Replies to reviewer 1:

Our responses to the reviewer 1 comments are provided below. The comments from the reviewer are in *italic* and our responses are in normal font. For changes to the MS text, please see the new version, in which the changes are marked in red.

The authors present a study on estimating methane emissions in northern high latitudes during the spring melting season using two different inverse modeling set-ups. The study also includes a detailed description and analysis of the estimation of the spring melting season in four different permafrost zones using SMOS F/T data. This study is a valuable contribution in reducing uncertainties in estimating the length of the spring melting season in permafrost regions, which are increasingly affected by climate change, as well as estimating the resulting CH4 emissions in those regions.
In my opinion, this study is well prepared and carefully thought out, so only minor improvements are necessary. Specifically, I believe there are three points that should be taken into account when revising the manuscript:

We thank the reviewer for the kind overview and invaluable comments to our manuscript. In the following comments we aim to answer to the given concerns.

1. There are a few details about the inverse modeling set-up and the analysis that I didn't quite understand from the description. You describe the model domain of the transport model, but are the CH4 fluxes also optimized over the whole domain (globally)? And in the results, do you evaluate the total CH4 fluxes (anthropogenic+natural) or only the natural fluxes or only the biogenic fluxes? If you evaluate all natural fluxes, what about the contribution from other natural sources, since you predominantly want to estimate wetland emission? Please add these details in your description.

We thank the reviewer for this helpful comment. The emissions were optimized globally and in this paper we only analyzed the optimized biospheric emissions. Here the biospheric emissions only include emissions from the wetlands as well as soilsink. We have added information to the chapter 2.2.3 regarding the prior fluxes in the following way:

"Biospheric and anthropogenic fluxes were optimized globally. Other fluxes were not optimized. We only analyze the optimized biospheric fluxes in this study. The biospheric prior LPX-Bern DYPTOP represents ecosystem area fractions across several land-cover types: (i) peatlands suitable for peat growth as defined by DYPTOP (Stocker et al., 2014); (ii) rice paddies coinciding with croplands and the presence of rice paddies (Spahni et al., 2011); (iii) inundated wetlands other than peatlands or rice paddies; (iv) wet mineral soils, which are not wetlands, peatlands, rice paddies, permanent freshwater bodies, or ice/sea water covered areas, but are ocassionally wet; and (v) dry mineral soils, which are areas identical to wet mineral soils but are "dry" in general. Of these categories, we did not include rice paddies in our prior as they are not present in the northern high latitude region. Soilsink was included in the biospheric prior."

We added the following to the results chapter:
"The biospheric CH_4 emissions were analyzed with both the region-based and grid-based approach. From this point onward, we will focus exclusively on biospheric emissions, regardless of whether this is explicitly mentioned. Biospheric emissions refer to optimized fluxes for which prior

estimates were derived from ecosystem model simulations of wetland emissions as well as terrestrial sink fluxes (See section 2.2.3).”

2. In some cases, the figures shown are not adequately described in the accompanying text. For example, Fig. 4 has four sub-figures and displays multiple set-ups, but there is only one brief sentence describing it. Please ensure that all figures are described properly and that it is clear what they display.

We added more text to the Results chapter to make sure that all figures are described enough. We also added references to the figures to some previously existing sentences. For example Fig. 4 was referenced in the following sentence: “Using the grid-based approach, the average length of the melt period was the longest in the southernmost zone, non-permafrost (12 days), and the shortest in the northernmost zone, continuous permafrost (7 days) (Fig. 2, Fig. 3 and Fig. 4).”

We hope that all the figures are now described properly.

3. Since you are using inverse modeling, it would also be useful to include a brief comparison with the prior fluxes. So far, this has only been mentioned briefly in the discussion. For instance, you state that the CH4 fluxes are highest in the non-permafrost zone, which you attribute to it being the largest zone. However, could this also be related to the fact that the prior was possibly already estimated to be higher in these areas? The inversion can only optimize the fluxes to a certain extent. For example, if there are large areas in the continuous permafrost zone where the prior fluxes are zero, these will remain zero in the posterior state. These are some points to consider when discussing the results.

We agree that taking the prior more into account is important. We added the prior emissions to Fig. 6, and plotted the difference between prior and posterior emissions of Fig.7 and Fig. 8 and added these figures to the Appendix. We also added more text comparing the prior and posterior emissions to the results and discussion. For example we added a chapter 3.2.1 “Comparison to prior emissions” in the results. From our results we can see that the posterior emissions follow the prior emissions quite well but the posterior decreases from the prior in the northernmost region (continuous permafrost) and increases in the southernmost region (non-permafrost). Additionally, the posterior usually increased from the prior in the Western Siberian Lowlands and Hudson Bay Lowlands regions. Overall the total melt period emissions were increased from the prior with both region- and grid-based methods. In the discussion we added analysis related to the prior and missing observations:

“The increase in emissions from prior to posterior estimates was also more pronounced in these two regions than across the northern high-latitude domain as a whole. This may be attributed to the greater extent of continuous wetlands in these regions and/or the higher density of the observational network (Fig. A1), which likely influenced the prior estimates. Additionally, there are large areas in the high northern latitudes, where the difference between the posterior and prior emissions was close to zero during the melt period (Fig. A7). In grid cells where prior emissions were zero, posterior emissions during the melt period were also zero. This likely contributed to the minimal differences observed between prior and posterior estimates in those areas.”

We hope that the added details answer to the reviewer’s concerns.

Specific comments

We changed the sentence to:
"A large portion of the total soil carbon is stored in northern wetlands and
the underlying permafrost, containing ~80% (415 ± 150 Pg C (Hugelius et al., 2020)) of the total
global peatland carbon, with nearly half being permafrost affected peatland (Hugelius et al., 2020;
Scharlemann et al., 2014)"

We agree that this part of the text needs to be more clear. We changed the text to:

" Due to climate change and Arctic amplification, thawing permafrost could affect this carbon stock
(Schuur et al., 2015; Knoblauch et al., 2018; Voigt et al., 2019; Turetsky et al., 2020). Even though
permafrost thaw will likely lead to soil drying and increased drainage, which potentially accelerates
organic matter decomposition and CO2 emissions while suppressing CH4 emissions (Lawrence et
al., 2015), the effect of the released CH4 might be as large due to its stronger global warming
potential (Schuur and Abbott, 2011). Increasing rainfall and warming soils could increase near-term
global warming, and the total annual boreal CH 4 emissions could rise 4 Tg per year Neumann et al.
(2019). The study by Poulter et al. (2017) using a biochemical model concluded that boreal wetland
CH4 emissions have already increased by 1.2 Tg yr−1 between 2000–2012. Even if the permafrost
does not fully thaw, the deepening of the active layer – the top layer of soil that thaws in summer
and freezes in winter – can still release a significant amount of carbon."

We added the citation:
Rawlins, M. A. and Karmalkar, A. V.: Regime shifts in Arctic terrestrial hydrology manifested from
impacts of climate warming, The Cryosphere, 18, 1033–1052, https://doi.org/10.5194/tc-18-1033-
2024, 2024

We have now changed the sentence structure to the suggested.

We modified the chapter 2.1 after comments from the second reviewer. We also added the following
explanation of the L-band: "L-band refers to low frequency (1–2 GHz) passive microwave
observations (Rautiainen et al., 2025)."

Modified the wording to: "Of the three categories, the thawed soil state is used in this study to define the melt period."

Added the suggested references to the section 2.2.

We added a sentence to clarify that the soil sink is included in the biospheric prior.

We added information regarding the excluded areas:
"This masking excluded areas such as southern regions below 40 ° N where almost no permafrost is located, as well as oceans, most of Greenland, and some areas close to the Great Lakes in the USA."

We modified the sentence to:
"The boundaries used in this study were similar to the ones used by Erkkilä et al. (2023) to define different seasons in the northern high latitude wetlands, but instead of frozen or partially frozen state of the SMOS F/T data, we used the thawed soil state to define the melt period."

We did not want to add too much information regarding the boundaries defined by Erkkilä et al. (2023), so that the reader does not get confused by the difference to our boundaries. However, we added some comparison to the study in the Results chapter 3.1.1.

We took out the word spring. In this context the word spring only represented the season during the spring time when the soil turned from frozen to thaw, not any specific months.

Added the suggested change for clarity in that sentence.

P10, L198-L291:
"The mean values of the length and temperature of the grid-based melting
season might not have been the best to describe the relationship…" Since you
state that it's not the best way, what would be a better method in your
opinion?

We modified this statement to better explain the relationship between the variables:
"The mean values of the length, temperature and starting day of the grid-based melt period may be insufficient to describe their relationship because the variation between different grid cells is not seen."

P12, Fig. 3:
Could you add more spaces between the tick labels in the lower panels? It
would be easier to read.
We made the font size of the ticks smaller so that it is easier to read. We also made some other modifications to the figure so that it looks better, e.g. fixed an issue with missing values in the previous figure.

P12, L317 – P13, L318:
"Hudson Bay lowlands and Western Siberian lowlands are some of the largest
methane emitting wetlands in the northern high latitudes." Do you have a
source for that or was it concluded from your emission dataset?

We added the following sources:
Pickett-Heaps, C. A., Jacob, D. J., Wecht, K. J., Kort, E. A., Wofsy, S. C., Diskin, G. S., Worthy, D. E. J., Kaplan, J. O., Bey, I., and Drevet, J.: Magnitude and seasonality of wetland methane emissions from the Hudson Bay Lowlands (Canada), Atmospheric Chemistry and Physics, 11, 3773–3779, https://doi.org/10.5194/acp-11-3773-2011, 2011

Umezawa, T., Machida, T., Aoki, S., and Nakazawa, T.: Contributions of natural and anthropogenic sources to atmospheric methane variations over western Siberia estimated from its carbon and hydrogen isotopes, Global Biogeochemical Cycles, 26, https://doi.org/https://doi.org/10.1029/2011GB004232, 2012.

It can also be concluded from our dataset as these 2 regions have some of the highest emissions in the whole northern high latitude region.

P14, L335:
"The average annual region-based melting season emissions" Does that
include anthropogenic emissions or only natural?

This only includes the biospheric emissions. We added that to the text for clarity.

P15, L371:
"Figures 7 and A6" Is there a reason why one of the figures is in the main text
and the other in the supplements?

We only included one of the figures in the main text as the two figures are similar to each other and thus both are not needed in the main text.

"as the whole area is not permafrost or wetlands" Could you please re-formulate to clarify this wording?

We reformulated the wording to:
"Within a single permafrost region, fluxes vary widely because the area does not consist entirely of permafrost or wetlands."

Are the high share of 31% share of the emissions in the Hudson Bay and Western Siberian lowlands also related to higher emission estimates in the prior fluxes? Also, did you adjust the scale of the NIES measurements before including them in the inverse modeling framework?

We added some comparison between prior and posterior in the Hudson Bay lowlands and Western Siberian lowlands which can be seen in the reply to your comment Nr. 3. We did not adjust the NIES measurements before including them in the inverse model. We added this to the discussion chapter:

"However, the emissions in the Western Siberian lowlands could have been overestimated, because the NIES observation sites, which we did not adjust before using the measurements in the inversion, had a different calibration scale (3.0 to 5.5 ppb higher) than WMO CH4 X2004A scale as in the (Sasakawa et al., 2025)."

We have modified the manuscript according to the following technical corrections.:

Missing article? "for three permafrost zones and for a seasonally frozen non-permafrost zone"
Consider splitting the sentence in two sentences. Also "over a 100-year timescale"
"from the increasingly dry Arctic"
No article: "but reliable soil temperature data"
"at a resolution of 25 km"
Singular: "for the whole northern high latitude region"
"spring CH4 emissions have been studied"
"spring melting season and its CH4 emissions" Better: "spring melting season and the corresponding CH4 emissions"
"the spring melting season"

"the melting snow during daytime affects the descending orbit"
This sentence is deleted from the final version of this chapter.
P6, L160:
One set of parentheses too much: "(Obu et al., 2021)"
P6, L164:
"data had no values" ?
P6: L167-L168:
Please check sentence structure, it's not clear
P8, L208:
"There were a maximum of 18 SMOS F/T pixels and a minimum of"
P9, L255:
"Other areas with a noticeably longer melting season"
P10, L183:
Missing comma: "Additionally, there was a positive correlation"
P10, L286:
"not as strong a correlation"
P15, L343:
Fig. 8 is mentioned before Fig 7, they should probably be switched?
P16, L378:
"However, there is no major difference"
P22, L465:
One comma too much "Even though methane emissions"
P24, L530 – L531
One "model" too much "with multiple process-based ecosystem models for the northern wetlands"
P24, L534:
"the mean annual emissions in the Hudson Bay lowlands and Western Siberian lowlands"
P25, L556:
No dashes "melting season lengths varied more from year to year than."
P25, L562:
"in estimating the spring melting season"