FLUXNET-CH4: A global, multi-ecosystem dataset and analysis of methane seasonality from freshwater wetlands

Kyle B. Delwiche1, Sara Helen Knox2, Avni Malhotra3, Etienne Fluet-Chouinard1, Gavin McNicol1, Sarah Feron1, Zutao Ouyang1, Dario Papale4,5, Carlo Trotta6, Eleonora Canfora3, You-Wei Cheah7, Danielle Christianson8, M. M. Carmelita R. Alberto7, Pavel Alekseychik8, Mika Aurela9, Dennis Baldocchi10,11, Sheel Bansal11, David P. Billesbach12, Gil Bohrer13,

1 Department of Earth System Science, Stanford University, Stanford, California
2 Department of Geography, The University of British Columbia, Vancouver, British Columbia, Canada
3 Department of Physics, University of Santiago de Chile, Santiago, Chile
4 Dipartimento per la Innovazione nei Sistemi Biologici, Agroalimentari e Forestali, Università degli Studi della Tuscia, Largo dell’Universita, Viterbo, Italy and Forestali, Universita
euroMediterranean Center on Climate Change CMCC, Lecce, Italy
Earth and Environmental Sciences Area, Lawrence Berkeley National Lab, Berkeley, California
International Rice Research Institute, Los Banos, Laguna, Philippines
Natural Resources Institute Finland (LUKE), Helsinki, Finland
Finnish Meteorological Institute, PO Box 501, 00101 Helsinki, Finland
Department of Environmental Science, Policy and Management, University of California, Berkeley, CA, USA
U.S. Geological Survey, Northern Prairie Wildlife Research Center, 8711 37th St Southeast, Jamestown, ND
58401 USA
University of Nebraska-Lincoln, Department of Biological Systems Engineering, Lincoln, NE 68583, USA
Department of Environmental Science, Policy and Management, University of California, Berkeley, CA, USA
U.S. Geological Survey, Northern Prairie Wildlife Research Center, 8711 37th St Southeast, Jamestown, ND
58401 USA
University of Nebraska-Lincoln, Department of Biological Systems Engineering, Lincoln, NE 68583, USA
Department of Environmental Science, Policy and Management, University of California, Berkeley, CA, USA
U.S. Geological Survey, Northern Prairie Wildlife Research Center, 8711 37th St Southeast, Jamestown, ND
58401 USA
University of Nebraska-Lincoln, Department of Biological Systems Engineering, Lincoln, NE 68583, USA
Department of Environmental Science, Policy and Management, University of California, Berkeley, CA, USA
U.S. Geological Survey, Northern Prairie Wildlife Research Center, 8711 37th St Southeast, Jamestown, ND
58401 USA
Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, PR China.
Climate and Ecosystem Sciences Division, Lawrence Berkeley National Lab, Berkeley, CA 94702, USA
Universidade de Cuiaba, Cuiaba, Mato Grosso, Brazil
Dept of Atmospheric and Oceanic Sciences, University of Wisconsin-Madison, Madison, WI 53706 USA
Department of Ecology and Evolutionary Biology, Princeton University, Princeton NJ, USA
Department of Earth Sciences, Vrije Universiteit, Amsterdam, Netherlands
School of Biology and Environmental Science, University College Dublin, Ireland
University of Alaska Fairbanks, Institute of Arctic Biology, Fairbanks, AK, USA
C NR - institute for Mediterranean Agricultural and Forest Systems, Piazzale Enrico Fermi, 1 ,Portici (Napoli), Italy
University of Copenhagen, Department of Geosciences and Natural Resource Management
Institute of Meteorology and Climate Research - Atmos. Environ. Research, Karlsruhe Institute of Technology (KIT Campus Alpin), 82467 Garmisch-Partenkirchen, Germany
Max Planck Institute for Biogeochemistry, Jena, Germany
ISTO, Université d’Orléans, CNRS, BRGM, UMR 7327, 45071, Orléans, France
Okavango Research Institute, University of Botswana, Maun, Botswana.
GFZ German Research Centre for Geosciences, Telegrafenberg, 14473 Potsdam, Germany
Manasik Whenua - Landscape Research, Lincoln, NZ
Université de Montréal, Département de géographie, Université de Montréal, Montréal, QC H2V 0B3, Canada
Canada & Dalhousie University, Department of Physics and Atmospheric Science, Halifax, NS B2Y 1P3, Canada
UK Centre for Ecology and Hydrology, Edinburgh, UK
Woods Institute for the Environment, Stanford University, Stanford, California
Research Faculty of Agriculture, Hokkaido University, Sapporo, Japan
Northern Research Station, USDA Forest Service, Durham, NH 03824, USA
Department of Environmental Science, Faculty of Science, Shinshu University
Stockholm University, Department of Geological Sciences
University of Rostock, Rostock, Germany
National Center for Agro Meteorology, Seoul, South Korea
Department of Geography, University of Tartu, Vanemuise st 46, Tartu, 51410, Estonia
Department of Forestry and Environmental Resources, North Carolina State University, Raleigh, NC, USA
Vegetation Ecology, Institute of Ecology and Landscape, Department Landscape Architecture, Weihenstephan-Triesdorf University of Applied Sciences, Am Hofgarten 1, 85354 Freising, Germany
Department of Geography and Resource Management, The Chinese University of Hong Kong, Shatin, New Territories, Hong Kong SAR, China
Institute for Atmospheric and Earth System Research/Physics, Faculty of Science, University of Helsinki, Helsinki, Finland
Abstract. Methane (CH\textsubscript{4}) emissions from natural landscapes constitute roughly half of global CH\textsubscript{4} contributions to the atmosphere, yet large uncertainties remain in the absolute magnitude and the seasonality of emission quantities and drivers. Eddy covariance (EC) measurements of CH\textsubscript{4} flux are ideal for constraining ecosystem-scale CH\textsubscript{4} emissions, including their seasonality, due to quasi-continuous and high temporal resolution of CH\textsubscript{4} flux measurements, coincident measurements of carbon dioxide, water, and energy fluxes, lack of
ecosystem disturbance, and increased availability of datasets over the last decade. Here, we 1) describe the newly published dataset, FLUXNET-CH4 Version 1.0, the first open source global dataset of CH4 EC measurements (available at https://fluxnet.org/data/fluxnet-ch4-community-product/). FLUXNET-CH4 includes half-hourly and daily gap-filled and non gap-filled aggregated CH4 fluxes and meteorological data from 79 sites globally: 42 freshwater wetlands, 6 brackish and saline wetlands, 7 formerly drained ecosystems, 7 rice paddy sites, 2 lakes, and 15 uplands. Then, we 2) evaluate FLUXNET-CH4 representativeness for freshwater wetland coverage globally, because the majority of sites in FLUXNET-CH4 Version 1.0 are freshwater wetlands. Bottom-up and top-down estimates of CH4 emissions vary considerably across latitudinal bands. In freshwater wetlands (except those between 20° S to 20° N) the spring onset of elevated CH4 emissions starts three days earlier, and the CH4 emission season lasts 4 days longer, for each degree C increase in mean annual air temperature. On average, the spring onset of increasing CH4 emissions lags soil warming by one month, with very few sites experiencing increased CH4 emissions prior to the onset of soil warming. In contrast, roughly half of these sites experience the spring onset of rising CH4 emissions prior to the spring increase in gross primary productivity (GPP). The timing of peak summer CH4 emissions does not correlate with the timing for either peak summer temperature or peak GPP. Our results provide seasonality parameters for CH4 modeling, and highlight seasonality metrics that cannot be predicted by temperature or GPP (i.e., seasonality of CH4 peak). The FLUXNET-CH4 dataset provides an open-access resource for CH4 flux synthesis, has a range of applications, and is unique in that it includes coupled measurements of important CH4 drivers such as GPP and temperature. Although FLUXNET-CH4 could certainly be improved by adding more sites in tropical ecosystems and by increasing the number of site-years at existing sites, it is a powerful new resource for diagnosing and understanding the role of terrestrial ecosystems and climate drivers in the global CH4 cycle. Future additions of sites in tropical ecosystems and site-years of data collection will provide added value to this database. All seasonality parameters are available at https://doi.org/10.5281/zenodo.4408468. Additionally, raw FLUXNET-CH4 data used to extract seasonality parameters can be downloaded from https://fluxnet.org/data/fluxnet-ch4-community-product/, and a complete list of the 79 individual site data DOIs is provided in Table 2 in the Data Availability section of this document.

1 Introduction

Methane (CH4) has a global warming potential that is 28 times larger than carbon dioxide (CO2) on a 100-year time scale (Myhre et al., 2013), and its atmospheric concentration has increased by >1000 ppb since 1800 (Etheridge et al., 1998). While atmospheric CH4 concentrations are substantially lower than those of CO2, CH4’s higher effectiveness at absorbing longwave radiation means that CH4 has contributed 20-25% as much radiative forcing as CO2 since 1750 (Etminan et al., 2016). Despite its importance to global climate change, natural CH4 sources and sinks remain poorly constrained, and with uncertain attribution to the various biogenic and anthropogenic sources (Saunois et al., 2016, 2020). Bottom-up and top-down estimates differ by 154 TGTg/yr (74 TGTg/yr versus 591 TGTg/yr, respectively), much of this difference arises from natural sources (Saunois et al., 2020). Vegetated wetlands and inland water bodies account for most natural CH4 emissions, as well as the majority of uncertainty in bottom-up emissions estimates (Saunois et al., 2016). Better diagnosis and prediction of terrestrial CH4 sources to the
atmosphere requires high frequency and continuous measurements of CH$_4$ exchange across a continuum of ecological time (hours to years) and space (meters to kilometers) scales.

Tower-based eddy covariance (EC) measurements provide ecosystem-scale CH$_4$ fluxes at high temporal resolution across years, are coupled with measurements of key CH$_4$ drivers such as temperature, water and recent substrate input (inferred from CO$_2$ flux), and thus help constrain bottom-up CH$_4$ budgets and improve CH$_4$ predictions. Although EC towers began measuring CO$_2$ fluxes in the late 1970s (Desjardins 1974; Anderson et al., 1984), and some towers began measuring CH$_4$ in the 1990s (Verma et al., 1992), most CH$_4$ flux EC measurements began within the last decade. Given that many EC CH$_4$ sites are relatively new, the flux community has only recently compiled them for global synthesis efforts (e.g., Chang et al., in press) and is still working to standardize CH$_4$ flux measurements and establish gap-filling protocols (Nemitz et al., 2018; Knox et al., 2019). Furthermore, the growth of EC networks for CH$_4$ fluxes has sometimes taken place in a relatively ad hoc fashion, often at sites that were already measuring CO$_2$ fluxes or where higher CH$_4$ fluxes were expected, potentially introducing bias. The representativeness and spatial distribution of CO$_2$ flux tower networks has/have been assessed to evaluate its ability to upscale fluxes regionally (Hargrove et al., 2003; Hoffman et al., 2013; Papale et al., 2015; Villareal et al., 2018, 2019) and globally (Jung et al., 2009, 2020, Kumar et al., 2016). However, a relatively sparse coverage of CH$_4$ flux towers prompts the question of how well the current observation network provides a sufficient sampling of global or ecosystem-specific bioclimatic conditions.

Broad-scale wetland CH$_4$ seasonality estimates, such as when fluxes increase, peak, and decrease and the predictors of seasonality, remain relatively unconstrained across wetlands globally. These key seasonality metrics vary considerably across high-emitting systems such as wetlands and other aquatic systems (Desjardins, 1974; Dise, 1992; Melloh and Crill 1996; Wåk et al., 2013; Zona et al., 2016; Treat et al., 2018). Few continuous CH$_4$ flux datasets across representative site-years make it difficult to establish trends in seasonal dynamics, though monthly or annually aggregated estimates of CH$_4$ fluxes from different seasons do exist for high latitudes (Zona et al., 2016; Treat et al., 2018). Seasonal variability in freshwater wetland CH$_4$ fluxes is expected to be driven by changes in air and soil temperature, soil moisture (including water table dynamics), and recent carbon substrate availability, which influence the rates of CH$_4$ production and consumption (Lai, 2009; Bridgham et al., 2013; Dean et al., 2018). Temperature has widely been found to strongly affect CH$_4$ flux (Chu et al., 2014; Yvon-Durocher et al., 2014; Sturtevant et al., 2016), but the relationship is complex (Chang et al., 2020) and varies seasonally (Koebsch et al., 2015; Helbig et al., 2017). Methane CH$_4$ flux is also driven by inundation depth since anoxic conditions are typically necessary for methanogenesis (Lai, 2009; Bridgham et al., 2013), though CH$_4$ production under bulk-oxic conditions has been observed (Angle et al., 2017). Substrate availability influences CH$_4$ production potential and is linked with gross primary productivity (GPP) because recent photosynthate fuels methanogenesis though this relationship can vary by ecosystem type, plant functional type and biome (Mengoni et al., 1999; Chanton et al., 2008; Hatala et al., 2012; Lai et al., 2014; Malhotra and Roulet, 2015; Sturtevant et al., 2016), Chanton et al., 2008; Hatala et al., 2012; Lai et al., 2014; Malhotra and Roulet, 2015; Sturtevant et al., 2016). In process models, the seasonality of CH$_4$ emissions from wetlands globally is primarily constrained by inundation (Poulter et al., 2017), with secondary within-wetland influences from temperature and availability of carbon (C) substrates (Melton et al., 2013; Castro-Morales et al., 2018). Bottom-up and top-down global CH$_4$ estimates continue to disagree on total CH$_4$ flux magnitudes and seasonality, including the timing of annual peak emissions (Spahni et al., 2011; Saunois et al., 2020). Thus, the variability and predictors of wetland CH$_4$ seasonality globally remain a knowledge gap that high-frequency and long-term EC data can help fill.

Here, we describe Version 1.0 of the FLUXNET-CH4 dataset (available at https://fluxnet.org/data/fluxnet-ch4-community-product/). Version 1.0 of the dataset expands and formalizes the publication of data scattered among regional flux networks as described previously in Knox et al.— (2019.). FLUXNET-CH4 includes half-hourly and daily gap-filled and non gap-filled aggregated CH$_4$ fluxes and meteorological data from 79 sites globally: 42 freshwater wetlands, 6 brackish and saline wetlands, 7 formerly drained
ecosystems, 7 rice paddy sites, 2 lakes, and 15 upland ecosystems. FLUXNET-CH4 includes an additional 2 wetland sites (RU-Vrk and SE-St1), but they are not available under the CC BY 4.0 data policy and thus are excluded from this analysis. Since the majority of sites in FLUXNET-CH4 Version 1.0 (hereafter referred to solely as “FLUXNET-CH4”) are freshwater wetlands, and freshwater wetlands are a substantial source of total atmospheric CH4 emissions, we use the subset of data from freshwater wetlands to then evaluate the representativeness of freshwater wetland coverage in the FLUXNET-CH4 dataset relative to wetlands globally, and provide the first assessment of global variability and predictors of freshwater wetland CH4 flux seasonality. We quantify a suite of CH4 seasonality metrics and evaluate temperature and GPP (a proxy for recent substrate input) as predictors of seasonality across four latitudinal bands (northern, temperate, subtropical, and tropical). Due to a lack of high-temporal resolution water table data at all sites, our analyses are unable to evaluate the critical role of water table on CH4 seasonality. Here we provide parameters for better understanding and modeling seasonal variability in freshwater wetland CH4 fluxes and generate new hypotheses and data resources for future syntheses.

2. Methods

2.1 FLUXNET-CH4 dataset

2.1.1 History and data description

The FLUXNET-CH4 dataset was initiated by the Global Carbon Project (GCP) in 2017 to better constrain the global CH4 budget (https://www.globalcarbonproject.org/methanebudget/index.htm). Beginning with a kick off meeting in May 2018 in Washington DC, hosted by Stanford University, we coordinated with the AmeriFlux Management Project, the European Ecosystem Fluxes Database, and the ICOS Ecosystem Thematic Centre (ICOS-ETC) to avoid duplication of efforts, as most sites are part of different regional networks (albeit with different data products). We have collected and standardized data for FLUXNET-CH4 with assistance from the regional flux networks, AmeriFlux’s “Year of Methane”, FLUXNET, the EU’s Readiness of ICOS for Necessities of Integrated Global Observations (RINGO) project, and a USGS US. Geological Survey Powell Center working group. FLUXNET-CH4 is a community-led project, so while we developed it with assistance from FLUXNET, we do not necessarily use standard FLUXNET data variables, formats, or methods.

FLUXNET-CH4 includes gap-filled half-hourly CH4 fluxes and meteorological variables. Gaps in meteorological variables (TA - air temperature, SW_IN - incoming shortwave radiation, LW_IN - incoming longwave radiation, VPD - vapor pressure deficient, PA - pressure, P - precipitation, WS - wind speed) were filled with the ERA-Interim (ERA-I) reanalysis product (Vuichard and Papale, 2015). We used the REddyProc package (Wutzler et al., 2018) to filter flux values with low friction velocity (u*) based on relating nighttime u*, to fill gaps in CO2, latent heat, and sensible heat fluxes, and to partition net CO2 fluxes into gross primary production (GPP) and ecosystem respiration (RECO) using both the daytime (Lasslop et al., 2010) and nighttime (Reichstein et al., 2005) approaches in REddyProc. Data gaps of CH4 flux data-gaps were filled using artificial neural network (ANN) methods first described in Knox et al. (2015) and in Knox et al. (2019), and summarized here in Sect. 2.1.2. Gap-filled data for gaps exceeding two months are provided and flagged for quality. Please see Table B1 for variable description and units, as well as quality flag information. For the seasonality analysis in this paper we excluded data from gaps exceeding two months, and we encourage future users of FLUXNET-CH4 to critically evaluate gap-filled values from long data gaps before including them in analyses (Dengel et al., 2013; Kim et al., 2020).

In addition to half-hourly data, the FLUXNET-CH4 Version 1.0 release also contains a full set of daily mean values for all parameters except wind direction and precipitation. Daily precipitation is included as the daily sum of the half-hourly data, and daily average wind direction is not included.
2.1.2 Gap-filling methods and uncertainty estimates

As described in Knox et al. (2015) and in Knox et al. (2019), the ANN routine used to gap-fill the CH$_4$ data was optimized for generalizability and representativeness. To avoid biasing the ANN toward environmental conditions with typically better data coverage (e.g., summer-time and daytime measurements), the explanatory data were divided into a maximum of 15 clusters using a k-means clustering algorithm. Data used to train, test, and validate the ANN were proportionally sampled from these clusters. For generalizability, the simplest ANN architecture with good performance (≤5% gain in model accuracy for additional increases in architecture complexity) was selected for 20 extractions of the training, test, and validation data. Within each extraction, each tested ANN architecture was reinitialized 10 times, and the initialization with the lowest root-mean-square-error was selected to avoid local minima. The median of the 20 predictions was used to fill each gap. A standard set of variables available across all sites was used to gap-fill CH$_4$ fluxes (Dengel et al., 2013), which included the previously mentioned meteorological variables TA, SW_IN, WS, PA, and sine and cosine functions to represent seasonality. These meteorological variables were selected since they are relevant to CH$_4$ exchange and were gap-filled using the ERA-I reanalysis data. Other variables related to CH$_4$ flux (e.g., water table depth [WTD] and soil temperature [TS]) were not included as explanatory variables as they were not available across all sites or had large gaps that could not be filled using the ERA-I reanalysis data (Knox et al., 2019). The ANN gap-filling was performed using MATLAB (MathWorks 2018, version 9.4.0).

While the median of the 20 predictions was used to fill each gap, the spread of the predictions was used to provide a measure of uncertainty resulting from the ANN gap-filling procedure. Specifically, for gap-filled values, the combined annual gap-filling and random uncertainty was calculated from the variance of the cumulative sums of the 20 ANN predictions (Knox et al., 2015; Anderson et al., 2016; Oikawa et al., 2017). The (non-cumulative) variance of the 20 ANN predictions was also used to provide gap-filling uncertainty for each half-hourly gap-filled value included in the dataset. While this output is useful for data-model comparisons, it cannot be used to estimate cumulative annual gap-filling error because gap-filling error is not random, which is why the cumulative sums of the 20 ANN predictions are used to estimate annual gap-filling error.

Random errors in EC fluxes follow a double exponential (Laplace) distribution with the standard deviation varying with flux magnitude (Richardson et al., 2006; Richardson et al., 2012). For half-hourly CH$_4$ flux measurements, random error was estimated using the residuals of the median ANN predictions, providing a conservative “upper limit” estimate of the random flux uncertainty (Moffat et al., 2007; Richardson et al., 2008). The annual cumulative uncertainty at 95% confidence was estimated by adding the cumulative gap-filling and random measurement uncertainties in quadrature (Richardson and Hollinger, 2007; Anderson et al., 2016). Annual uncertainties in CH$_4$ flux for individual site-years are provided in Table B7B2. Throughout this paper, we include uncertainties on individual site years when discussing single years of data. In sites with multiple years of data, we report the standard deviation of the multiple years.

2.1.3 Dataset structure and site metadata

To enable data use by the broader flux community, we have partnered with regional flux networks and FLUXNET to provide standardized and gap-filled EC CH$_4$ data. FLUXNET-CH4 Version 1.0-CH4 contains two comma-separated data files per site at half-hourly and daily resolutions. Half-hourly and daily aggregations which are available for download at https://fluxnet.org/data/fluxnet-ch4-community-product/, along with a file containing select site metadata. Each site has a unique FLUXNET-CH4 DOI. All site data from the 79 sites used in this analysis are available under CC BY 4.0 (https://creativecommons.org/licenses/by/4.0/) copyright license. (FLUXNET-CH4 has an additional 2 sites available under the FLUXNET Tier 2 license (https://fluxnet.org/data/data-policy/), though these sites are not included in our analysis).
2.1.5 Subset analysis on freshwater wetland CH$_4$ flux

In addition to the FLUXNET-CH4-wide description of site class distributions and annual CH$_4$ fluxes, we also include a subset analysis on freshwater wetlands, given that it is the dominant ecosystem type in our dataset and previously could have been wetlands, seasonally flooded pastures, or agricultural areas. To the extent possible, we followed classification systems of previous wetland CH$_4$ syntheses (Olefeldt et al., 2013; Turetsky et al., 2014; Treat et al., 2018). Drained systems are former wetlands that have subsequently been drained but may maintain a relatively shallow water table, which can contribute to occasional methane emissions, although we do not have specific water table depth information at all drained sites. Upland ecosystems are further divided into alpine meadows, grasslands, needleleaf forests, mixed forest, crops, tundra, and urban. Freshwater wetland classifications follow hydrological definitions of bog (ombrorhocholic), fen (minerotrophic), wet tundra, marshes and swamps, and were designated as per primary literature on the site. For all sites, vegetation was classified for presence or absence of brown mosses, Sphagnum mosses (any species from the division Bryophyta except those in the class Sphagnopsida), Sphagnum mosses (any species from class Sphagnopsida), ericaceous shrubs, trees (of any height) and aerchymatous species (mostly Order Poales but includes exceptions). These categories closely follow Treat et al., (2018), except that aerchymatous species had to be expanded beyond Cyperaceae to incorporate wetlands globally. Presence/absence of vegetation groups was designated based on species lists in primary literature from the site. Out of the vegetation groups present, the dominant (most abundant) group is also reported and is based on data from a survey of information provided by lead site investigators.

In addition to the variable description table (Table B1) and the site metadata (Table B2B3), we provide several more tables to complement our analysis. Table B3B4 includes the climatic data focused in the representativeness analysis. SeasonalityTable 5 provides seasonality parameters for CH$_4$ flux, air temperature, soil temperature (for sites with multiple probes). Table B4 includes parameters from the probe closest to the ground surface), and GPP are provided in Table B4, with. For sites with multiple soil temperature probes, the full set of soil temperature parameters from all probes are in Table B5. Table B6 contains the soil temperature probe depths. Table B7B2 contains the annual CH$_4$ flux and uncertainty. All Appendix B tables are also available at https://doi.org/10.5281/zenodo.44084684672601.
an important global CH$_4$ source (Saunois et al., 2016). First, we analyze freshwater wetland representativeness, and subsequently the seasonality of their CH$_4$ emissions. Freshwater wetlands included in the seasonality and representativeness analysis are indicated in Table B2B3, column “IN_SEASONALITY_ANALYSIS”.

2.2 Wetland representativeness

2.2.1 Principal Component Analysis

To understand how compare the FLUXNET-CH4 site distribution of FLUXNET-CH4 Version 1.0 sites compares with the global wetland distribution, we evaluated their representativeness of the FLUXNET-CH4 Version 1.0 wetland sites in the entire global wetland cover along four bioclimatic gradients. Only freshwater wetland sites were included in this analysis, with coastal. Coastal sites were excluded because, due to a lack of global gridded datasets, salinity could not be included as an environmental variable despite being an important control on CH$_4$ production, could not be evaluated across the tower network due to a lack of global gridded salinity data (Bartlett et al., 1987; Poffenbarger et al., 2011). The four bioclimatic variables used were: mean annual air temperature (MAT), latent heat flux (LE), enhanced vegetation index (EVI), and simple ratio water index (SRWI; data sources in Table B3-B4). We use EVI because it is a more direct measurement than GPP from global gridded products and is considered a reasonable proxy for GPP (Sims et al., 2006). Thus, we used EVI instead of GPP. Together, these environmental variables account for, or are, proxies for key controls of CH$_4$ production, oxidation at the surface, and transport (Bridgham et al., 2013). We use a principal components analysis (PCA) to visualize the site distribution across the four environmental drivers at once. For this analysis, we consider the annual average bioclimatic conditions over 2003-2015. In the PCA output, we evaluate the coverage of the 42 freshwater sites over 0.25° grid cells containing >5% wetland mean cover in Wetland Area and Dynamics for Methane Modeling (WAD2M; Zhang et al., In Review, 2020; Zhang et al., 2021) for the same time period.

2.2.2 Global Dissimilarity and Constituency Analysis

To further identify geographical gaps in the coverage of the FLUXNET-CH4 Version 1.0 network, we quantified the dissimilarity of global wetlands from the tower network, using a similar approach to that taken for CO$_2$ flux towers (Kasnás et al., 2016; Meyer and Pebesma 2020). We calculated the 4-dimensional Euclidean distance from the four bioclimatic variables between every point at the land surface to every tower location at the FLUXNET-CH4 network. We then divided these distances by the average distance between towers to produce a dissimilarity index. Dissimilarity scores <1 represent areas whose nearest tower is closer than the average distance among towers, while areas with scores >1 are more distant. Lastly, we identified the importance of an individual tower in the network by estimating the geographical area to which it is most analogous in bioclimate space. We divided the world’s land surface according to closest towers in bioclimatic space. The area to which each tower is nearest is defined as the tower’s constituency.

2.3 Wetland CH$_4$ seasonality

To examine freshwater wetland CH$_4$ seasonality across the global range of sites in FLUXNET-CH4 Version 1.0, we extracted seasonality parameters for CH$_4$, temperature, and GPP using Timesat, a software package designed to analyze seasonality of environmental systems (Jönsson and Eklundh, 2002; Jönsson and Eklundh, 2004; Eklundh and Jönsson, 2015). Timesat calculates a range of several seasonality parameters, including baseline flux, peak flux, and the slope of spring flux increase and fall decrease (Fig. 1). We also calculate parameters such as amplitude (=peak flux - baseline, which is the average of baseline and fall baselines; “e” - in Fig. 1), and relative peak timing (= (spring - fall) / (spring - fall)) in Fig. 1). Timesat uses a double-logistic fitting function to create a series of localized fits centered on data minima and maxima. Localized fits are minimized using a merit function and the Levenberg-Marquardt method (Madsen et al., 2004; Nielsen, 1999).
These localized fits are then merged using a global function to create a smooth fit over the full time interval. To fit \( CH_4 \) time-series in Timesat, we used gap-filled data after removing gaps exceeding two months. We do not report Timesat parameters when large gaps occur during \( CH_4 \) emissions spring increase, peak, or fall decrease.

We estimate ‘start of elevated emissions season’ when \( CH_4 \) emissions begin to increase in the spring (“f” in Fig. 1), and ‘end of elevated emissions season’ when the period of elevated \( CH_4 \) flux ends in the fall (“h” in Fig. 1), as the intercept between the Timesat fitted baseline parameter and shoulder-season slope (similar to Gu et al., 2009). To extract seasonality parameters with Timesat, sites need a sufficiently pronounced seasonality, a sufficiently long time period, and minimal data gaps (we note that while Timesat is capable of fitting two peaks per year, all the freshwater wetland sites have a single annual peak). We excluded site-years in restored wetlands when wetlands were still under construction. We were able to fit 36 of the 42 freshwater wetland sites using Timesat, within FLUXNET-CH4 Version 1.0, 36 had sufficient data series to extract seasonality parameters. These 36 wetlands had 141 site-years of data; using total, which we fit with the double-logistic fitting method which followed site data well (representative examples in Fig. 2). For extratropical sites in the Southern Hemisphere, we shifted all data by 182 days so that maximum solar insolation seasonality would be congruent across the globe.

We also used Timesat to extract seasonality metrics for GPP, partitioned using the daytime-based approach (Lasslop et al., 2010) (GPP_DT), air temperature (TA), and soil temperature (TS_1, TS_2, etc). For sites where winter soil temperatures fall significantly below 0 °C, Timesat fits a soil temperature “start of elevated season” date to periods when the soil is still frozen. In order for Timesat to define the soil temperature seasonality within the thawed season, we converted all negative soil temperatures to zero (simply removing these values results in too many missing values for Timesat to fit). Many sites have more than one soil temperature probe, so we extracted separate seasonality metrics from each individual probe (although we used the metrics from the shallowest temperature probe in our analysis). Tables B4 contain the Timesat seasonality parameters used in the seasonality analysis. We did not include water table depth in the seasonality analysis because many sites either lack water table depth measurements or have sparse data.
Figure 1: TIMESAT parameter description. (a) and (b) base values (Timesat reports the average of these two values), (c) and (d) slopes of seasonal curves (lines drawn between 20% and 80% of the amplitude), (e) peak value, and day of year (DOY) for the start (f), peak (g), and end (h) of the elevated methane (CH\textsubscript{4}) emissions season. Data points are the mean daily gap-filled CH\textsubscript{4} fluxes from site JP-Bby in 2015.
We regressed the CH$_4$ seasonality parameters from Timesat against a range of annual temperature, moisture, annual water table depth, and Timesat seasonality parameters for air temperature, soil temperature, and GPP (proxy for recent carbon input available as substrate) using linear mixed-effect modeling with the lmer command (with site as a random effect) from the R (R Core Team 2018, version 3.6.2) package lmerTest (Kuznetsova et al., 2017). For these regressions we present the marginal $R^2$ outputs from lmer, which represent the variance explained only by the fixed effects. Mixed-effect modeling was necessary to account for the non-independence between measurements taken at the same site during different years (Zona et al., 2016; Treat et al., 2018). We also compared how seasonality metrics varied across latitudinal bands by dividing sites into northern (>60° N), temperate (between 40° N and 60° N), subtropical (absolute value between 20° and 40° latitude, with site NZ-KOP being the only Southern hemisphere site), and tropical (absolute value below 20°). Site-year totals for the northern, temperate, subtropical, and tropical bands were $n = 57, 36, 39, and 9$, respectively. We used the Kruskal-Wallis test to establish whether groups (either across quarters or across latitudes) were from similar distributions, and the post hoc multiple comparison “Dwass, Steel, Critchlow, and Fligner” procedure for inter-group comparisons. Kruskal-Wallis and post-hoc tests were implemented in Python Version 3.7.4, using stats from scipy for Kruskal-Wallis and posthoc_dscf from scikit_posthocs.

In addition to comparing CH$_4$ flux seasonality across latitudinal bands and to the seasonality of potential drivers, we also compared quarterly CH$_4$ flux sums by dividing data into quarterly periods: January/February/March (JFM), April/May/June (AMJ), July/August/September (JAS), and October/November/December (OND). For the sake of simplicity, we chose to compare quarterly periods rather than site-specific growing/non-growing season periods so that all time periods would be the same length. Quarterly sums were computed from the gap-filled CH$_4$ fluxes when the longest continuous data gap within the quarter did not exceed 30 days, leading to site-year counts of 67, 92, 95, 72 for JFM, AMJ, JAS, and OND, respectively. We compared quarterly CH$_4$ fluxes across latitudinal bands both for the total CH$_4$ flux, and for the quarterly percentage of the annual CH$_4$ flux. Quarterly statistics were also conducted with the Kruskal-Wallis test and the post hoc
multiple comparison “Dwass, Steel, Critchlow, and Fligner” procedure implemented in Python. Quarterly values are provided in Table B2B3, and the sum of mean quarterly CH$_4$ flux does not always equal mean annual CH$_4$ flux because some quarters either do not have data, or have data gaps that exceed 30 days.

3. Results and Discussion

3.1 FLUXNET-CH$_4$ dataset

3.1.1 Dataset description

Version 1.0 of the FLUXNET-CH$_4$ dataset contains 79 unique sites, 293 total site-years of data, and 201 site-years with sufficient data to estimate annual CH$_4$ emissions. A previous synthesis paper, published prior to the public data release of FLUXNET-CH$_4$ Version 1.0, had 60 unique sites and 139 site-years with annual CH$_4$ emissions estimates (Knox et al., 2019). Freshwater wetlands make up the majority of sites ($n = 42$), and the dataset also includes five salt marshes and one mangrove wetland. Notable additions to FLUXNET-CH$_4$ Version 1.0 from the previous unpublished dataset used in Knox et al., (2019) include six tropical sites (between 20° S and 20° N), including one site in South America, two sites in southern Africa, and three sites in Southeast Asia. The 15 upland sites include six needleleaf forests, three crop sites (excluding rice), two alpine meadows, one grassland, one mixed forest, one tundra, and one urban site. The drained sites represent former wetlands that have been artificially drained for use as grasslands ($n = 3$) or croplands ($n = 3$). FLUXNET-CH$_4$ Version 1.0 sites span the globe, though are concentrated in North America and Europe (Fig. 3). Table B2B3 includes characteristics of all sites in the dataset.
Figure 3. Global map of FLUXNET-CH4 Version 1.0 site locations colored by site type. The bog and upland site insets (a)-(d) show sites that were too closely located to distinguish in the Northwest Territories of Canada have been slightly offset from each other so that both are visible on the global map.
Figure 4. Histogram of annual CH₄ methane fluxes ($F_{CH4}, \text{g C m}^{-2}\text{yr}^{-1}$) grouped by site type.

Sites represent a range of ecosystem types, latitudes, median fluxes, and seasonality patterns (Table 1).

Across all FLUXNET-CH₄ Version 1.0 sites, mean average annual CH₄ flux is positively skewed with a median flux of 9.5 g C m⁻² yr⁻¹, a mean flux of 16.9 g C m⁻² yr⁻¹, and numerous annual CH₄ fluxes exceeding 60 g C m⁻² yr⁻¹. The addition of 19 sites from the 60 sites aggregated in Knox et al., (2019) therefore do not significantly change the distribution of annual CH₄ fluxes. Marshes and swamps have the highest median flux, and upland, salt marsh, and tundra sites have the lowest (Fig. 4). Lake emissions are highly variable due to one high-flux lake site (JP-SWL). Flux data at many sites show strong seasonality in CH₄ emissions, but data coverage is also lower outside the
growing season (Table 1). Data coverage is lowest during the JFM quarter (on average 20% of half-hourly time periods contain flux data) reflecting the predominance of Northern hemisphere sites and the practical difficulties in maintaining EC tower sites during colder winter months (Table 1). Bogs, fens, and marshes have pronounced seasonality, with fluxes being highest in the AMJ and JAS quarters. In contrast, CH$_4$ fluxes from uplands, drained sites, and salt marshes are more uniform and low year-round.

| Site Class       | # of Sites | Ann_Flux g C m$^{-2}$ year$^{-1}$ | Ann_Flux_SD g C m$^{-2}$ year$^{-1}$ | JFM coverage (%) | AMJ coverage (%) | JAS coverage (%) | OND coverage (%) | JFM flux (med.) | AMJ flux (med.) | JAS flux (med.) | OND flux (med.) |
|------------------|------------|-----------------------------------|--------------------------------------|------------------|------------------|------------------|------------------|----------------|----------------|----------------|----------------|
| Salt marsh       | 5          | 2.9                               | 4.7                                  | 42               | 50               | 37               | 1.5              | 1.7            | 2.1            | 1.6            |
| Wet tundra       | 11         | 3.8                               | 1.8                                  | 8                | 28               | 18               | 0.4              | 2.6            | 8.1            | 3.2            |
| Upland           | 15         | 4.0                               | 10.5                                 | 23               | 35               | 28               | 1.2              | 0.5            | 1.4            | 0.8            |
| Drained          | 7          | 6.3                               | 7.1                                  | 22               | 39               | 29               | 4.6              | 3.6            | 5.1            | 3.6            |
| Bog              | 7          | 10.5                              | 6.4                                  | 8                | 27               | 18               | 7.2              | 11.0           | 24.8           | 9.5            |
| Mangrove         | 1          | 11.1                              | 0.5                                  | 46               | 28               | 30               | 41               | 3.2            | 7.2            | 22.5           | 14.1           |
| Rice             | 7          | 14.4                              | 8.8                                  | 16               | 37               | 45               | 27               | 3.2            | 11.9           | 43.1           | 4.2            |
| Fen              | 8          | 20.5                              | 16.0                                 | 29               | 43               | 40               | 30               | 2.8            | 14.2           | 26.0           | 6.4            |
| Swamp            | 6          | 26.4                              | 19.9                                 | 24               | 34               | 29               | 19               | 14.7           | 24.9           | 31.0           | 24.4           |
| Lake             | 2          | 28.2                              | 33.4                                 | 15               | 13               | 27               | 36               | 0.2            | 47.6           | 90.2           | 40.3           |
| Marsh            | 10         | 40.8                              | 20.7                                 | 22               | 43               | 53               | 30               | 13.5           | 55.0           | 85.8           | 36.1           |
3.1.2 Freshwater wetland CH₄ characteristics

The FLUXNET-CH4 Version 1.0 dataset contains 42 freshwater wetlands that span 37°S to 69°N, including bogs, fens, wet tundra, marshes, and swamps, and a range of annual CH₄ emission rates (Fig. 4). The majority of freshwater wetlands in our dataset emit 0-20 g C m⁻² yr⁻¹, with 10 emitting 20-60 g C m⁻² yr⁻¹, and one more than 60 g C m⁻² yr⁻¹. Differences in annual CH₄ flux among wetland types is partially driven by temperature (which is often linked to site type), with mean annual air temperature explaining 51% of the variance between sites (Fig. 5, exponential relationship). The global relationship between annual methane emissions and temperature can be described using a Q₁₀ relationship where \( Q_{10} = \frac{R_2}{R_1} \left( \frac{T_2 - T_1}{10} \right) \), with \( R_2 \) and \( R_1 \) being the mean annual CH₄ emission rates at temperatures \( T_2 \) and \( T_1 \), respectively (temperature in degrees C). The \( Q_{10} \) based on Fig. 5 data is 2.57. We also note that annual CH₄ flux from individual biomes may have different relationships with temperature, as previous work has shown biome-specific trends in CH₄ flux with environmental drivers (Abdalla et al., 2016). However, there currently are not enough data points in each biome category to compare relationships between mean annual CH₄ flux and temperature. Annual CH₄ flux is not correlated with mean annual water table depth in FLUXNET-CH4 Version 1.0, unlike in Knox et al. (2019), which used a subset of the FLUXNET-CH4 Version 1.0 sites where CH₄ flux was correlated with water table depth only for sites with water table below ground for 90% of measured days (\( r^2 = 0.31, p<0.05, n = 27 \) site years, Knox et al., 2019). Freshwater wetland seasonality is further described in Sect. 3.3.
Figure 5: Relationship between mean annual wetland methane (CH$_4$) flux (g C m$^{-2}$ yr$^{-1}$), logarithmic scale and mean annual air temperature (°C, logarithmic scale) for each freshwater wetland site, with wetland type indicated by symbol. The difference in emissions across site types is partially driven by difference in mean annual temperature. Markers represent individual site means, with vertical error bars representing the standard deviation of interannual variability.

3.1.3 Non-wetland Upland, rice and urban CH$_4$ characteristics

Upland agricultural sites are characterized by a lack of seasonal pattern in CH$_4$ emissions, relatively low flux, and sometimes negative daily flux (i.e., CH$_4$ uptake) averages. All of the upland non-agricultural sites in FLUXNET-CH4 Version 1.0 are net (albeit weak) CH$_4$ sources except for the needleleaf forest site US-Ho1, which has mean annual CH$_4$ flux of -0.1 ± 0.1 g C m$^{-2}$ yr$^{-1}$ (see Table B2B3 for site acronyms and metadata). The average agricultural site emissions are 1.3 ± 0.8 g C m$^{-2}$ yr$^{-1}$ and non-agricultural site emissions are 1.6 ± 1.2 g C m$^{-2}$ yr$^{-1}$ across sites.

Rice sites (n = 7) have average annual emissions across all sites of 16.7 ± 7.7 g C m$^{-2}$ yr$^{-1}$ and are characterized by strong seasonal patterns, with either one or more CH$_4$ emission peaks per year depending on the number of rice seasons and field water management. One peak is typically observed during the reproductive period for the continuously flooded sites with one rice season (i.e., US-HRC, JP-MSE) (Iwata et al., 2018; Runkle et al., 2019; Hwang et al., 2020). For sites with only one rice season but with single or multiple drainage and re-flooding periods, a secondary peak may appear before the reproductive peak (i.e., KR-CRK, IT-Cas, and US-HRA; Meijide et al., 2011; Runkle et al., 2019; Hwang et al., 2020). Two reproductive peaks appear for sites with two rice seasons (i.e., PH-RiF), and each reproductive peak may be accompanied by a secondary peak due to drainage events (Alberto et al., 2015). Even sites with one, continuously flooded rice season may experience a second peak if the field is flooded during the fallow season to provide habitat for migrating birds (e.g., US-Twt; Knox et al., 2016).
The dataset has one year of urban data from site UK-LBT in London, England. UK-LBT observes CH$_4$ fluxes from a 190 m tall communications tower in the center of London, and had a mean annual CH$_4$ flux of 46.5 ± 5.6 g C m$^{-2}$ yr$^{-1}$. This flux is more than twice as high as the mean annual CH$_4$ flux across all FLUXNET-CH4 Version 1.0 sites, 16.9 g C m$^{-2}$ yr$^{-1}$. The London site has higher CH$_4$ emissions in the winter compared to summer, which is attributed to a seasonal increase in natural gas usage (Helfter et al., 2016.)

3.1.4 Non-freshwater/Saltwater and mangrove wetland CH$_4$ characteristics

Three of the five saltwater wetlands in FLUXNET-CH4 Version 1.0 (US-Edn, US-MRM, and US-Str) have a very low mean annual CH$_4$ flux (see Table B2B2 for individual site-year CH$_4$ flux sums and associated uncertainty) and minimal seasonality. Two other FLUXNET-CH4 Version 1.0 saltwater sites (US-La1, and US-StJ) have significantly higher fluxes, with annual sums of 12.6 ± 0.6 and 9.6 ± 1.0 g C m$^{-2}$ yr$^{-1}$, respectively, while the mangrove site HK-MPM has annual mean fluxes of 11.1 ± 0.5 g C m$^{-2}$ yr$^{-1}$. This range of CH$_4$ fluxes across different saltwater ecosystems could be valuable for exploring the effect of salinity and different biogeochemical pathways of CH$_4$ production, oxidation, and transport of CH$_4$ (Bartlett et al., 1987; Poffenbarger et al., 2011). Saltwater wetlands along the coast have unique CH$_4$ dynamics attributable to the presence of abundant electron acceptors, most importantly sulphates, which inhibit methanogenesis (Pattnaik et al., 2000; Mishra et al., 2003; Weston et al., 2006), but at low concentrations can have no effect (Chambers et al., 2011) or even increase methanogenesis (Weston et al., 2011). In fact, estuarine wetlands with moderate salinity can still be significant sources of CH$_4$ (Liu et al., 2020). Even under sulfate-rich conditions, high CH$_4$ production can be found via methylotrophic methanogenesis (Seyfferth et al., 2020)(Dalcin Martins et al. 2017; Seyfferth et al., 2020,) or because the processes of sulfate reduction and methanogenesis are spatially separated (Koebsch et al., 2019). Consequently, representing the biophysical drivers of ecosystem-scale CH$_4$ fluxes in non-freshwater wetlands is challenging and may represent a combination of competing or confounding effects (Vazquez-Lule and Vargas 2021).

3.2 Wetland Representativeness

We evaluated the representativeness of freshwater wetland sites in the FLUXNET-CH4 Version 1.0 dataset against wetlands globally. Specifically, we asked how representative the bioclimatic conditions of our sites are, relative to bioclimatic conditions in all wetlands globally. Parameters defining bioclimatic conditions are selected from those known to affect CH$_4$ production, consumption, and transport processes (e.g., energy, moisture, substrate availability, and vegetation), based on bioclimatic conditions of our sites. When evaluating bioclimatic variables individually, the distribution across the network was significantly different from the global distribution (alpha > 0.05; two-tailed Kolmogorov-Smirnov tests; see Table B3B4).

When considering the four bioclimatic variables, MAT, LE, EVI and SRWI in a PCA, we found that our tower network generally samples the bioclimatic conditions of global wetland cover, but some noticeable gaps remain (Fig. 6). Three clusters of the world’s wetland-dense regions are identified, but are not equally sampled by the network. A cluster of low temperature wetlands is sampled by a large number of high-latitude sites. The other two wetland clusters are not as well sampled: a high temperature and LE cluster is represented only by two towers (ID-Pag and MY-MLM), while drier and temperate and subtropical wetlands including large swathes of the Sahel in Africa only have a site in Botswana (BW-Npw) as their closest-analog tower.
Figure 6: Principal Component Analysis displaying the distribution of freshwater wetland sites (blue points) along the two main principal components together accounting for 91.9% of variance. Tower sites are represented as the larger points with shapes representing their wetland type and color shade representing the annual methane (CH4) flux (greyed points represent sites for which <6 months of flux data was available to estimate annual budget). The size of wetland points are made larger for visual clarity and site codes are labelled in blue. The background shades of grey represent the density of land pixels (excluding Greenland and Antarctica) that have a >5% wetland fraction according to the WAD2M map (Zhang et al., In Review). Text for selected sites deviating from average conditions. Loading variables are represented by the arrows: mean annual temperature (MAT), simple ratio water index (SRWI), latent heat flux (LE).
and enhanced vegetation index (EVI). The background shades of gray are a qualitative representation of the density of global wetland pixels and their distribution in the PCA climate-space, with darker color representing higher densities (excluding Greenland and Antarctica). Only grid cells with >5% average wetland fraction according to the WAD2M over 2000-2018 are included (Zhang et al., 2020). The loading variables are represented by the arrows: mean annual temperature (MAT), simple ratio water index (SRWI), latent heat flux (LE) and enhanced vegetation index (EVI).

Evaluating the bioclimatic dissimilarity of global wetlands to the FLUXNET-CH4 Version 1.0 network shows the least captured regions are in the tropics and mountainous regions (Fig. 7A). Sparse coverage in the tropics also means that the few existing towers occupy a critical place in the network, particularly as tropical wetlands are the largest CH4 emitters (Bloom et al., 2017; Poulter et al., 2017). Highly dissimilar wetlands are limited in extent and distributed across all latitudes, but the average dissimilarity is higher in north temperate (55° to 65°) and tropical (-5° to 5°) latitudes (Fig. 7B). To evaluate the importance of individual towers in the network, we estimated the geographical area to which it is most analogous in bioclimatic space (Fig. 7C). We found that some towers have disproportionately large constituencies (i.e., wetland areas that share the same closest bioclimatic analog tower). Towers in Indonesia (ID-Pag), Brazilian Pantanal (BR-Npw), and Botswana floodplains (BW-Nxr) represent the closest climate analog for much of the tropics (678, 300 and 284 thousand km², respectively) while CA-SCB represents a vast swath (291 thousand km²) of boreal/arctic regions (Fig. 7D).
Figure 7: (Aa) Distance in bioclimatic space between global land surface and the FLUXNET-CH4 Version 1.0 tower network. (Gray areas indicate no mapped wetlands). The Euclidean distance was computed on the five bioclimatic variables and was then standardized by the average distance within-network. Most of the land surface has a dissimilarity score lower than 1, meaning these areas are closer than the average tower distance (lower dissimilarity score means a similar bioclimate to that represented by towers in the network). However, this pattern reflects more the sparsity of the tower network than a similarity of the land surface to the network. Areas with <5% coverage by wetlands were excluded to focus on wetland-dense regions. (Bb) Latitudinal distribution of dissimilarity score, (Cc) Map of the four largest tower constituencies, (Dd) Scatterplot of wetland area in each tower constituency plotted against the average dissimilarity score (point) and +/- standard deviation (error bar).

Our assessment of wetland CH$_4$ tower coverage determines the ability of our dataset to represent global wetland distributions and highlights some clear representation gaps in the network—particularly in tropical, and humid and mountainous regions. Other geographic regions such India, China and Australia, where towers exist but are not included in the current network should be prioritized when expanding the network, even though they are not among the most distant areas to the current network. Similar representativeness assessments have been developed for CO$_2$ tower networks to identify gaps and priorities for expansion (Jung et al., 2009; Kumar et al., 2016). To improve the geographic coverage of the network for representing global-scale fluxes, locations for new tower sites can be targeted to cover bio-climatically distant areas from the current network (Villarreal et al., 2019). Candidate regions for expansion that are both high CH$_4$ emitting (Saunois et al., 2020) as well as located in under-sampled climates are: African Sahel, Amazon basin, Congo basin, South-East Asia. Climatic conditions over boreal and arctic biomes are generally better represented (primarily at lower elevations), but there is scope to expand the network in wetland-dense regions like the Hudson Bay Lowlands and Northern Siberian Lowlands. Moreover, establishing sites should be established in other ecosystem types, especially lakes and reservoirs (Bastviken et al., 2011; Deemer et al., 2016; Matthews et al., 2020) (see Deemer et al. 2016, Bastviken et al. 2011, Matthews et al. 2020) in most climatic zones in order to would help capture CH$_4$ fluxes from these ecosystems.
Understanding the representativeness of the network is essential when inferring general patterns of flux magnitude, seasonality, and drivers from the tower data (Villarreal et al., 2018). We produced a first-order representation of average bioclimatic conditions, but temporal representativeness (across seasons, climate anomalies and extreme events) is particularly needed given the episodic nature of CH$_4$ fluxes (Chu et al., 2017; Mahecha et al., 2017; Göckede et al., 2019).

Assessing representation of wetland CH$_4$ sites is complicated by the fact that wetlands occupy only a fraction of most landscapes (except wetland dense regions such as Northern Siberian Lowlands, Hudson Bay Lowlands, Congo basin, etc.) and that not all relevant factors affecting CH$_4$ production and consumption could be considered in our analysis. For instance, our assessment of representation did not consider wetland types as such maps are limited by the inherent difficulties in remotely sensing wetland features (Gallant, 2015). The attribution of representativeness is further complicated by the fact that many EC tower locations are subject to small-scale variability within the field of view, or footprint, of the sensor. Consequently, the individual time steps within EC flux time series may represent a mixture of different wetland types, or different fractions of wetland contribution to the total CH$_4$ flux, varying with wind direction, atmospheric stability, or season. (Chu et al. 2021). This further complicates upscaling efforts.

Additionally, this representativeness analysis did not apply weights to the drivers to reflect their varying influence on CH$_4$ flux. Such weights can be included in future versions as they are generated by a cross-validated machine learning approach (Jung et al., 2020). Future efforts will include the dissimilarity index from this analysis as a metric of extrapolation in a CH$_4$ flux upscaling effort.

### 3.3 Freshwater wetland flux seasonality

We used seasonality parameters extracted by Timesat to describe typical seasonal patterns in freshwater wetland CH$_4$ fluxes, and to compare them with seasonality in soil temperature and GPP. Of the 42 freshwater wetland sites in FLUXNET-CH4 Version 1.0, 36 had sufficient data series to extract seasonality parameters.

#### 3.3.1 Seasonal flux comparisons by latitudinal bands

CH$_4$ flux and seasonality varied substantially across latitudinal bands (northern, temperate, subtropical, and tropical) (Fig. 8). Annual CH$_4$ fluxes for temperate, and subtropical sites were significantly higher than for northern sites (8.7 ± 5.0, 29.7 ± 25.2, 40.1 ± 14.6, and 24.5 ± 20.7 g C m$^{-2}$ yr$^{-1}$ for northern, temperate, subtropical, and tropical, respectively, p<0.0001 using Kruskal Wallis and post hoc comparisons; Fig. 8a), and tropical sites were similar to all other latitudinal bands likely because of their small sample size. The ratio of seasonal amplitude to peak flux provides a measure of the relative seasonal increase in emissions compared with baseline, where a ratio of zero indicates no seasonal change in amplitude, a ratio of one indicates the off-season flux is zero, and values over one means the off-season baseline CH$_4$ fluxes were negative (i.e., uptake). Average amplitude to peak flux ratios were similar across all latitudinal bands (0.9 ± 0.1, 0.9 ± 0.1, 0.9 ± 0.1, 1.0 ± 0.7, for northern, temperate, subtropical, and tropical, respectively; Fig. 8b). The spring increase in CH$_4$ emissions began later in northern sites compared with temperate and subtropical sites (end of May versus April, respectively, p<0.001; Fig. 8c), while tropical sites vary widely in elevated emission season start date. Northern sites also had shorter elevated CH$_4$ flux season lengths (138 ± 24 days) compared to temperate sites (162 ± 32 days), and both were shorter than subtropical sites (209 ± 43 days; p<0.0001; Fig. 8d). On average, CH$_4$ flux peaked earlier for temperate sites compared to northern (p = 0.008) and subtropical sites (p = 0.02; mid to late July compared with early August; Fig. 8e), while tropical sites again vary widely. Given their unique seasonality, and low number of site-years (n = 9), tropical systems are discussed separately in Sect. 3.3.3, and not included in the comparisons in the remainder of this section. While our results on CH$_4$ seasonality corroborate expected trends for these latitudinal bands, they provide some of the first estimates of CH$_4$ seasonality parameters and ranges across a global distribution of sites.
Figure 8: (a) Annual methane \( \text{CH}_4 \) flux (g C m\(^{-2}\) yr\(^{-1}\)), (b) Ratio of seasonal amplitude to seasonal peak, where values of 0 indicate uniform annual \( \text{CH}_4 \) flux, values of one indicate zero off-season fluxes, and values exceeding one indicate negative off-season fluxes, (c) \( \text{CH}_4 \) flux \( (F_{\text{CH}_4}) \) elevated emissions season start, by day of year (DOY), (d) \( F_{\text{CH}_4} \) elevated emissions season end by DOY, (e) Length of elevated \( F_{\text{CH}_4} \) flux season, (days), and (f) DOY of peak timing metrics for high, mid, low \( \text{CH}_4 \), Northern (dark blue, solid line), Temperate (blue, dashed line), Sub-tropical (green, dot-dash line) and Low latitude Tropical (light green, solid line) wetlands (purple, green, red, respectively) plotted using the kernel density function.

We found that latitudinal groups showed strong differences in absolute \( \text{CH}_4 \) flux across quarters, and narrower differences in percentage of annual \( \text{CH}_4 \) flux (Fig. 9a versus 9b). Thus, the AMJ quarter showed a similar relative contribution to the annual \( \text{CH}_4 \) flux across latitudes, regardless of the absolute annual \( \text{CH}_4 \) flux. Methane \( \text{CH}_4 \) fluxes (Fig. 9a) showed highest during JAS for northern, temperate, and subtropical sites and highest in AMJ and JAS for temperate sites (p<0.01). Though \( \text{CH}_4 \) fluxes in northern sites are most commonly measured during warm summer months (Sachs et al., 2010; Parmentier et al., 2011), fluxes in JFM and OND (50% of the yearly duration) on average make up 18.1 ± 3.6%, 15.3 ± 0.1%, and 31.2 ± 0.1% (northern, temperate, subtropical, respectively) of annual
emissions. This pattern indicates that a substantial fraction of annual CH$_4$ fluxes occurs during cooler months. The fraction would be even higher if we added April, May, and September emissions to the northern (> 60°N) sites, as done in (Zona et al., 2016), where > 50% of emissions were found to come from non-growing season months. The contribution of non-growing season CH$_4$ emissions to annual CH$_4$ fluxes has previously been described for arctic and boreal regions (Zona et al., 2016; Treat et al., 2018; Treat et al., 2018) and our analysis suggests comparable contributions in temperate and subtropical systems for the same quarterly periods.

Figure 9: (Aa) Quarterly contribution to total annual CH$_4$ flux in g C m$^{-2}$, and (Bb) percentage of annual CH$_4$ flux. Sites were divided into northern (> 60° N), temperate (40° N - 60° N), and subtropical (20° N - 40° N). Quarters with continuous data gaps exceeding 30 days were excluded. We used the following quarterly periods:
January/February/March (JFM), April/May/June (AMJ), July/August/September (JAS), and October/November/December (OND). Tropical sites are discussed separately in Sect. 3.3.3 because of their unique seasonality and low number of sites.

3.3.2 Predictors of CH$_4$ flux phenology

The start of the elevated CH$_4$ flux season, and how long the elevated flux season lasts, correlates strongly with mean annual air temperature (Fig. 10; $p<0.0001$ for each). Methane flux began to increase roughly two months earlier in the warmest systems (mean annual temperature $> 20$ °C) compared to the coldest (mean annual temperature near -10 °C), though several of the warmer sites had high variability. Our data suggest that the CH$_4$ season started 2.8 ± 0.5 days earlier for every degree Celsius increase in mean annual temperature (Fig. 10a). In contrast, the end of the CH$_4$ emission season was not correlated with mean annual temperature, but a positive trend existed despite high variability in warmest and coldest sites (Fig. 10b). The high variability seen in the end of CH$_4$ season at northern sites is important to note and would likely be better resolved by incorporating other seasonality or phenological characteristics, such as moisture, active layer depth, and plant community composition. (e.g., Kittler et al., 2017). Plants with aerenchymatous tissue, for example, influence the timing of plant-mediated CH$_4$ flux and are a key source of uncertainty while predicting CH$_4$ seasonality for northern wetlands (Xu et al., 2016; Kwon et al., 2017). Despite the relative lack of trend with season end date, the season length increased still positively correlated with mean annual temperature, with the warmest sites having roughly three more months of seasonally elevated CH$_4$ emissions than the coldest sites (Fig. 10c). Methane season length increased 3.6 ± 0.6 days for every degree Celsius increase in mean annual temperature (note that these relationships are correlations, and we cannot disentangle causality with this analysis). Temperature is highly correlated with other parameters (i.e., radiation, days of snow cover, etc.), so CH$_4$ flux is also likely to correlate with other environmental parameters.
Figure 10. The (a) start of the elevated methane (CH$_4$) emission season ($y = -2.8x + 130$, with ‘x’ in °C and ‘y’ in day of year, (DOY)), (b) the end of the elevated emission season in DOY, and (c) the length of the emission season with mean annual site air temperature ($y = 3.6x + 176.6$, with ‘x’ in °C and ‘y’ in days). Each point represents a site-year of data and all reported $r^2$ are significant to $p < 0.0001$. Tropical sites are discussed separately in Sect. 3.3.3.

Although the spring onset of increasing CH$_4$ emissions correlated with mean annual air temperature, on average it lags the spring increase in the shallowest soil temperatures by 31 ± 40 days (Fig. 11), lag is significantly different than zero, $p < 0.001$, with very few instances of CH$_4$ emissions beginning before seasonal soil temperatures increase (and by 20 ± 50 days for the deepest temperature probes). In contrast, for roughly half of the sites, CH$_4$ emission increased prior to seasonal GPP (a proxy for fresh substrate availability) increases. This suggests that the initiation of increased CH$_4$ fluxes at the beginning of the season was not limited by availability of substrate derived from recent photosynthetic, especially in cooler climates. Additionally, the onset of CH$_4$ fluxes tended to occur closer to the onset of soil temperature increase for cooler temperature sites (sites with later start dates tend to be cooler; Fig. 11a). This result is likely attributable to the direct influence of increased temperature on microbial processes (Chadburn et al., 2020), as well as the indirect influences of snow melt, both via release of CH$_4$ from the snowpack as well as a higher water table leading to more CH$_4$ production (Hargreaves et al., 2001; Tagesson et al., 2012; Mステpov et al., 2013; Helbig et al., 2017). These observed trends hold for the entire temperature or GPP range of freshwater wetland sites, but are not necessarily applicable within individual latitudinal bands.
Figure 11. Relationship between the onset of the methane (CH$_4$) emission season to (a) the beginning of the air warming, by day of year (DOY), (b) soil warming at the shallowest probe depth per site, by DOY, and (c) gross primary productivity (GPP) increase for the subset of sites with soil temperature data by DOY. Each point represents a site-year of data. Dashed lines represent a 1:1 relationship, solid lines are significant (p < 0.05) regression fits. On average, the CH$_4$ emission season lags the soil temperature increase by 31 ± 40 days, and is more synchronous with GPP.

In contrast with the CH$_4$ season-start timing, the timing of the CH$_4$ peak did not correlate with either the timing of the soil temperature peak or the GPP peak (Fig. A1). For 63% of the sites, the average timing of peak CH$_4$ emissions lagged the soil temperature peak, and at 83% of the sites average peak CH$_4$ lagged peak GPP (Fig. A1). Although there was no simple relationship between absolute CH$_4$ peak timing and the environmental drivers we investigated, there was a correlation (p = 0.0005) between the relative timing of peak CH$_4$ compared to season onset (calculated as described in Section 2.3) and mean annual air temperature (Fig. 12a). For cooler sites, the peak of seasonal CH$_4$ emissions occurred closer to the onset of the CH$_4$ emission season than the end of the season, resulting in an asymmetrical seasonal CH$_4$ flux shape that is illustrated in Fig. 2a. Soil temperature also peaked earlier in the season for cooler wetlands, though the relationship is not as pronounced (p = 0.009, Fig. 12b). In contrast, GPP peaked later in the season for cooler wetlands (p = 0.009, Fig. 12c). Previous work on Arctic sites (sites US-Ivo, US-Beo, US-Atq, US-Bes, and RU-CH2) highlighted the asymmetrical annual CH$_4$ peak, with higher fall emissions being attributed to the “zero curtain” period when soil below the surface remains thawed for an extended period of time due to snow insulation (Zona et al., 2016; Kittler et al., 2017). Furthermore, soils can stay above the “zero curtain” range for an extended time into the fall and winter (Helbig et al., 2017), which may also be caused by snow insulation. The rapid onset of emissions in the spring following snowmelt could be attributed to the release of accumulated CH$_4$ (Friborg et al., 1997), and other high latitude sites have seen similarly sharp increases in CH$_4$ emissions at snowmelt (Dise, 1992, Windsor, 1992). However, not all studies in high latitudes have observed asymmetrical CH$_4$ emission peaks, pointing to the inherent complexity of these ecosystems (Rinne et al., 2007; Tagesson et al., 2012).
Figure 12. Site-year peak methane (CH$_4$) emission (a) and peak soil temperature (b) occur earlier in the season for sites with lower mean annual temperatures. (c) Gross primary productivity (GPP) tends to peak earlier in the season for warmer sites, though the trend is weak. All $r^2$ values are significant at $p < 0.001$. Each point represents a site-year of data.

3.3.3 Uniqueness of tropical wetlands

Tropical wetlands typically do not experience the large swings in temperature and GPP that contribute to CH$_4$ flux seasonality in temperate and northern sites. Indeed, the relatively constant high temperatures and high GPP in tropical ecosystems may lead to the lower ratio between seasonal amplitude and peak CH$_4$ flux compared with temperate and northern sites (Fig. 8b). Tropical flux sites have historically been under-studied, leading to a lack of synthesized information about these ecosystems. FLUXNET-CH$_4$ Version 1.0 has five tropical wetland sites (latitude between 20° S and 20° N), and one tropical rice site, representing 13 site-years of data. These sites are especially insightful as they provide the first estimates of CH$_4$ fluxes from tropical, large seasonal floodplain systems found in the tropics.

We found a broad range of annual CH$_4$ fluxes across tropical sites in FLUXNET-CH$_4$ Version 1.0. Annual CH$_4$ flux emissions from two Southeast Asian flooded peat forests were relatively low, 0.01 ± 0.1 and 9.5 ± 0.6 g C m$^{-2}$ yr$^{-1}$ for ID-PAG and MY-MLM, respectively, which is consistent with annual CH$_4$ fluxes measured at another peat forest in Indonesia (Deshmukh et al., 2020). In contrast, mean annual CH$_4$ flux for a seasonally flooded swamp in the Brazilian Pantanal region (BR-NPW) was over twice as high as MY-MLM, at 19.2 ± 2.5 g C m$^{-2}$ yr$^{-1}$. Similarly high annual CH$_4$ fluxes were observed at the two Botswana swamp sites in the Okavango Delta (51.7 ± 10.6 and 47.3 ± 3.7 g C m$^{-2}$ yr$^{-1}$ for BW-GUM and BW-NXR, respectively), one of which is seasonally inundated and surrounded by grassland (BW-NXR) and the other is a permanently flooded lagoon covered in a floating papyrus mat (BW-GUM). The relatively low fluxes found at the two Southeast Asian peat forest sites indicate that these ecosystems may be smaller CH$_4$ sources than expected, given their location in the humid tropics. Even the higher-emitting tropical sites in Brazil and Botswana are still well within the range of annual CH$_4$ flux typical in cooler latitudes (Fig. 1).

In addition to having highly variable CH$_4$ flux magnitudes, the tropical sites differ from each other in their seasonality. Methane CH$_4$ flux hit a minimum around July for two sites (BW-GUM, latitude 18.965 °S and MY-MLM, latitude 1.46 °N), while CH$_4$ flux increased through July and the subsequent months for the other Botswana site, BW-NXR (latitude 19.548 °S). Site ID-Pag (latitude 2.32 °S) had minimal seasonality, whereas
the flooded forest site in Brazil (BR-NPW, latitude 16.49 °S) had near-zero fluxes from approximately July to January, and consistently high fluxes for the remainder of the year. The rice site PH-RIF (latitude 14.14 °N) had two annual CH$_4$ flux peaks, which is consistent with some other rice sites and likely reflects management practices. Baseline CH$_4$ flux values also differed, with the two Botswana sites having the highest off-season fluxes (29 and 133 nmol m$^{-2}$ s$^{-1}$ for BW-NXR and BW-GUM, respectively, estimated by Timesat), MY-MLM having an intermediate baseline CH$_4$ flux (16 nmol m$^{-2}$ s$^{-1}$, estimated by Timesat), and the remainder of the sites having essentially zero flux at baseline. While more tropical wetland data will be needed to extract broad scale conclusions about these ecosystems, the six tropical sites in FLUXNET-CH4 provide an important starting point for synthesis studies and highlight tropical wetland CH$_4$ variability.

4.0 Data Availability

Half-hourly and daily aggregations are available for download at https://fluxnet.org/data/fluxnet-ch4-community-product/, along with a table containing site metadata compiled from Table B2B3. Variable descriptions and units are provided in Table B1, and at https://fluxnet.org/data/fluxnet-ch4-community-product/. Each site has a unique FLUXNET-CH4 DOI as listed in Table B2B3. All site data used in this analysis are available under the CC BY 4.0 (https://creativecommons.org/licenses/by/4.0/) copyright policy. Additional sites in FLUXNET-CH4 are available under the more restrictive Tier 2 data policy, https://fluxnet.org/data/data-policy/; these sites are not used in our analysis. The individual site DOIs are provided below in Table 2. All seasonality parameters used in these analyses are available at https://doi.org/10.5281/zenodo.4408468.

Table 2: Site identification (SITE_ID), data DOI, and DOI reference for each FLUXNET-CH4 site.

| SITE_ID | DOI | DOI_REFERENCE |
|---------|-----|---------------|
| AT-Neu  | 10.18140/FLX/1669365 | Wohlfahrt et al., 2020. |
| BR-Npw  | 10.18140/FLX/1669368 | Vourlitis et al., 2020. |
| BW-Gum  | 10.18140/FLX/1669370 | Helfter, 2020a. |
| BW-Nxr  | 10.18140/FLX/1669518 | Helfter, 2020b. |
| CA-SCB  | 10.18140/FLX/1669613 | Sonnentag and Helbig, 2020a. |
| CA-SCC  | 10.18140/FLX/1669628 | Sonnentag and Helbig, 2020b. |
| CH-Cha  | 10.18140/FLX/1669629 | Hörtäogl et al., 2020a. |
| CH-Dav  | 10.18140/FLX/1669630 | Hörtäogl et al., 2020b. |
| CH-Oe2  | 10.18140/FLX/1669631 | Hörtäogl et al., 2020c. |
| Country | Code | Reference | Year |
|---------|------|-----------|------|
| CN-Hgu  | 10.18140/FLX/1669632 | Niu and Chen, 2020. |
| DE-Dgw  | 10.18140/FLX/1669633 | Sachs et al, 2020a. |
| DE-Hte  | 10.18140/FLX/1669634 | Koebisch and Juranski, 2020. |
| DE-SfN  | 10.18140/FLX/1669635 | Klatt et al., 2020. |
| DE-Zrk  | 10.18140/FLX/1669636 | Sachs et al., 2020b. |
| FI-Hyy  | 10.18140/FLX/1669637 | Mammarella et al. 2020. |
| FI-Lom  | 10.18140/FLX/1669638 | Aurela et al., 2020. |
| FI-Si2  | 10.18140/FLX/1669639 | Vesala et al., 2020a. |
| FI-Sii  | 10.18140/FLX/1669640 | Vesala et al., 2020b. |
| FR-LGt  | 10.18140/FLX/1669641 | Jacotot et al., 2020. |
| HK-MPM  | 10.18140/FLX/1669642 | Lai and Liu, 2020. |
| ID-Pag  | 10.18140/FLX/1669643 | Sakabe et al., 2020. |
| IT-BCi  | 10.18140/FLX/1669644 | Magliulo et al., 2020. |
| IT-Cas  | 10.18140/FLX/1669645 | Manca and Goded, 2020. |
| JP-BBY  | 10.18140/FLX/1669646 | Ueyama et al., 2020. |
| JP-Mse  | 10.18140/FLX/1669647 | Iwata, 2020a. |
| JP-SwL  | 10.18140/FLX/1669648 | Iwata, 2020b. |
| KR-CRK  | 10.18140/FLX/1669649 | Ryu et al., 2020. |
| MY-MLM  | 10.18140/FLX/1669650 | Tang et al., 2020. |
| NL-Hor  | 10.18140/FLX/1669651 | Dolman et al., 2020a. |
| NZ-Kop  | 10.18140/FLX/1669652 | Campbell and Goodrich, 2020. |
| PH-Rif  | 10.18140/FLX/1669653 | Alberto and Wassmann, 2020. |
| RU-Ch2  | 10.18140/FLX/1669654 | Groeckede, 2020. |
| RU-Che  | 10.18140/FLX/1669655 | Merbold et al., 2020. |
| RU-Cok  | 10.18140/FLX/1669656 | Dolman et al., 2020b. |
| Code    | DOI                  | Authors and Year |
|---------|----------------------|------------------|
| RU-Fy2  | 10.18140/FLX/1669657| Varlagin, 2020.  |
| SE-Deg  | 10.18140/FLX/1669659| Nilsson and Peichl, 2020. |
| UK-LBT  | 10.18140/FLX/1670207| Helfter, 2020c. |
| US-A03  | 10.18140/FLX/1669661| Billesbach and Sullivan, 2020a. |
| US-A10  | 10.18140/FLX/1669662| Billesbach and Sullivan, 2020b. |
| US-Atq  | 10.18140/FLX/1669663| Zona and Oechel, 2020a. |
| US-Beo  | 10.18140/FLX/1669664| Zona and Oechel, 2020b. |
| US-Bes  | 10.18140/FLX/1669665| Zona and Oechel, 2020c. |
| US-Bi1  | 10.18140/FLX/1669666| Rey-Sanchez et al., 2020a. |
| US-Bi2  | 10.18140/FLX/1669667| Rey-Sanchez et al., 2020b. |
| US-BZB  | 10.18140/FLX/1669668| Euskirchen and Edgar, 2020a. |
| US-RZF  | 10.18140/FLX/1669669| Euskirchen and Edgar, 2020b. |
| US-BZS  | 10.18140/FLX/1669670| Euskirchen and Edgar, 2020c. |
| US-CRT  | 10.18140/FLX/1669671| Chen and Chu, 2020a. |
| US-DPW  | 10.18140/FLX/1669672| Hinkle and Bracho, 2020. |
| US-EDN  | 10.18140/FLX/1669673| Oikawa, 2020. |
| US-EML  | 10.18140/FLX/1669674| Schuur, 2020. |
| US-Ho1  | 10.18140/FLX/1669675| Richardson and Hollinger, 2020. |
| US-HRA  | 10.18140/FLX/1669676| Runkle et al., 2020. |
| US-HRC  | 10.18140/FLX/1669677| Reba et al., 2020. |
| US-ICs  | 10.18140/FLX/1669678| Euskirchen et al., 2020d. |
| US-Ivo  | 10.18140/FLX/1669679| Zona and Oechel, 2020d. |
| US-LA1  | 10.18140/FLX/1669680| Holm et al., 2020a. |
| US-LA2  | 10.18140/FLX/1669681| Holm et al., 2020b. |
| US-Los  | 10.18140/FLX/1669682| Desai and Thom, 2020a. |
5.0 Conclusions

The breadth and scope of CH₄ flux data in the FLUXNET-CH₄ Version 1.0 dataset make it possible to study the global patterns of CH₄ fluxes, particularly for global freshwater wetlands which release a substantial
To help data users understand seasonal patterns within the dataset, we provide the first global estimates of CH₄ flux patterns and predictors in CH₄ seasonality using freshwater wetland data. In the seasonality analysis, we find that, on average, the seasonal increase in CH₄ emissions begins about three months earlier and lasts about four months longer at the warmest sites compared with the coolest sites. We also find that the beginning of the CH₄ emission season lags the beginning of seasonal soil warming by approximately one month, with almost no instances of CH₄ emissions increasing before temperature increases. Additionally, roughly half the sites have CH₄ emissions increasing prior to GPP increase; highlighting the importance of substrate versus temperature limitations on wetland CH₄ emissions. Furthermore, relative to warmer climates, wetland CH₄ emissions in cooler climates increase faster in the warming season and decrease slower in the cooling season. This phenomenon has previously been noted on a regional scale and we show that it persists at the global scale. Constraining the seasonality of CH₄ fluxes on a global scale can help improve the accuracy of global wetland models.

FLUXNET-CH4 is an important new resource for the research community, but critical data gaps and opportunities remain. The current FLUXNET-CH4 Version 1.0 dataset is biased towards sites in boreal and temperate regions, which influence the relationships presented in our analyses. Tropical ecosystems are estimated to account for 64% of potential natural CH₄ emissions (<30° N, Saunois et al., 2020) but only account for 13% of the FLUXNET-CH4 Version 1.0 sites in the dataset. Unsurprisingly, tropical sites in our network do not represent the range of bioclimatic wetland conditions present in the tropics. Therefore, while maintaining flux towers in tropical ecosystems is challenging, it is necessary to further constrain the global CH₄ cycle. Coastal wetlands are also poorly represented in FLUXNET-CH4 even though there is evidence of substantial CH₄ emissions from these ecosystems, so better representation across salinity gradients is warranted. Lastly, the average time series for FLUXNET-CH4 Version 1.0 is relatively short, only 3.7 site-years on average compared with 7.2 for CO₂ sites in FLUXNET (Pastorello et al., 2020). Adding additional site-years of data from existing sites, as a complement to adding new sites, will increase the community’s ability to explain interannual variability in CH₄ emission and seasonality. Nevertheless, FLUXNET-CH4 is an important and unprecedented resource with which to diagnose and understand drivers of the global CH₄ cycle.

Author contribution

Kyle B. Delwiche oversaw the data release, performed the seasonality analysis, gathered metadata, and prepared the manuscript with contributions from all co-authors. Sara Helen Knox gathered and standardized the data, and gap-filled the CH₄ flux data. Avni Malhotra prepared the manuscript and gathered metadata. Etienne Fluet-Chouinard did the representativeness analysis and prepared the manuscript. Gavin McNicol gathered data and prepared the manuscript. Robert B. Jackson oversaw the data collection, processing, analysis, and release. Danielle Christianson and You-Wei Cheah oversaw the FLUXNET-CH4 dataset release on fluxnet.org. Dario Papale, Eleonora Canfora, and Carlo Trotta did the data collection, curation, and processing for a majority of the non-American sites, outside North and South America. Remaining co-authors contributed eddy-covariance data to FLUXNET-CH4 Version 1.0 dataset and/or participated in editing the manuscript.

Competing interests

The authors declare that they have no conflict of interest.
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Figure A1: Peak methane (CH₄) flux timing versus peak gross primary productivity (GPP) timing (A) and peak soil temperature timing by day of year (B). Points represent site average and error bars represent standard deviations. Dotted line represents 1:1 relationship.
APPENDIX B

Table B1: Data variable names, descriptions, and units

**FLUXNET-CH4 Data Variables**

This webpage describes data variables and file formatting for the FLUXNET-CH4 Community Product.

### 1. Data Variable: Base names

Base names indicate fundamental quantities that are either measured or calculated/derived. They can also indicate quantified quality information.

Table 1. Base names for data variables

| Variable           | Description                                      | Units         |
|--------------------|----------------------------------------------------|---------------|
| **TIMEKEEPING**    |                                                    |               |
| TIMESTAMP_STAR     | ISO timestamp start of averaging period, used in half-hourly data | YYYYMMDDHHMM  |
| TIMESTAMP_END      | ISO timestamp end of averaging period, used in half-hourly data | YYYYMMDDHHMM  |
| TIMESTAMP          | ISO timestamp used in daily aggregation files     | YYYYMMDD      |
| **MET_RAD**        |                                                    |               |
| SW_IN              | Shortwave radiation, incoming                     | W m\(^{-2}\)  |
| SW_OUT             | Shortwave radiation, outgoing                     | W m\(^{-2}\)  |
| LW_IN              | Longwave radiation, incoming                      | W m\(^{-2}\)  |
| LW_OUT             | Longwave radiation, outgoing                      | W m\(^{-2}\)  |
| Variable   | Description                                      | Unit       |
|------------|--------------------------------------------------|------------|
| PPFD_IN    | Photosynthetic photon flux density, incoming     | µmolPhoton m\(^{-2}\) s\(^{-1}\) |
| PPFD_OUT   | Photosynthetic photon flux density, outgoing     | µmolPhoton m\(^{-2}\) s\(^{-1}\) |
| NETRAD     | Net radiation                                    | W m\(^{-2}\)       |
| MET_WIND   |                                                   |             |
| USTAR      | Friction velocity                                | m s\(^{-1}\)       |
| WD         | Wind direction                                    | Decimal degrees |
| WS         | Wind speed                                        | m s\(^{-1}\)       |
| HEAT       |                                                   |             |
| H          | Sensible heat turbulent flux (with storage term if provided by site PI) | W m\(^{-2}\)       |
| LE         | Latent heat turbulent flux (with storage term if provided by site PI) | W m\(^{-2}\)       |
| G          | Soil heat flux                                    | W m\(^{-2}\)       |
| MET_ATM    |                                                   |             |
| PA         | Atmospheric pressure                              | kPa         |
| TA         | Air temperature                                   | deg C       |
| **VPD** | Vapor Pressure Deficit | hPa |
|---------|-----------------------|-----|
| **RH**  | Relative humidity, range 0-100 | %   |

**MET_PRECIP**

| **P**  | Precipitation | mm |

**PRODUCTS**

| **NEE** | Net Ecosystem Exchange | µmolCO₂ m⁻² s⁻¹ |
|---------|------------------------|-----------------|
| **GPP** | Gross primary productivity | µmolCO₂ m⁻² s⁻¹ |
| **RECO** | Ecosystem respiration | µmolCO₂ m⁻² s⁻¹ |

**GASES**

| **FCH4** | Methane (CH₄) turbulent flux (no storage correction) | nmolCH₄ m⁻² s⁻¹ |

**MET_SOIL**

| **TS**  | Soil temperature | deg C |
|---------|------------------|-------|
| **WTD** | Water table depth (negative values indicate below the surface) | m    |
2. Data Variable: Qualifiers

Qualifiers are suffixes appended to variable base names that provide additional information about the variable. For example, the _DT qualifier in the variable label GPP_DT indicates that gross primary production (GPP) has been partitioned using the flux partitioning method from Lasslop et al. 2010.

Multiple qualifiers can be added, and they must follow the order in which they are presented here.

2.1. Qualifiers: General

General qualifiers indicate additional information about a variable.

- _F : Variable has been gap-filled by the FLUXNET-CH4 team. Gaps in meteorological variables (including air temperature (TA), incoming shortwave (SW_IN) and longwave (LW_IN) radiation, vapor pressure deficit (VPD), pressure (PA), precipitation (P), and wind speed (WS)) were filled with ERA-Interim (ERA-I) reanalysis data (Vuichard and Papale 2015). Other variables were filled using the MDS approach in REddyProc (see Delwiche et al. 2020 for more details).
- _DT : Variable acquired using the flux partitioning method from (Lasslop et al. 2010), with values estimated by fitting the light-response curve.
- _NT : Variable acquired using the flux partitioning method from (Reichstein et al. 2005), with values estimated from night-time data and extrapolated to day time.
- _RANDUNC : Random uncertainty introduced from several different sources including errors associated with the flux measurement system (gas analyzer, sonic anemometer, data acquisition system, flux calculations), errors associated with turbulent transport, and statistical errors relating to the location and activity of the sites of flux exchange (“footprint heterogeneity”) (Hollinger and Richardson 2005).
- _ANNOPTLM : Gap-filled variable using an artificial neural net routine from Matlab with the Levenberg-Marquardt algorithm as the training function, and parameters optimized across runs (more detail in (Sara Helen Knox et al. 2016; Sara H. Knox et al. 2019)).
- _UNC : Uncertainty introduced from ANNOPTLM gap-filling routine, as described in Knox et al. 2016 and Knox et al. 2019.
- _QC : Reports quality checks on FCH4 gap-filled data (_ANNOPTLM) based on length of data gap. 1 = data gap shorter than 2 months, 3 = data gap exceeds 2 months which could lead to poor quality gap-filled data. Nondimensional.

2.2. Qualifiers: Positional (_V)

Positional qualifiers are used to indicate relative positions of observations at the site. For FLUXNET-CH4, positional qualifiers are used to distinguish soil temperature probes for sites with more than one probe. Probe depths for each positional qualifier per site are included in the metadata file included with data download and also in Table B6 of Delwiche et al. 2020. For sites where the original database file release in Ameriflux, AsiaFlux, or EuroFlux contains multiple probes at the same _V depth, we average values and report only the average for each _V position. The one exception to this is site US-UAF where the original positional qualifier from the data we downloaded from Ameriflux had different depths for the
same qualifier. We still averaged the probe data, so _V qualifiers from US-UAF represent an average of more than one depth.

3.0 Missing data

Missing data are reported using -9999. Data for all days in a leap year are reported.

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