RC2: 'Comment on egusphere-2025-3059', Anonymous Referee #2, 28 Oct 2025

We thank the reviewer for taking the time to read and review our paper. The comments helped us to improve the manuscript and clarify inaccuracies. We restructured and clarified the information on pond formation and properties both in Study area (Sect. 2) and Methods sections (Sect. 3), following the reviewer's recommendations.

In the following, we respond to the issues raised by the reviewer and indicate where we implement changes in the revised manuscript. Reviewer comments appear in black, our responses appear in blue, and the revised manuscript text appears in *blue italics*.

This is an interesting study that highlights the importance of thermokarst peatland ponds as sources of overwinter methane. Measurements and their uncertainties were carefully conducted and explored with respect to a variety of pond metrics and water and ice characteristics. The results are comprehensively presented with a fulsome discussion that places these results in context of annual methane budgets and with other circumpolar lakes and ponds.

I only have a few small editorial questions/suggestions:

Line 63. Is it possible that some of these shallow ponds are ephemeral and satellite imagery may show ‘dry’ terrain at certain times of year/different years, which might confound aging? Either way, I suggest a summary of how the age of ponds was determined be included here in the main text as there appears to be several lines of evidence used for the age evaluation. Additional details such as dates of aerial imagery, etc. could perhaps be given in the Supplemental Materials.

We thank the reviewer for the suggestion. We reorganized the Methods in the revised manuscript and added a new Sect. 3.7, “*Thermokarst pond formation ages*.” We also added Figures S1–S3 in the revised Supplementary Materials that show all aerial images used for age estimation, with corresponding references in the main text.

Our aerial-image analysis (Sect. 3.7, revised manuscript) shows that once water accumulates in the thermokarst depressions, the ponds do not dry out intermittently. However, we do not have arial images available before the 1950s and between 1955 (1958 for Áidejávri) and 2003, so we cannot track annual changes for these periods. For the ponds A7 and A8, the water surface area is large and remains nearly unchanged across the available imagery, so the drying of such large waterbodies is unlikely. The Iškoras pond was relatively small in 1955 but had expanded markedly by 2003 when it became hydrologically connected with the surrounding mire. For the ponds formed before 2003, our age uncertainty is large. For the ponds formed during last 10 years (by 2023) we have good aerial image coverage from drone surveys. In our study we interpret pond formation age as driven primarily by permafrost collapse (Sect. 3.7, revised manuscript). So, even if a newly formed depression briefly held little or no water, this will not affect age of permafrost collapse and depression formation.

The new Sect. 3.7. on thermokarst pond formation age reads:

"The thermokarst pond formation age was defined as the time of collapse of the peat plateau section, which typically coincided with water accumulation; however, there can be exceptions with the accumulation of water starting several years after collapse, as observed in the case of pond A4 (Fig. S1). We used 2023 as the baseline year for the age estimation. The thermokarst pond formation age was determined using geo-referenced historical aerial images (1955, 1958, 2003 and 2013) from the Norwegian Mapping Authority, as well as drone images (2015, 2020 and 2023) obtained from the Drone Infrastructure Lab, University of Oslo. The earliest available photographs are from 1955 for Iškoras (Kartverket survey WF-688 H-13) and 1958 for Áidejávri (Norgeibilder.no, 2025). The ortho-rectified drone imagery was processed following Martin et al. (2021) and has a ground resolution of 3 cm (2023), 5 cm (2020), and 10 cm (2015). The estimation of formation age was limited by the available imagery. No imagery from before the 1950s was available, and there is a gap between the 1950s and 2003. For the oldest pond types, which were already present in 1955 at Iškoras and 1958 at Áidejávri, it is not possible to constrain formation age prior to 1955.

Based on the area change, we classified pond developmental stages as stable, expanding, or overgrowing. If the net area change from 2015 to 2023 (including both permafrost degradation and succession) was less than 15%, ponds were identified as "stable". If the pond was formed or its area increased by more than 15% since 2015, it was named "expanding". If the pond area decreased by more than 15% because of vegetation succession, it was classified as "overgrowing". Succession by Sphagnum or sedges was identified based on the predominant species observed in aerial imagery and validated during fieldwork."

Line 76. Again, it wasn't immediately clear that ice formation timing was monitored using several methods. Please clarify in the main text.

The start of ice formation in 2023 was determined from both meteorological data and Sentinel-2 satellite imagery available for October 2023. We reorganized Methods Sect. 3.6, "*Winter CH_4 bottom flux*," to describe how we estimate the time interval between the start of ice formation and the sampling day in March 2024, Δt. *"Δt was estimated using meteorological data and Sentinel-2 satellite imagery available for October 2023. Initial ice formation at Iškoras started between October 1 and 2, 2023, coinciding with the first substantial drop in air temperature (Fig. S5). In Áidejávri, the onset of ice growth occurred between October 6 and 13 as indicated by temperature data from the meteorological station Sihccajavri and Sentinel-2 satellite imagery (Fig. S6)*"

All data supporting our Δt estimation appear in the revised Supplementary Material (Fig. S5-6).

Line 94. Give some detail about non-thermokarst pond formation processes in this region.

Most lakes of non-thermokarst origin in this area formed after deglaciation and are remnants of larger post-glacial water bodies. We reorganized the Study area section in the revised manuscript into two subsections: 2.1 "*Climatic and environmental settings*" and 2.2 "*Sampling sites*". In Sect.

2.1 we now provide a broader context on peatland development. In Sect. 2.2 we explain why pond A8 is classified as a non-thermokarst pond and give details on its formation.

The information on the non-thermokarst pond A8 in the revised manuscript reads: "*Finally, we sampled pond A8, located north of the main study area, which is being slowly overgrown by sedges (Figs. S2c-d). Unlike the thermokarst ponds in the area, A8 has an elongated shape, and a strongly different pH compared to the thermokarst ponds (Sect. 4.1). For these reasons, we rather interpret A8 as a remnant of a larger post-glacial water body which has partly transitioned into a mire than a thermokarst pond. A8 is therefore referred to as "non-thermokarst" pond in the following.*"

Line 299. w.e. ?

We express CH_4 concentrations measured in ice samples as water-equivalent (w.e.) concentrations. We clarified the abbreviation "w.e." in the section where it first appears.

Line 334. This statement is unclear without skipping ahead. Perhaps briefly state here how methane storage in ice is related to thermokarst pond formation age.

We thank the reviewer for this suggestion and agree that the original statement was unclear. The relationship between the thermokarst pond formation age and wintertime CH_4 bottom flux are assessed for the main study area (A1–A6) and are now first presented in Results Sect. 4.4. We discuss this relationship more broadly (including additional ponds) in Discussion Sect. 5.4. For clarity, we have removed the passage on pond age from the Results subsection on CH_4 ice and water storages (addressed only in Sects. 4.4 and 5.4 in the revised manuscript).

Line 378. Recommend this statement be changed to "the relationship between pond age and bottom flux is not statistically significant ($p = 0.07$)."

During the revision process, we changed one of the substeps in the calculation of the winter bottom fluxes, i.e. we included the dry peat and gas bubble volumes in the ice sample volume calculation (Sect. 3.5, revised manuscript), which changed the CH_4 volumetric concentrations and thus winter bottom fluxes by up to a few percent. In particular, for the pond A5, the winter bottom flux was reduced from 29 ± 4.3 to 26 ± 4.2 mg CH_4-C m-2 d-1 following this correction. Prior to this correction, the statistical test between winter bottom fluxes and pond ages yielded $p = 0.07$, i.e. just above the threshold to being statistically significant (i.e. marginally non-significant). After recalculation, we re-evaluated the correlation between pond age and wintertime CH_4 bottom flux and obtained $p = 0.0048$, which is just below the threshold to be statistically significant (with the revised numbers for A5 being the most important factor for this change in significance level). In the revised manuscript (Sect. 4.4) we therefore report: *"The relationship between CH_4 winter bottom flux and the age of thermokarst pond formation was statistically significant by a narrow margin ($p = 0.0048$), although the limited number of ponds makes the statistical evaluation challenging."*

Lines 549-552. Are these moss mats on the margins of the ponds and not below the water? If so, how would aerated peat layers or endophytic methanotrophs on the margins of the ponds limit pond bottom fluxes of methane as measured in this study?

We thank the reviewer for this question. The formulation in the submitted manuscript was indeed misleading. Sphagnum mosses occurs both submerged in the Iškoras pond and on the surface. We now state in Sect. 2.2 that submerged Sphagnum was found at the Isk-1 sampling site. In the Discussion section 5.4 we note that during ice-free conditions submerged Sphagnum can reduce methane bottom fluxes via oxidation mediated by symbiotic or endophytic methanotrophic bacteria (Raghoebarsing et al., 2005; Parmentier et al., 2011). However, under ice cover the water column is generally anoxic, so Sphagnum-associated methane oxidation is likely negligible.

In the revised manuscript, we now address the issue at the end of Sect. 5.4: "*The old, stable thermokarst ponds at both Iškoras and Áidejávri (Isk-1 and -2 and A7), exhibited low winter* CH_4 *bottom flux (*< 15 *mg* CH_4*-C* m^{-2} d^{-1}*). At Iškoras, submerged Sphagnum was observed at the bottom of the sampling location Isk-1. In the ice-free season, submerged Sphagnum can reduce* CH_4 *bottom flux via oxidation mediated by symbiotic, endophytic methanotrophic bacteria (Raghoebarsing et al., 2005, Parmentier et al., 2011). In winter, however, the water column is predominantly anoxic, so Sphagnum-associated* CH_4 *oxidation is likely not a controlling factor. The low winter* CH_4 *bottom flux in Iškoras and A7 could indirectly be linked to pond age as Sphagnum succession marks the late stages of thermokarst pond development (Magnusson et al., 2020).*"

References*:*

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