A top-down evaluation of bottom-up estimates to reduce uncertainty in methane emissions from Arctic wetlands

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General comments:

This study is focused on wetlands in the Arctic boreal region. The authors alter the parameters f_{CH4} (fraction of baseline methane) and Q_{10} in JSBACH to produce a total of 9 forward simulations. They compare these to eachother, then use them as priors in atmospheric inversions from 2010 to 2021. The inversion that yields the smallest difference between prior and posterior fluxes is interpreted as indicating the JSBACH configuration that best matches the atmospheric observations, evaluated at annual, monthly, and regional scales. The results show that different combinations of Q_{10} and f_{CH4} perform best across different seasons and subregions, highlighting the need for regionally and seasonally varying process model parameters. Overall, the study provides a valuable proof of concept demonstrating how atmospheric observations can help guide the optimization of process-model parameters.

I believe the paper makes a meaningful contribution to the integration of bottom-up and top-down approaches. However, several sections require significant improvement to more clearly convey the key messages and strengthen the methodological transparency. I recommend publication after consideration of the comments below.

Improvement of general paper structure and text.

The introduction provides a thorough overview of methane biogeochemistry and modeling approaches, but it currently reads more like a literature review than a focused lead-in to the study. The research gap and specific objectives only become clear after several pages. I suggest condensing the detailed process descriptions (e.g., lines 43–78) and emphasizing earlier why reconciling bottom-up and top-down CH4 estimates is scientifically important and what this study contributes. A shorter, more focused introduction would make the study's novelty clearer to readers.

Some specifics:

- There is not enough emphasis on why improving process models in the Arctic specifically is important. This context could appear near the start. Highlighting the magnitude or

consequences of Arctic top-down vs. bottom-up discrepancies would strengthen the motivation.

- The discussions of bottom-up and top-down approaches are disjointed, even though their integration is central to the paper.
- You could note that process models are often evaluated against flux or site-level data, but less commonly constrained by atmospheric observations. That contrast nicely sets up the study's novelty.
- The research question appears midway through, before introducing top-down methods. The introduction should build logically from the knowledge gap to the research question, with the final paragraph outlining how the study addresses it.

Similar to the introduction, Section 2.2 is longer than needed and includes detail that is not directly relevant to the study's research question or required to understand the methodology. Much of this description could be replaced with references to existing JSBACH publications or model documentation. For example, lines 146–158 provide an in-depth explanation of inundation and hydrology processes, which are not examined in the subsequent analysis. Parts of the following paragraph (lines 159–178), could be summarized briefly, cited, or moved to a supplement or appendix. As a reader with an inversion rather than process modelling background, I found this paragraph (lines 159-178), difficult to follow. It aims to introduce the relationship between f_{CH4} and the CH4:CO2. I would suggest revising this section and perhaps including a mathematical relationship between f_{CH4} and CH4:CO2.

Discussion and conclusion:

As you state, this work provides a valuable initial approach but not a long-term solution -future models will need to allow dynamic changes in Q_{10} to reflect varying environmental conditions. I think this study is timely and also naturally leads into a broader discussion of methane data assimilation techniques, which aim to optimise process-model parameters using observational constraints. For example, Montiel et al. (2025) conduct inversions with a process model (LPJ-GUESS) that has been optimised using eddy covariance fluxes and compare these with simulations using unoptimised parameters, drawing conclusions about the potential of data assimilation. Bernard et al. (2025) also discusses this direction. However, these studies do not yet address regional or seasonal optimization, which your results highlight as particularly important. I think a discussion on this would support the position of your work.

In the conclusions section, almost the entire second paragraph focuses on the general limitations of using top-down inversions. This material would fit better in the discussion, where reflection on the limitations of your own inversion setup should be included. Shifting it there would help keep the conclusions concise and focused on the study's main findings.

Data and code availability

I notice there is no data or code availability section. Please could this be included for transparency? Could you please properly acknowledge the data providers?

Specific comments:

Line 36: bottom-up methods also include inventories

Line 98: “used a prior” or “used as priors”

Line 102: Do you mean the combined wetlands and inland freshwater sources?

Line 114: Can you make it clear here or somewhere before how fch4 relates to CO2:CH4.

Section 2.1 Please could you include a list of sites and site years as a table. Potentially in an Appendix?

Figure 1. Why is there a gap between Alaska and Eastern Russia regions?

Line 140: What is the resolution of the climate data?

Line 155: As I mentioned above, I don’t think that this level of description is necessary, however here ‘the sensitivity study’ is mentioned, but I am not sure what that is? Is that in this paper?

Line 184: Please can you justify why you chose these values and their limits?

Line 188: Since this is a linear Bayesian system, a short description of the cost function or posterior solution would be useful.

Line 196: Are you optimizing by grid cell? By region? Are you running TM3 daily and optimizing daily?

Line 196: What is the resolution of the meteorology?

Line 197: This spatial resolution seems quite coarse. Perhaps this could also be discussed in the limitations.

Line 199: So, is the model data mismatch the same for every site? Are your covariance matrices diagonal, or do you take into account spatial/temporal correlations?

Line 200: Please could you provide a short description of the weighting scheme?

Line 202: I think I understand from later in the paper that the emissions are optimized together and not separately (i.e. one scaling for all sources). Please could you make that clear here? Perhaps this could also be discussed in the limitation section.

Lines 202: Please include information on the fire emissions prior! And also, you don't include an inland water/freshwater prior. Please mention this.

Line 225: Taking into account uncertainties in the model/transport etc.

Section 2.4: Could this section be broken into multiple paragraphs for readability? Perhaps one for each top-down result (pan-Arctic, seasonal, regional).

Figure 2: Figure 2a is a bit fuzzy. Could this be exported as a vector file? Maybe in a and b you could use colors/patterns that nicely show how the results are grouped more by Q10 than they are by fch4. I think the B labelling is not necessary, you also use this in Table 1, but B1_low etc. is not used in the text anywhere.

Figure 3. In c, it's quite difficult to see Alaska, perhaps you could plot this as percentage difference? There is a small typo in the title "dif**f**erence"

Figure 4. I think these results are really important! Please could you 'zoom-in' on the Arctic-boreal region? Perhaps you could highlight in the legend the experiment that was the best on a pan-Arctic scale, which is clearly not the best regionally.

References

Monteil, G., Theanutti Kallingal, J. & Scholze, M. CH_4 emissions from Northern Europe wetlands: compared data assimilation approaches. *Atmospheric Chemistry and Physics* **25**, 14251–14277 (2025).

Bernard, J. *et al*. Satellite-based modeling of wetland methane emissions on a global scale (SatWetCH4 1.0). *Geoscientific Model Development* **18**, 863–883 (2025).