Replies to the editor:

Dear Dr. Bernard,

I have read your response letter and the two rounds of comments by the reviewers. As you can see in the second round, both reviewers remain concerned about the ~50% underestimation of wetland emissions at high-emission sites and on a global scale. While I recognize that your model provides a new, independent estimate of wetland emissions, this issue requires further discussion. For example, how well does the fitting perform? Would it be possible to show a scatter plot of the observed versus modelled points and assess deviations from the 1:1 line? Additionally, if you are able to tune the parameters to match the global budget, would it bias the site-level estimates?

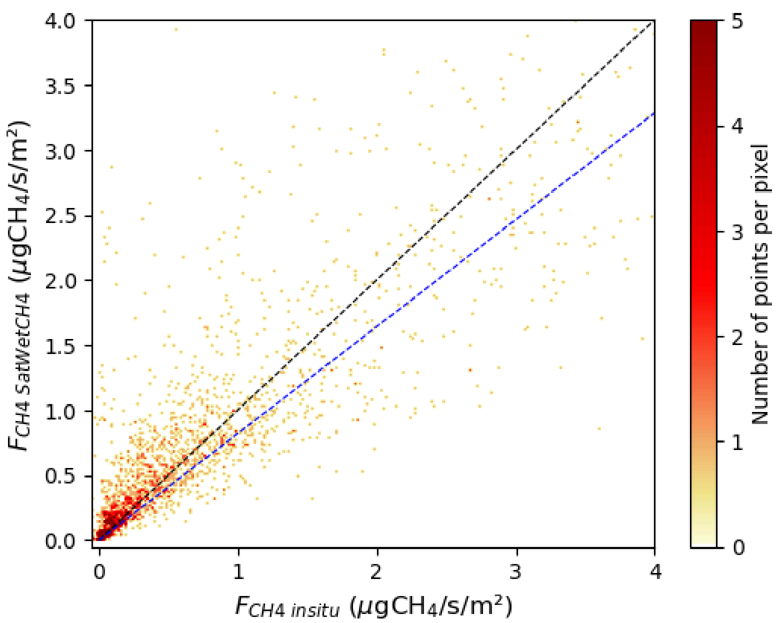
I would appreciate it if you could provide further details on these points.

Best regards,
Yilong

Dear Yilong,

Thank you very much for reading the exchanges of the review process and for your suggestions.

To address the issue raised by the reviewers and following your advice, we have made a scatter plot of the observed and modeled fluxes at site levels, where the colorbar represents the density of the measurements, as it is most commonly done, with a 1:1 line (dashed dark line) and the linear regression through the origin (0,0) (dashed blue line). This Figure shows that the model is slightly biased toward lower values when comparing to monthly site data. We have included this Figure in the Supplementary as Figure S1. Regarding the tuning of k and Q10 to match other global budget estimates (e.g. GMB), 2 parameters (k and Q10) are sufficient to achieve both a constraint on the monthly site data and a constraint on the global estimates, with similarly low biases on the monthly estimate scatter plot. However, this estimate would then lose its independence from the others estimates.



Indeed, the total output of SatWetCH4 in this manuscript (86TgCH4/yr) is below the bottom-up estimates, e.g., estimates of the Land Surface Models (102-182TgCH4/yr) or McNicol et al. 2023 (103-189 TgCH4/yr). SatWetCH4 certainly underestimates global methane emissions. Though, we would like to remind here that the LSMs have been generally calibrated against top-down estimates or other historical values and that such calibrations lack independence across LSMs.

SatWetCH4 is a simplified model, with the aim of running it on a global scale, using satellite observations as input data to provide independent estimates from top-down or LSMs estimates. While the model's emissions estimate is lower than the GMB LSMs estimates, it remains within a comparable range and captures similar spatio-temporal variations, making it suitable for further studies. We also show in the manuscript that adding more variables at 0.25° resolution (such as WTD or SWC) with currently available datasets does not improve model accuracy. This issue of the local scale to large scale representativity is never challenged in the global models' design, which extrapolate relationships observed at the site level.

This manuscript, submitted to Global Model Development, aims to describe the approach of SatWetCH4. **We believe that the value and strength of this method does not lie in providing a precise total global wetland methane budget, but in offering a straightforward and efficient tool for investigating large-scale spatio-temporal changes in wetland emissions.** We are currently carrying out two studies based on the development presented in this manuscript.

1. The first study is to **run SatWetCH4 using satellite data to examine large changes** in terms of inter-annual variations, long-term trends, and spatial patterns that could be explained by changes in temperature and wetland extent. The aim is to determine if such a simple approach can explain the spatial pattern of wetland methane emissions and the recent atmospheric methane changes over the last decades in terms of concentration and isotopic signature. This was not possible due to the limitations of WAD2M, but we have recently derived a new dataset of wetland extent (in review in ESSD https://doi.org/10.5194/essd-2024-466) that allows us to model and study wetland methane emissions over 30 years.
2. Another study aims also to **calibrate SatWetCH4 using an inversion model.** Here, we calibrated the two parameters k and Q10 in using in situ measurements, which are limited (58 sites), and really sparse over the Tropics. The use of an atmospheric inversion framework will allow optimizing the k and Q10 with global satellite data of methane concentration (e.g., GOSAT data). This approach will also provide observational constraints on total methane emissions and sinks. As more data with a global coverage will be available, the optimization of Q10 (and k) could be refined and performed per latitudinal band or wetland types (provided by a prescribed map such as GLWDv2).

We have revised the manuscript, particularly in the conclusion, to better clarify our objectives, which we believe are now more apparent. While we feel the manuscript clearly conveys its goals, we remain open to further revisions if the editors or reviewers suggest alternative wording.

Best regards,

Dear Dr. Bernard,

Thank you for your response letter. The review's report 1 raised the concern that SatWetCH4 underestimate at high-emission sites (years). It is indeed visible in your revised Figure S1, with a slope of only 0.8, indicating that you model underestimate the emissions by about 20%. Why the calibration did not achieve a close fit near the 1:1 line? This is also the reviewer's concern whether the parameterization or model structure is too simplified.

Best regards,

Yilong

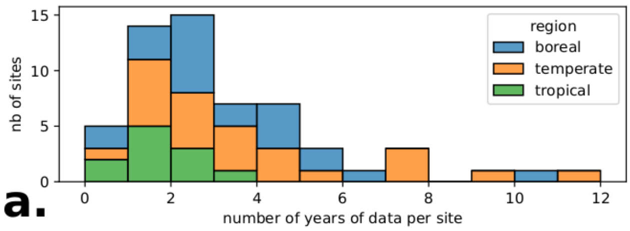
Dear Yilong,

thanks for your reply and raising concerns.

Indeed, this does not match the 1:1 (regression through 0,0 gives 1:0.83) with individual monthly data for 2 reasons :

1) the cost function does not imply a linear regression through (0,0).

2) also, and more importantly, we weighted the cost function to give different weights to the monthly data. These weights are described in lines 197-205 of the manuscript. We did this because some sites have much longer time series than others. In particular, boreal and temperate sites have longer time series than tropical sites. Giving the same weight to each monthly data would therefore lead to an even worse under-representation of tropical sites. This is why the calibration was not done by a simple regression on all monthly data.



Least squares regression is performed simultaneously on all sites using the Broyden-Fletcher-Goldfarb-Shanno algorithm (Byrd et al., 1995). For sites with less than 12 months of data, a weight proportional to the number of monthly measurements is assigned to the site data. Sites with more than 12 months of data are given equal weights. The minimized cost function is :

$$J = \sum_{sites} w_{site} MSD_{site} = \sum_{sites} w_{site} \overline{(F_{CH_4obs} - F_{CH_4sim})^2_{site}} \quad (3)$$

where w_{site} is the site weight, MSD is the Mean Square Deviation, F_{CH_4obs} is the in situ methane flux observed at the sites, and F_{CH_4sim} is the methane fluxes simulated by the model. If the number of monthly methane flux measurements at the site, n_{site}, is greater than or equal to 12, $w_{site} = 1$ otherwise $w_{site} = \frac{n_{site}}{12}$. Different initial parameter sets for $k_{firstguess}$ (0.01, 0.1, 1, and 10) and $Q^0_{10\,firstguess}$ (1.5, 2.5, 3, and 4) are tested to evaluate the influence of the calibration initialization and to ensure the global nature of the found minimum.

We hope this clarifies and justifies why the regression does not match the 1:1 of monthly data.

We respond to the reviewer concerns below.

Best regards,

Report 1 (Referee 3):

Most of my comments were addressed. I appreciate the authors' efforts. However, my biggest concern is that the model is over-simplified so it couldn't capture the variability of CH4 flux across 58 EC sites. Figure 3c is a clear demonstration that the model significantly underestimates CH4 emission, at high-emission sites (years).

Given the model is not parameterized well at EC sites (or even not capable of being sufficiently parameterized due to over-simplification), SatWetCH4 wetland emission estimate became so low. I just couldn't be convinced that global wetland CH4 emission is only 85.6 Tg CH4 yr−1 when upscaled with WAD2M (or 70.3 when upscaled with TOPMODEL). Either improving parameterization of the model or updating the model structure is needed 1) to sufficiently capture the CH4 emission dynamics (Figure 3c), 2) to make reliable upscaling products at global wetlands.

Thank you for reviewing the modified manuscript and for your valuable feedback. Below are our responses to your concerns.

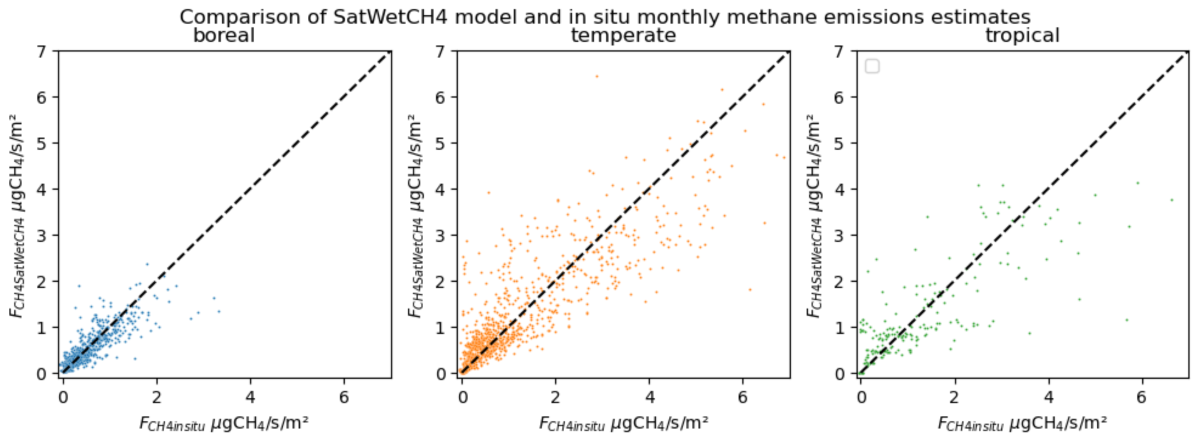
We acknowledge that the SatWetCH4 model output (86 Tg CH4/yr) is lower than current bottom-up estimates, such as those from GMB's Land Surface Models (102-182 Tg CH4/yr) or McNicol et al. (2023) (103-189 Tg CH4/yr). While SatWetCH4 certainly underestimates global methane emission, we would like to remind here that the LSMs have been generally calibrated against top-down estimates or other historical values, which introduces dependencies across models and approaches. Also LSM studies usually do not provide any assessment against flux tower measurements.

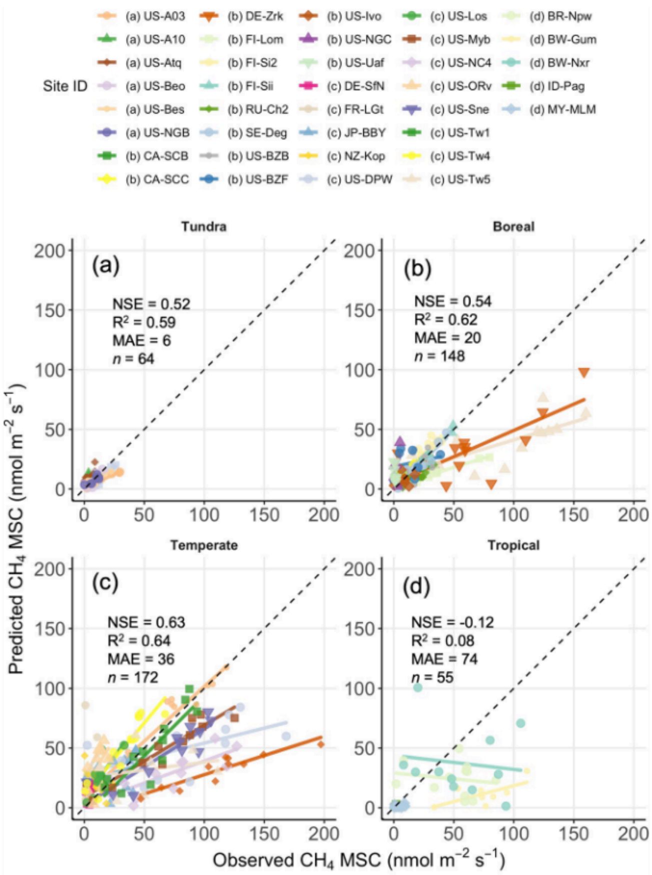
The objective of this manuscript is to present the SatWetCH4 approach. While the model's emissions estimate is lower than the GMB LSMs estimates, it remains within a comparable range and captures similar spatio-temporal variations, demonstrating its potential for large-scale analysis. We believe that the value and strength of this method does not lie in providing a precise total global wetland methane budget, but in offering a straightforward and efficient tool for investigating large-scale spatio-temporal changes in wetland emissions (detailed in the reply to the editor).

SatWetCH4 is a simplified model designed for global-scale use, utilizing satellite observations as input data to provide independent estimates from top-down and LSMs methods. As such, it is not intended to precisely replicate site-level observations, which would require more detailed input data at high resolution (e.g., Water Table Depth, as discussed in the manuscript). Multisite optimization is challenging, especially when sites from all latitudes are included. Indeed, most studies focus exclusively on boreal and/or temperate regions, where the seasonal cycle is more predictable. For example, the Figure 3 below from the global study by McNicol et al (2023) , shows similar discrepancies than SatWetCH4, especially at tropical sites (e.g., BW-Gum), despite using more complex machine learning-based upscaling approaches with a greater number of predictors. This can also be seen in Figure 7 of Salmon et al. (2022) below: multi-site optimization is challenging and leads to underestimating the most emitting sites and overestimating the least emitting sites, even when the model used is complex and only tested for temperate and boreal peatlands.

Finally, we also show in the manuscript that adding more variables at 0.25° resolution (such as WTD or SWC) does not improve model accuracy, even though we see relationships between these variables and methane fluxes at the local site scale. This highlights an inherent challenge in global modeling: extrapolating relationships observed at site-level measurements to large-scale estimates. This issue of the local scale representativeness to large scale is often not challenged in global models' design, which extrapolate relationships observed at the site level.

The manuscript has been revised to better clarify our objectives, which we believe are now clearer. While we feel that the manuscript clearly communicates its aims, we remain open to further suggestions for alternative wording.





Part of Figure 3 from McNicol et al (2023). Random forest model predicted versus observed values for(a–d) the mean seasonal cycle (MSC) of methane (CH4) flux for sites in (a) tundra,

(b) boreal, (c) temperate, and (d) tropical climate regions [...] The 1:1 fit is shown as a dashed black line.

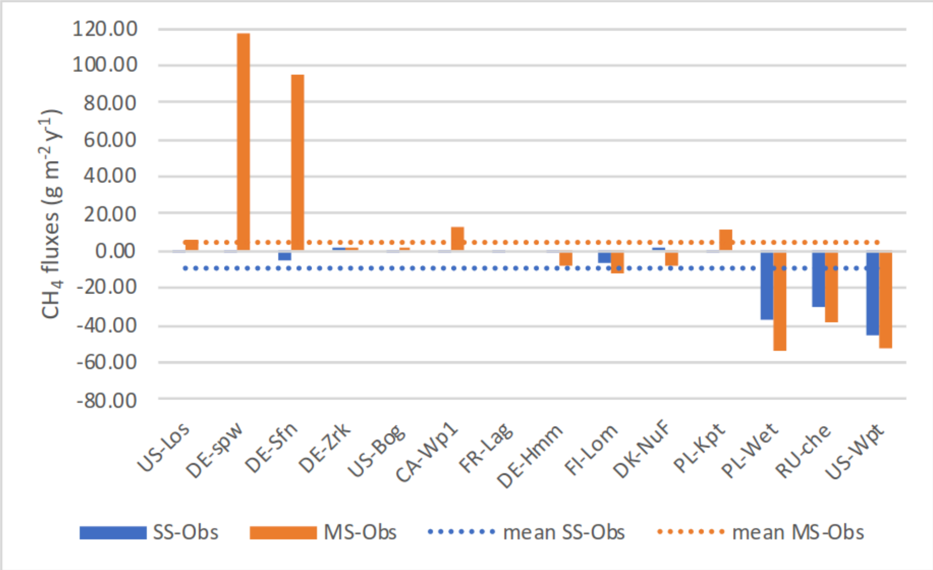


Figure 7 from Salmon et al. (2022): Differences in annual methane emissions defined between the observed data (Obs), and simulations employing parameters optimized by the single site (SS) and by multi-site (MS) approaches.

Report 2 (Referee 1):

While I appreciate the authors' efforts to address all the previous comments, I have the same concern raised by the other two reviewers regarding the underestimation of global methane emissions. This issue might confuse readers about the global budget and needs to be discussed in more detail. The authors suggested that the scaling factor k could be easily tuned to match the global values, but it remains unclear how this adjustment would impact the model's performance? For example, would such a correction improve or degrade the site-level results, and to what extent? I would be pleased to see further discussions on this issue.

Thank you for your review of the revised manuscript. Below is our response to the concerns you have raised.

We acknowledge that the SatWetCH4 model output (86 Tg CH_4/yr) is lower than current bottom-up estimates, such as those from Global Methane Budget (GMB)'s Land Surface Models (102-182 Tg CH_4/yr) or McNicol et al. (2023) (103-189 Tg CH_4/yr). While SatWetCH4 certainly underestimates global methane emissions, we would like to remind here that the LSMs have been generally calibrated against top-down estimates or other historical values, which introduces dependencies across models and approaches. The objective of this manuscript is to present the SatWetCH4 approach. While the model's emissions estimate is lower than the GMB LSMs estimates, it remains within a comparable range and captures similar spatio-temporal variations, demonstrating its potential for large-scale analysis. We believe that the value and strength of this method does not lie in providing a precise total global wetland methane budget, but in offering a straightforward and efficient tool for investigating large-scale spatio-temporal changes in wetland emissions (see the details of these studies in the reply to the editor). We have revised the manuscript to better clarify the goal of SatWetCH4, and remain open to further suggestions for alternative wording.

Concerning the tuning of the model parameters to match other global budget estimates (e.g. GMB), this would be possible by modifying the cost function (eq 3) to also add a constraint on the global estimates. Having 2 parameters to adjust (k and Q10) is sufficient to obtain a regression with similarly small biases on the monthly estimate. However, this estimate would then lose its independence from the other estimates.