

Replies to reviewer 2:

Our responses to the reviewer 2 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 study attempts to technically redefine the seasons/time period of spring melting in northern high-latitudes using SMOS satellite freeze/thaw data by accurately identifying the start of melting season and examine how it relates to the total methane flux emissions. Authors have attempted two different approaches to mark the beginning and end of melting seasons using a region-based estimation and a grid cell-based estimation. Both the methods provide largely variable results but they serve different purposes, which I would suggest needs to be made clear in the manuscript. The work is solid, and would be a valuable contribution to the high-latitude methane research. However, I would suggest the authors to address the following comments which I believe would make it methodologically stronger.

We thank the reviewer for the invaluable and thoughtful comments to our manuscript. In these following comments we aim to give answers to the reviewer's concerns.

1. The Introduction section should clearly articulate the practical benefits and added value of redefining the melting season boundaries using the study's specific criteria rather than relying on the standard (MAM) period. How can redefining the spring melting season help improving the modelling (process-based or inverse) of hydrology and methane emissions in the northern high latitudes? Please include them in the introduction.

We have previously mentioned in the introduction that using the SMOS F/T data to define the melt period in the northern high latitude wetlands gives us a dynamic picture of the soil thawing including the active layer of the permafrost during the spring instead of using a static definition for the whole spring season. We added clarification to the chapter that this does not cover the spring season as a whole, by removing the word "spring" from many sentences. Melt period only covers the beginning of the spring season when the soil thaws. We also changed the term "melting season" to "melt period" to further separate the period from the whole spring season.

In our results we observe a distinct north-south difference in the timing of the melt period, suggesting that the conventional spring classification (MAM) is too strict to accurately reflect the spatial variability in this study.

We modified one sentence in the abstract to separate the melt period from the spring:

"To better understand the seasonality emissions of northern high latitude methane, we defined the melt period occurring in spring time using the remote sensing Soil Moisture and Ocean Salinity Freeze/Thaw data from 2011–2021."

We also added the following sentence to the introduction:

"This allows us to focus on the CH₄ emissions during the actual thawing of the soil instead of the whole spring season with inverse modeling."

2.Total melting-season emissions differ a lot between methods (region and grid) yet both are presented as valid “melting season” totals. This 4 times difference is large and needs a clear methodological explanation beyond just “region based vs grid based”. Authors are suggested to clearly mention the purpose of each method in the abstract and conclusion.

We thank the reviewer for this important comment. In the abstract, we have mentioned the following:

“The melt period was defined for three permafrost zones and for a seasonally frozen non-permafrost region using two approaches: region-based, which considered climatological conditions of permafrost regions, and grid-based, which defines the melt period at a finer 1° x 1° scale.”

as well as:

“Our dual-method approach allows for robust comparison with both large-scale regional studies and localized site-level research.”

To clarify the purpose of both methods at the start, we changed the end of Introduction to:

“The spring melt period is defined for four different permafrost zones (sporadic, discontinuous and continuous permafrost and a seasonally frozen zone non-permafrost) with a region-based approach, as well as individually for each 1°x 1° grid cell with a grid-based approach. For comparison between the two methods to define the melt period, we divided the grid-based melt period into the same four permafrost zones. This allows us to estimate emissions both in climatological and local scales.”

We edited one sentence in the conclusions to the following:

“The region-based method is comparable to studies with monthly emission estimates, as it focuses more on the climatological differences between large regions, while the grid-based method is more comparable to local studies.”

3.The implication of the following statement in the conclusion is not clear to me. “Increasing temperatures could lead to shorter melting seasons and lower melting season methane emissions but also a longer thaw season”. If total melt-season emissions directly change with melt-season length, then a shorter melt season would reduce emissions in that window, but the longer thawed period outside that window may increase annual emissions. Thus, can lead to confusions about the future total CH₄. The relations between temperature, season length and methane emission relationship needs to be explained better as it could confuse readers about whether warming increases or decreases overall emissions.

We modified the last part of conclusions to be more clear about the relationship between the variables. The modified chapter is below.

“The total melt period emissions in the northern high latitudes were only a small portion of the total annual emissions. However, future climate change and associated permafrost thawing could amplify melt period emissions, resulting in elevated CH₄ bursts. On the other hand, our results showed that a shorter melt period had smaller total emissions and a higher mean temperature on average. Increasing temperatures could lead to shorter melt periods and consequently lower melt period methane emissions. Subsequently, a longer summer thaw season could lead to higher annual

emissions. However, it is still unclear how climate change feedback loops will affect emissions and shoulder season lengths in the northern high latitudes, as permafrost thawing and soil drying could lead to higher CO₂ emissions instead. To get a better look at the melt period emissions, the results from several inversions could be compared to each other. In addition, going further to the level of individual wetlands and comparing their flux measurements during the melting could bring more clarity to true wetland emissions.”

4. The thresholds (e.g., +10% from min thaw, 80% of max) feel somewhat arbitrary without sensitivity tests or comparison to ground data (e.g., soil temps, snowmelt onset).

We thank the reviewer for this important comment. We agree that threshold choices should be justified. In the region-based approach, the purpose is to define a *robust*, climatologically representative transition window for each permafrost zone rather than to identify the exact onset of soil thaw at the pixel level. During early spring, SMOS L-band F/T retrievals can respond to wet snow as well as thawed soil, because wet snow produces a microwave signature similar to thawed soil; therefore the earliest changes in thawed fraction are not always uniquely attributable to soil thaw.

We therefore used a start criterion based on the thawed fraction rising 10 percentage points above the annual minimum and an end criterion at 80% of the maximum, to avoid defining season boundaries from the most noise-sensitive extremes (near 0% or near 100%) and to better capture the bulk, sustained transition at the regional scale.

Using the grid-based approach, we defined the onset of the melt period as the point at which at least one 25 km × 25 km pixel within a grid cell had thawed. This approach allows us to account for the finer spatial resolution of the original pixels. To define the end of the melt period with the grid-based approach, we wanted use a method consistent with the region-based approach.

We examined the daily mean thaw fraction in the four permafrost zones in relation to the region-based melt-period onset and end dates. We found that once the thaw fraction increased by approximately 10% above its minimum value, it began to rise more steadily. Conversely, after reaching about 80% of its maximum value, the rate of increase slowed considerably.

Importantly, our key conclusions rely on relative differences in melt period length and their relationship to methane emissions, and we consistently find a positive relationship between melt period length and total melt period emissions in all permafrost zones using both the region-based and grid-based definitions.

We added the following to the chapter 2.5.1:

“The selected thresholds were chosen to define a robust, zone-mean transition period rather than the exact timing of soil thaw at individual grid cells. In early spring, the SMOS F/T signal can respond to wet snow in addition to thawed soil, as liquid water in the snowpack produces a microwave signature similar to that of thawed soil (Rautiainen et al., 2025). Consequently, thawing fractions very close to 0% or 100% are more sensitive to short-term fluctuations in the microwave signal. Defining the season boundaries away from these extremes ensures that the melt period reflects a sustained, large-scale transition.”

5.The original feedback suggests the title may be confusing because the definition of the season is based on the melting process, yet the term "spring melting season" might be too specific or misleading.

We agree that the title can be a little misleading as our method to define the melt period does not necessarily cover the whole spring season as the melting usually occurs in the beginning of the spring. We changed the title to:

“Melt period methane emissions in northern high latitude wetlands are governed by the length of the period and presence of permafrost”

6.Soil Moisture and Ocean Salinity Freeze/Thaw data from 2011–2021. Were there specific data quality or processing limitations that demanded ending the analysis in 2021?

The analysis period ends in 2021 because a marked increase in radio frequency interference (RFI) affecting SMOS observations occurred later, starting in late 2022, particularly over Europe and western Eurasia. This increase has been widely associated with changes in the radio-frequency environment following the escalation of the war in Ukraine. SMOS is an L-band aperture synthesis radiometer and is therefore especially sensitive to RFI contamination, which substantially reduces data availability and degrades retrieval reliability. To ensure temporal consistency and robust spatial coverage across the study domain, we therefore restricted the analysis to the period 2011–2021, during which the SMOS freeze–thaw product exhibits relatively stable data quality. This rationale is now explicitly described in Sect. 2.1.

7.Line 95 -100: who developed The SMOS F/T soil state detection algorithm? Give details

The SMOS FT soil state detection algorithm was developed by the Finnish Meteorological Institute (FMI) in collaboration with GAMMA Remote Sensing, Switzerland. The algorithm is first described in Rautiainen et al. (2016) and in more details in its latest updated and validated form in Rautiainen et al. (2025). We have clarified this in the manuscript and explicitly refer readers to the most recent algorithm description paper for full methodological details.

8.Line 98 – 100: We require additional detail regarding the methodology used for soil categorization and thawed soil identification. How are the thresholds for soil categorisation estimated? Please provide a brief but explicit explanation of the algorithm used to identify and classify thawed soil based on the observations? What is the estimated uncertainty of this soil classification?

We agree that readers need a clear understanding of what the SMOS freeze–thaw product represents and how thawed conditions are identified. We therefore revised Sect. 2.1 to include a concise description of (i) the physical observable used (normalized polarization ratio, NPR), (ii) the use of grid-cell-specific frozen and thawed reference states, and (iii) the threshold-based classification into thawed, partially frozen, and frozen soil states. Full algorithmic details, validation, and uncertainty characterization are provided in Rautiainen et al. (2025), which is now explicitly referenced.

9.Line 102 -104: What exactly are the reasons for this? Attenuation?

We clarified the rationale for using only ascending-orbit SMOS freeze–thaw observations. Oliva et al. (2016) document the spatial structure and severity of SMOS radio frequency interference (RFI), particularly over Europe and Asia. In addition, ESA’s operational RFI monitoring (ERMIT) shows orbit-dependent differences in data availability. To maximize data quality and spatial coverage in

our study region, we therefore restricted the analysis to ascending-orbit observations. This orbit selection rationale is now described in Sect. 2.1.

10. Line 108: not very clear to me. what fraction of the combining pixels is considered to be taken as a thawed pixel?

We implied that the original resolution of the SMOS F/T data was 25 km x 25 km and we needed to change the resolution to 1° x 1° to use it in our data-analysis together with the global CarbonTrackerEurope-CH4 inverse dataset. Each 25 km x 25 km pixel was classified as frozen, partially frozen or thawed, as is explained in the chapter 2.1. We deleted this sentence from the final version of the chapter 2.1. but added this explanation to the chapter 2.5.1:

“The resolution of the SMOS F/T data was changed from 25 km x 25 km to 1° x 1° by calculating the fraction of the thawed 25 km x 25 km pixels whose center was inside the 1° x 1° grid cell.”

11. Line 184 – 185: “However, methane emissions are possible even at the very beginning of the melting season because the air temperature rises above zero and melted water can trickle into the soil”. Please add references for the statement.

We added citations to the following articles:

Raz-Yaseef, N., Torn, M. S., Wu, Y., Billesbach, D. P., Liljedahl, A. K., Kneafsey, T. J., Romanovsky, V. E., Cook, D. R., and Wullschleger, S. D.: Large CO₂ and CH₄ emissions from polygonal tundra during spring thaw in northern Alaska, *Geophysical Research Letters*, 44, 504–513, <https://doi.org/10.1002/2016GL07122>, 2017.

Song, C., Xu, X., Sun, X., Tian, H., Sun, L., Miao, Y., Wang, X., and Guo, Y.: Large methane emission upon spring thaw from natural wetlands in the northern permafrost region, *Environmental Research Letters*, 7, 034 009, <https://doi.org/10.1088/1748-9326/7/3/034009>, 2012.

Rinne, J., Riutta, T., Pihlatie, M., Aurela, M., Haapanala, S., Tuovinen, J.-P., Tuittila, E.-S., and Vesala, T.: Annual cycle of methane emission from a boreal fen measured by the eddy covariance technique, *Tellus B: Chemical and Physical Meteorology*, 59, 449–457, <https://doi.org/10.1111/j.1600-0889.2007.00261.x>, 2007.

Hargreaves, K. J., Fowler, D., Pitcairn, C. E. R., and Aurela, M.: Annual methane emission from Finnish mires estimated from eddy covariance campaign measurements, *Theoretical and Applied Climatology*, 70, 203–213, <https://doi.org/10.1007/s007040170015>, 2001.

12. The second condition in region-based approach is not very clear to me. Do you mean that the spring melt must start after the day when the zone reaches its minimum annual mean thawing fraction?

Yes, this is exactly what we mean. As we explained next:

“During some years, the freezing of the soil continued past the turn of the year, which meant that the (1) boundary was reached before the maximum freezing of the soil. This meant that the additional (2) condition for the beginning of the melt period had to be defined. With the (2) condition, the melt period could be separated from the autumn freezing period. In regions with permafrost, the first (1) condition was surpassed later during the spring than the second (2) condition, but in the non-permafrost zone the second (2) condition was needed.”

We changed the first sentence to be more clear. It is now written as follows:

“With the region-based approach, the melt period was set to start 1) when the mean thawing fraction of a permafrost zone had surpassed the minimum thawing fraction of that year by 0.1 ($\text{thaw}(\%) \geq \text{thaw}_{\text{min,year}}(\%) + 10\%$), and 2) after the day when the zone reaches its minimum annual mean thawing fraction before mid July.”

13. Line 205: “The mean thawing fraction of all grid-cells in a permafrost zone was then calculated.” How does this solve the problem? Do you mean an area weighted average?

We agree that this might cause some confusion so we changes this part of the text to the following: “The melt period in each grid cell was defined from the amount of thawed pixels in a grid cell, emphasizing more the small grid cells in the north. The mean thawing fraction of all grid-cells in a permafrost zone was then calculated.”

Technical comments

1. Line 8 – 10: Statement not complete. Length and the mean temperature?

We fixed the sentence to say the following:

“The melt period generally occurred between March and June and was influenced by the air temperature, with a negative correlation between the length and the mean temperature of the melt period.”

2. Section 2.2.2: Please mention which parameters are measured at these stations. surface variables or CH₄?

We changed one of the sentences in the chapter 2.2.2 to mention CH₄:

“The data included weekly discrete air samples and hourly continuous measurements of CH₄, and the data was filtered according to the institutions' quality flags.”

3. I would suggest move figure 1 to section 2.3.

We moved the figure under section 2.3.