Replies to Referee 3

Juliette Bernard et al. developed a simple empirical model (SatWetCH4) to simulate global wetland methane emissions by leveraging large-scale remote sensing data. This model addresses uncertainties in wetland methane emissions and proposes a new approach for estimating substrate availability using MODIS data. Calibrated with eddy covariance flux data, the model aims to provide a simpler, faster alternative to more complex Land Surface Models. While I appreciate the authors' development of this new model and its contribution to global wetland CH4 monitoring, I have several major comments and concerns:

We thank you for reading the manuscript and your comments. Hereafter are point by point replies to your concerns.

The line numbers given hereafter refer to the tracking-changes PDF manuscript. Changes in the manuscript are given here in violet.

Major Issues:

1. Novelty and Approach:

One of the novel aspects of this paper is directly modeling large-scale substrate availability for methanogens. It uses NPP and soil organic carbon turnover (Eqn. 2) to estimate the carbon substrate mass balance. However, I have two questions regarding this approach:

Methanogens use CO_2 or acetate as substrates. What exactly does C_substrate represent? Is there evidence that the modeled C_substrate correlates with actual substrates for methanogens, making it a valid proxy variable? In other remote-sensing-based approaches (e.g., Bloom's WetCHARTS), soil respiration rate (CO_2 flux) is used as a proxy for substrate availability.

Methanogens are using low molecular weight soil organic compounds which are easily available: acetate, CO_2 or methylated substrates (Torres-Alvarado et al., 2005; Nzotungicimpaye et al., 2021). This available fraction of soil organic carbon (SOC) is not a measurable quantity, and a proxy has to be determined for methane emissions modelling purposes. The available SOC for methanogenesis is the remaining altered fraction of biopolymers produced by living organisms through photosynthesis, and methanogenesis has been shown to be correlated with plant productivity (NPP, GPP) (e.g., Whiting et al., 1993; Updegraff et al., 2001, Knox et al. 2021).

In the literature, three main approaches/proxies are used in bottom-up models for methanogenesis:

- the simplest approach is indeed suggesting that methane emissions are a fraction of CO_2 emissions by microbial decomposition (heterotrophic respiration) (e.g., WetCHARTs, LPJ model).
- some models use directly plant productivity NPP (or GPP) as proxy for available SOC (e.g., Walter et al., 2000, UW-Vic model)
- other approaches relies on simulated carbon pools (e.g., ORCHIDEE model)

Here we suggest a novel approach employing a fusion of the two last methods, a one-pool SOC model relying on NPP remote-sensing data for organic carbon input.

WetCHARTs, as our model, is a one-step approach model representing implicitly methane production and directly estimating methane emissions. Bloom et al. are using remote sensing products only to control the dynamic part of the wetland fraction, and not the SOC source. In WetCHARTs, methane emissions depend on heterotrophic respiration estimated from terrestrial biosphere models, consequently is not an independent approach. The heterotrophic respiration does not only represent available carbon but is a complex function, embedding dependence to other variables such as temperature.

How is C_substrate validated at sites in terms of its control over wetland CH4 emissions? Does eddy covariance site data show a strong relationship?

Validation Concerns:

The validation of C_substrate (Figure 5) is not convincing for two reasons. SoilGrids and HWSD provide benchmarks for upland soil carbon stock but not wetland C_substrate. Additionally, HWSD/SoilGrids provide total soil carbon stock, which does not necessarily turn over quickly. However, the defined residence time of C_substrate is less than 5.5 years (section 2.1).

Even the substrate availability plays a major role in methanogenesis, this is not a measurable quantity. We explicitly write in the submitted manuscript that HWSD and SoilGrids do not represent the same quantity as $C_{substrate}$, as these products represent total soil organic carbon (lines 274-279 cited below).

"The 2003-2020 mean map of the Csubstrate product is shown in Fig.5. This product is used as a representation of the soil carbon substrate available for methanogenesis. It should be noted that there are no analogous products for evaluation. We suggest a comparison with global estimates of 0-100cm SOC stocks derived from the World Soil Database (HWSD) (Wieder, 2014) and SoilGrids (Hengl et al., 2017) to see differences between our proxy for available substrate compared to total organic carbon stocks. The latitudinal distribution and the latitudinal distribution normalized by the latitudinal maximum of the three products are shown on the right side of the figure."

A comparison of this $C_{substrate}$ to total organic carbon stock is discussed, as no other dataset of carbon substrate is available. The soil carbon substrate $C_{substrate}$ variations present low temporal variations, and constrain the emissions spatial pattern in the model rather than the temporal variations (lines 287-293). Not taking into account a carbon availability parameter would be tantamount to assuming that SOC availability does not affect methane production/emission, which is false.

If the reviewer knows of another dataset to compare $C_{substrate}$ with, we would be happy to use it.

2. Q10 Parameter:

Q10 is a key parameter in the proposed modeling approach. However, Q10 is a complicated variable for wetland methane emissions due to different temperature sensitivities for various methanogens and methanotrophs. The emergent Q10 has been found to be small when constrained by satellite CH4 concentrations and inversions (Shuang Ma et al., 2021). This work uses a simply calibrated value of Q10 (2.99). I suggest a more in-depth discussion of the high Q10 value in existing literature, including reasons for discrepancies, implications, and biogeochemical processes.

Bloom et al. (2017) tested in WetWHARTs ensemble 3 fixed Q10 values : 1, 2 and 3. Shuang Ma et al. (2021) found that WetCHARTs outputs with Q10 = 1 were better agreeing with top-down inversion approaches. However, WetCHARTs equation includes heterotrophic respiration (Bloom et al., 2017):

$$F(t,x) = s\,A(t,x)\,R(t,x)\,q_{10}^{\frac{T(t,x)}{10}}, \qquad (1)$$

where A(t, x) is the wetland extent fraction, R(t, x) is the C heterotrophic respiration per unit area at time t, and T (t, x) is the surface skin temperature) and s is a global scaling factor. Their Q10 then represents “the temperature dependence of the ratio of C respired as CH4 (where Q10 is the relative CH4 : C respiration for a 10 ◦C increase)”, **and not the methane production dependence to temperature**. A temperature dependency is already embedded in the heterotrophic respiration term R. WetCHARTs Q10, named hereafter $Q10_{CH4:C}$ and our Q10, named hereafter $Q10_{CH4}$, are then different. The results from Shuang Ma et al. (2021) showed best emissions fitting with $Q10_{CH4:C}$=1 suggesting that using the temperature dependence for methane emissions already embedded in the heterotrophic respiration function R(t, x) is better than increasing the temperature dependency by adding the control of the second $Q10_{CH4:C}$, i.e., $Q10_{CH4:C}$ value >1.

In our case, having a $Q10_{CH4}$=1 in our equation would imply that temperature has no influence on methane emissions, which is absurd as temperature has been extensively documented to be a major driver of methane emissions variations (e.g., Know et al., 2021, Delwiche et al., 2021, Kuhn et al., 2022), at least in northern and temperate sites. Our $Q10_{CH4}$ value is in the range of other model values found in literature for methanogenesis which has been extensively discussed in Section 3.1 of our manuscript (lines 210-226):

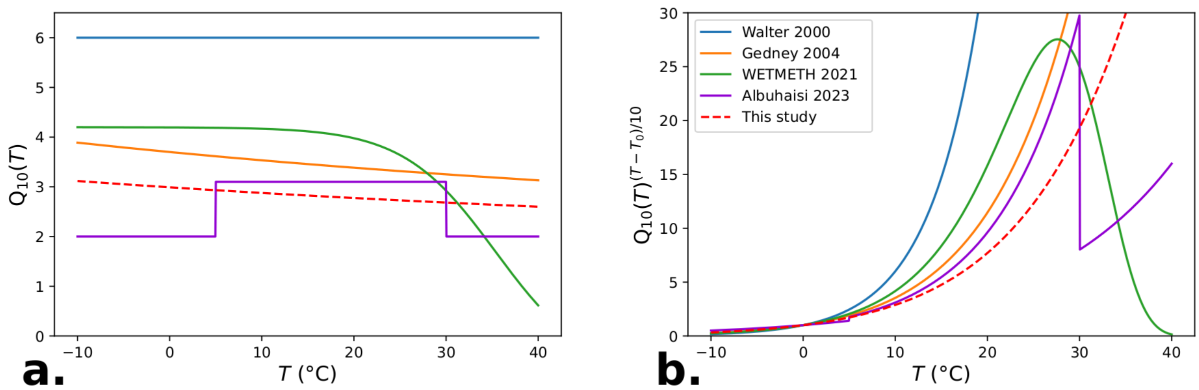

Figure 2

“Nzotungicimpaye et al. (2021) in WETMETH proposed a Q10 (T) formulation such that, when incorporated into the equation Q10 $(T)^{(T - T0)/10}$, it indicates an optimal temperature range for methanogenesis around 25-30°C.

Although we attempted a similar approach to formulate Q10 (T), it resulted in minimal changes in the flux outcomes while increasing the complexity of the formulation and hindering the convergence of the cost function. Albuhaisi et al. (2023) used a reduced Q10 for temperatures above 5°C or above 30°C, resulting in abrupt transitions at these temperature thresholds. However, this implementation may not be appropriate for global analyses, as tropical wetlands experience temperatures above 30°C, and such sudden changes do not reflect of physical reality. Therefore, the Gedney (2004) formulation Q10 (T) = $Q0_{10,opt\ 0}$ was used for calibration, resulting in Q10(T) from 3.12 (-10°C) to 2.60 (40°C), which is slightly lower than the Gedney (2004) value (3.89 at -10°C to 3.13 at 40°C). Our Q10(T) value contrasts with that of Walter and Heimann (2000) (Q10 = 6.0, no temperature dependence), but closely matches the value chosen by Albuhaisi et al. (2023) for the 5°C-30°C range (Q10 = 3.1 for T between 5°C and 30°C, Q10 = 2.0 below 5°C or above 30°C). Consequently, similar $Q10(T)^{(T-T0)/10}$curves are observed in Fig.2.b between our estimate and those of Gedney (2004) and the 5-30°C range of Albuhaisi et al. (2023), although our formulation exhibits slightly lower values. This would result in a slightly lower increase in methane fluxes with soil temperature."

We add a sentence (lines 226-228) for comparison with in situ data :

"The Q10(T) found in this study is also in agreement with meta-analysis of Q10 defined from in situ data, e.g., 2.8 in Kuhn et al. (2021) and 2.57 in Delwiche et al. (2021)."

Additionally, we removed WetCHARTs Q10 values from the comparison as it does not represent a $Q10_{CH4}$ but a $Q10_{CH4:C}$, as discussed above.

3. Model Simplicity and Missing Processes:

While I appreciate the simplicity of the model equation, capturing the major dynamics of wetland CH4 emissions, some important processes are not represented. Vegetation phenology (Carole Helfter et al.), which has remote sensing data available (EVI or NDVI), and atmospheric pressure, which controls the bubbling processes of wetland CH4, are significant. Including or at least discussing these variables/processes in the next version would be valuable.

This study indeed develops a simple model equation based on observations, capturing first order variations in methane production to temperature, wetland fraction and carbon substrate, that will serve in future studies to investigate time variations over long time periods and methane emissions trends.

In the near future, we would like that vegetation could be taken into account in a further version of SatWetCH4. However, in the present work we discussed two possibilities in Sect. 4:

- using factor/formulations for transport processes as modeled by LSMs. We excluded this approach because we want SatWetCH4 to provide CH4 emissions independently of the modeling parameters/outputs of LSMs.
- or taking into account implicitly these transport processes and vegetation dependency by fitting the equation parameters per vegetation or wetland type. This approach has been tested and discussed in the manuscript. Indeed, with only few sites per wetland type, it is difficult at the moment to calibrate the model per wetland type. More data in upcoming years would certainly enable future simple models to take transport processes and vegetation dependency into account. This is discussed in lines 456-474 of the manuscript.

"The simplified SatWetCH4 model we have developed makes important approximations that imply important shortcuts. In particular, no distinction is made between methane production and emissions. This supposes that SatWetCH4 one-step equation includes production, oxidation, and transport in a single formulation, which are sometimes distinguished in some of the more complex LSMs (Wania et al., 2013; Morel et al., 2019; Salmon et al., 2022). Among the 3 pathways of methane transport in wetlands, including diffusion, ebullition and plant-mediated transport, plant-mediated transport is the dominant one (Ge et al., 2024). Ge et al. (2024) have recently published a comprehensive review of the role of plants in methane fluxes, showing their influence not only on methane transport but also on methane production and oxidation. Feron et al. (2024) also show that trends in methane flux changes at the site level depend on ecosystem and vegetation type. Accounting for the different vegetation classes therefore appears to be a possible improvement to our simplified approach.

A simple way to account for this in the SatWetCH4 model at a first order would be to fit the scaling factor k and/or Q010 as a function of vegetation class or wetland type. We performed such calibration tests, taking into account the wetland classification. However, the cost function either did not converge due to the small number of sites per category, or the result was highly dependent on few sites, thus overfitting results. In fact, eddy covariance flux towers measuring methane emissions are not evenly distributed around the globe and their distribution is highly skewed, as discussed in part 2.2. Some wetland categories are poorly represented, for example, there are only two mangrove sites. This scarcity of data makes this type of calibration highly uncertain. However, we can expect an improvement in the coming years, as in situ methane measurement is a rapidly growing field, as shown by the increasing number of flux towers along the years in the Supplementary Table S1. Future data, especially in the tropics, will be essential to better constrain the models and to include more processes into account."

and in the conclusion (lines 494-499):

At the site level, the SatWetCH4 model reproduces well the boreal fluxes and most of the temperate fluxes, but poorly the emissions seasonality of the tropical sites. This could possibly be improved in future studies by adding high resolution information on local water availability (SWC). Another important improvement would be a calibration per wetland type, which would allow the influence of vegetation to be taken into account as major transport pathways. For this, more eddy covariance flux measurements in the tropics are essential to gain a deeper insight into the processes governing temporal variations in this latitudinal band, and to develop and calibrate this one-step model.

Atmospheric pressure is a predictor at multiday scale, but not at monthly ones (Knox et al., 2021).

4. Validation Performance:

Related to comment 4, the performance of SatWetCH4 at validation sites (Figure 3) is not satisfactory. This suggests that temperature and C_substrate alone may not be sufficient to capture the observed CH4 emission variability at the scale of eddy covariance sites. More effective calibration or the inclusion of missing dominant control variables in Eq. 1 may be necessary.

As discussed in comment 3, SatWetCH4 is a simplified model which, despite its simplicity, can estimate CH4 emissions as well as more complex LSMs and could be useful later for sensitivity studies, since it is constrained by observations. Only few flux data are available to constrain methane emissions models and accurately simulate methane emissions spatio-temporal variation. In the case of methane emissions, dominant control variables are numerous (temperature, available substrate, water, 3 types of transport processes, bacteria presence, etc.) and are formulated implicitly or explicitly in models which determine the level of model complexity. However, complex models ideally demand to be calibrated for each explicit process considered, which is not the case and result in increasing model uncertainties. Additionally, the level of the model complexity is usually determined based on the objective of the study, whether the study aims at understanding local processes or assessing global variability and trends. Here we wanted to develop an independent model, mainly constrained by satellite observations to study the methane fluxes spatial-temporal variability, therefore, we employed a simple model that is calibrated like other models using in situ site observations. Model limitations and missing processes, such as humidity or vegetation, are extensively discussed in the manuscript (Section 4, lines 419 to 487).

Other global models present the same level of uncertainties compared to site fluxes. It is for example interesting to note that data-driven machine learning approach from McNicol et al. (2023) has similar error values than SatWetCH4 (see Figure 3 of McNicol et al., 2023), even though they considered the 6 dominant predictors of methane fluxes. They also claim that the future flux data will make it possible to better describe the fluxes of all types of wetlands around the world.

5. Global Emission Estimates:

SatWetCH4 extrapolates site parameters to global wetlands. When compared with other products (GCP or WETCHARTS), SatWetCH4's emissions appear significantly lower, particularly tropical emissions throughout the year and boreal/arctic emissions in June/July/August. This may be due to SatWetCH4's low bias at sites with high emissions (Figure 3C).

WetCHARTs is constrained to match the mean value of total annual budget of GMB (GCP) models estimates, therefore it is not an independent estimation. Land surface models and Top-Down estimates and are calibrated with previous estimates (GMB, Saunois et al., 2020). Moreover, there is no evidence to suggest that these models represent an absolute truth.

SatWetCH4 global emissions are, indeed, remarkably low compared to GMB. We could also have calibrated the model to match other model estimates, but we think it is more interesting to present this independent approach. SatWetCH4 provides an independent estimates that is compared to most recent literature references work, and we did not claim that SatWetCH4 total value is more reliable than GMB estimates. The SatWetCH4 model is rather intended to study inter-annual variations based on independent remote sensing observational products. This low value was extensively discussed throughout the manuscript and more specifically in the section 3.3.4 which has been extended with a comparison to UpCH4 (McNicol et al. 2023) (see lines 360 to 381).

6. Summary

In summary, while I appreciate the authors' attempt to model global wetland CH4 emissions, I must point out that major variables and processes are missing in SatWetCH4. The site-level model calibration is not effective, and the global estimate of wetland CH4 emissions is significantly lower than values in the literature. I look forward to seeing an improved version during revision.

The purpose of this study is to develop SatWetCH4, which is indeed a simplified one-step model of methane emissions. A model is necessarily a simplification of reality. This simplification varies between approaches. Very complex LSMs try to represent many of the processes involved in methane emissions, but are then poorly constrained. We proposed here a simplified satellite-based approach, calibrated with available eddy covariance data. In a process-based approach, the processes can be represented explicitly or implicitly. Here we implicitly consider methane production, oxidation and transport by directly simulating methane emissions. We have discussed the advantages and limitations of such an approach in the manuscript and then in the responses to your comments.

Other variables, such as vegetation dependence, could be included in SatWetCH4 in the future as we expect new flux tower data to be available. Running the model at a finer scale would also help to account for variations in soil humidity, but at the moment wetland fraction datasets are not available at a finer resolution. The strengths of SatWetCH4 are to provide a new, independent approach, largely based on satellite data, and to offer the potential to study CH4 flux inter-annual variations.

Despite its simplicity, SatWetCH4 is as good (or as bad) as other more complex global models.

We hope that this improved version of the manuscript and these exchanges will clarify the aim of our study.