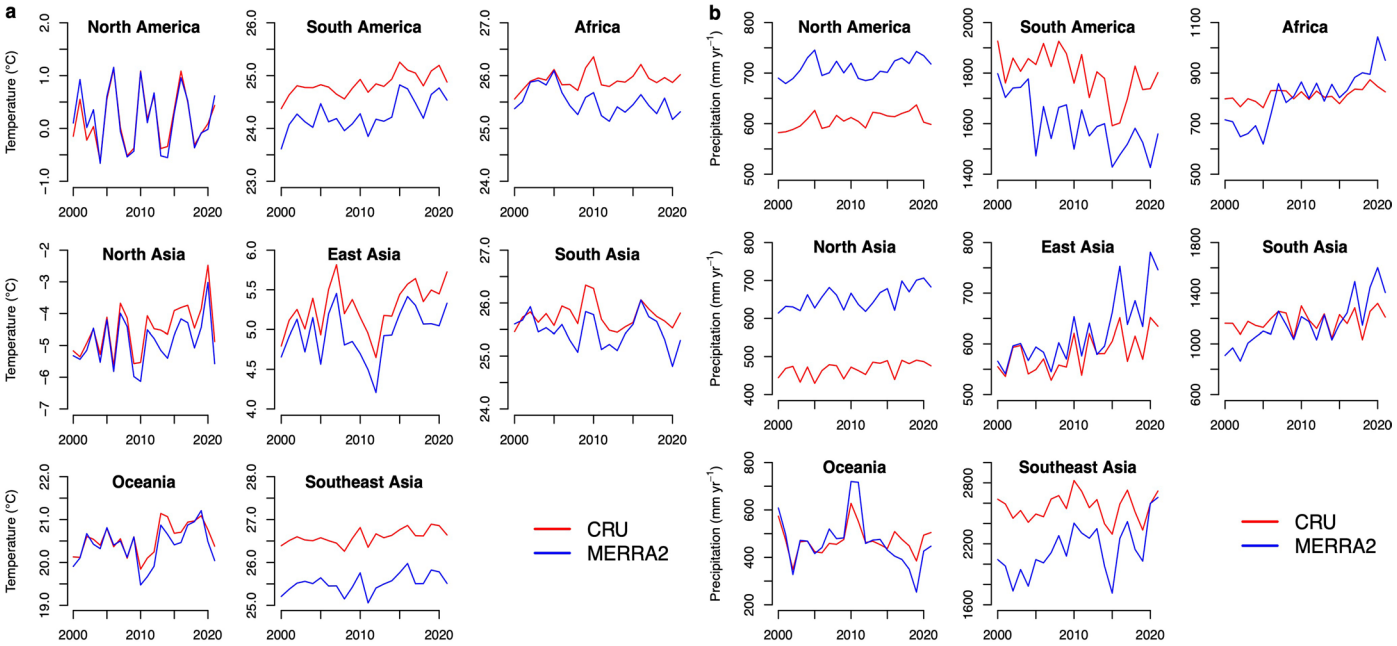
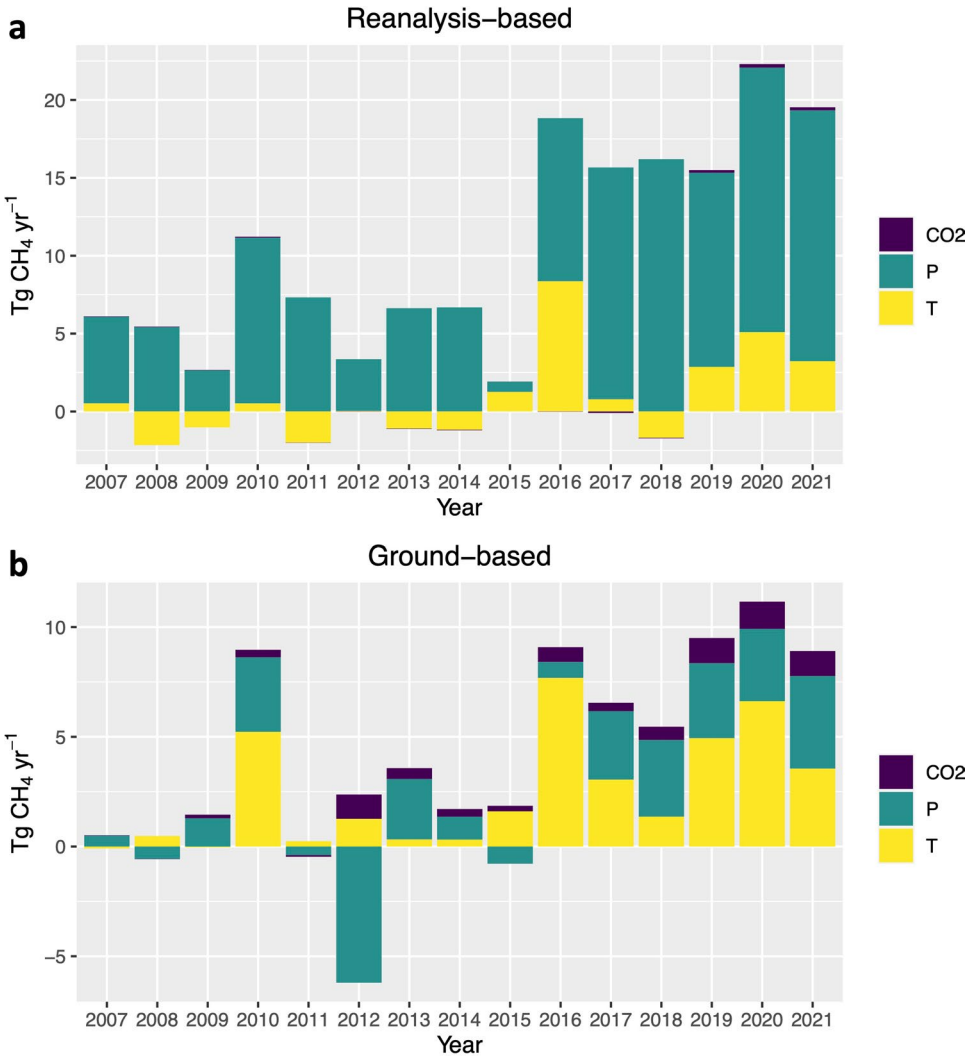


Extended Data Fig. 2 | Temporal variations of major climatic variables for 2000-2021. (a) annual mean temperature (°C) and (b) annual total precipitation (mm yr-1) for wetland regions from CRU and MERRA2. The wetland mask is defined by maximum areal extent of a wetland extent product Wetland Area and Dynamics for Methane Modeling (WAD2M)[37].

https://doi.org/10.1038/s41558-023-01629-0



Extended Data Fig. 3 | Attribution of the changes in wetland CH_4 emissions for 2007-2021. Three major factors (P: Precipitation; T: Temperature; CO2: atmospheric CO_2 concentration) are used for 2007–2021 relative to mean of 2000–2006 calculated from the factorial experiments (Supplementary Table 1).

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Last updated by author(s): Feb 6, 2023

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n/a	Confirmed	
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☐	☒	For Bayesian analysis, information on the choice of priors and Markov chain Monte Carlo settings
☐	☒	For hierarchical and complex designs, identification of the appropriate level for tests and full reporting of outcomes
☐	☒	Estimates of effect sizes (e.g. Cohen's *d*, Pearson's *r*), indicating how they were calculated

Our web collection on statistics for biologists contains articles on many of the points above.

Software and code

Policy information about availability of computer code

Data collection	Dynamic global vegetation model LPJ-wsl was used for the simulations.
Data analysis	Code and documentation for the LPJ-wsl model is publicly available at https://github.com/benpoulter/LPJ-wsl_v2.0.git. All the analyses were conducted with R 4.0.2 for Mac OS High Slerra 10.13.6. The R package used for the zonal analysis are freely available on CRAN at: https://cran.r-project.org/web/packages/raster/index.html.

For manuscripts utilizing custom algorithms or software that are central to the research but not yet described in published literature, software must be made available to editors and reviewers. We strongly encourage code deposition in a community repository (e.g. GitHub). See the Nature Portfolio guidelines for submitting code & software for further information.

Data

Policy information about availability of data

All manuscripts must include a data availability statement. This statement should provide the following information, where applicable:

- Accession codes, unique identifiers, or web links for publicly available datasets
- A description of any restrictions on data availability
- For clinical datasets or third party data, please ensure that the statement adheres to our policy

All the wetland CH4 emission data and regional masks used in this study are available in the publicly accessible Zenodo repository (doi: 10.5281/zenodo.7595223).

Human research participants

Policy information about studies involving human research participants and Sex and Gender in Research.

Reporting on sex and gender	N/A
Population characteristics	N/A
Recruitment	N/A
Ethics oversight	N/A

Note that full information on the approval of the study protocol must also be provided in the manuscript.

Field-specific reporting

Please select the one below that is the best fit for your research. If you are not sure, read the appropriate sections before making your selection.

☐ Life sciences ☐ Behavioural & social sciences ☒ Ecological, evolutionary & environmental sciences

For a reference copy of the document with all sections, see nature.com/documents/nr-reporting-summary-flat.pdf

Ecological, evolutionary & environmental sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description	The study analyze the spatio-temporal variations of terrestrial wetland methane (CH4) for 1980-2021.
Research sample	The data used in this study are from dynamic global vegetation model LPJ-wsl.
Sampling strategy	All the data available were used.
Data collection	Data were recorded using numeric model.
Timing and spatial scale	The dataset used are monthly and we use the results for 1980-2021. The wetland CH4 estimates cover global land. The spatial resolution is 0.5 deg.
Data exclusions	We did not exclude any simulated results from the wetland methane model.
Reproducibility	We did not collect measurements directly but use a dynamic global vegetation model that is publicly available on Github. We will also release a reproducibility work flow for the data processing.
Randomization	Permutation and randomization were not used in this study because the wetland CH4 model is a deterministic model.
Blinding	Blinding was not needed in this study because we do not have treatments.

Did the study involve field work? ☐ Yes ☒ No

Reporting for specific materials, systems and methods

We require information from authors about some types of materials, experimental systems and methods used in many studies. Here, indicate whether each material, system or method listed is relevant to your study. If you are not sure if a list item applies to your research, read the appropriate section before selecting a response.

Materials & experimental systems

n/a	Involved in the study
☒	☐ Antibodies
☒	☐ Eukaryotic cell lines
☒	☐ Palaeontology and archaeology
☒	☐ Animals and other organisms
☒	☐ Clinical data
☒	☐ Dual use research of concern

Methods

n/a	Involved in the study
☒	☐ ChIP-seq
☒	☐ Flow cytometry
☒	☐ MRI-based neuroimaging