We thank the reviewer for the thoughtful and constructive feedback on our manuscript *"Spatiotemporal Variability and Environmental Controls on Aquatic Methane Emissions in an Arctic Permafrost Catchment."* We have carefully considered all comments and revised the manuscript accordingly, providing clarifications or edits where necessary. Below, we present a detailed, point-by-point response. Each Reviewer Comment is reproduced in full, followed by our Response, including specific changes made to the manuscript (with line numbers referring to the revised manuscript).

General Comment — Overall Study and Conclusions
Reviewer Comment: *"The authors deployed floating chambers during 2023 and 2024 summer to measure CH_4 amount and applied General additive model (GAM) plus binary regression tree (BRT) to fit CH_4 fluxes and separate ebullition from diffusion in a small arctic permafrost catchment. Further analysis of CH_4 fluxes against dynamics of other environmental variables highlighted a dynamic and intertwined network of environmental variables affecting each other, and determined the spatial and temporal variations in CH_4 fluxes as the outcome. The major conclusion and explanation is valid, though I have questions on some of the details."*

Response: We thank the reviewer for this positive overall assessment. We are pleased that the major conclusions were found to be valid. The detailed questions and concerns are addressed in our responses below, and we have revised the manuscript to clarify all the specific points raised.

Ebullition Terminology — Usage in Abstract and Main Text
Reviewer Comment: *"I have one major concern on 'ebullition'. Based on the paper description, I did not find authors using other data sources to validate the ebullition detection. Authors explained that the 'ebullition' in their study is actually 'non-linear concentration increases', which I believe include ebullition events (since quasi-ebullition is steady and can be similar to diffusive fluxes) and sudden increase of diffusive fluxes. I would strongly suggest authors to reconsider using 'ebullition' in the main text, especially abstract, which is a well-defined gas transport pathway."*

Response: We appreciate the reviewer's concern regarding our use of the term "ebullition." We agree that our algorithm identifies non-linear concentration increases that are *indicative* of ebullition events, but were not independently confirmed in every case (e.g., by direct observations). To avoid misunderstanding, we have revised the wording in the Abstract and throughout the text to clarify this. In the Abstract, rather than stating "Diffusive and ebullitive fluxes were derived…", we now write on lines 14-17:

> "Diffusive fluxes dominated (~98% of observations), while only ~1% of chamber deployments exhibited non-linear concentration increases indicative of ebullition, while the other ~1% were attributed to uptake."

This revised sentence removes the implication that we directly measured classical ebullition and clearly frames those events as *"indicative of ebullition"*. We have similarly adjusted terminology in the main text. For example, in **Section 2.3 (Flux Algorithm & Ebullition Detection)** we added a clarifying statement on **lines 228-230**

""Ebullition" in the context of the algorithm refers to a sudden, non-linear CH_4 increase identified by the algorithm, which includes observed ebullitive events, but does not strictly infer all fluxes calculated this way were from bubbles entering the chamber."

We now also place the term in quotes (**on lines 263 and 281**) when describing these occurrences.

Line 19 — Timing of Shift to Biogeochemical Controls
Reviewer Comment: *"Line 19: 'later shifting to biogeochemical controls', how late? Several days or several weeks? A precise number can be the best."*

Response: We agree that the timing of the shift to biogeochemical controls should be specified. In the Abstract, we have added an approximate timeframe to clarify what *"later"* refers to. The sentence now reads (18-21):

"Model results suggest that thaw-season CH_4 fluxes were initially driven by meteorological conditions and catchment soil conditions, but shifted rapidly—within approximately one week after ice-off—to biogeochemical controls, including dissolved organic matter, oxygen saturation, and pH."

Line 28 — Microbial Production of Carbon (Rephrasing)
Reviewer Comment: *"Line 28: 'which produce carbon as a result of their metabolic processes' shall be 'which accelerate decomposition of soil organic carbon as a result of their metabolic processes' or 'which increase portable carbon input to atmosphere and riverine system as a result of their metabolic processes'."*

Response: We appreciate these suggestions for clarifying the role of microbial metabolism. We have revised the sentence in the Introduction to more accurately describe the process. The phrase has been changed **on lines 29-30**:

> "…which accelerate the decomposition of soil organic carbon as a result of their metabolic processes".

This wording makes it clear that microbes are breaking down organic carbon, thereby releasing carbon (in gaseous or dissolved form) rather than literally creating new carbon.

Line 66 — Redundant "systems" in Text
Reviewer Comment: *"Line 66: Shall remove 'systems' after 'freshwater ecosystems'."*

Response: We have removed the extra word *"systems"* so that the sentence now reads **on lines 66-67**: *"Therefore, freshwater ecosystems..."*

Figure 1 — Figure Quality and Compass Rose
Reviewer Comment: *"Figure 1: Can authors improve the figure quality? Could it be better if I use pictures with DPI >= 300? Also, it is better to add a simple compass rose to the map."*

Response: We have improved Figure 1 as suggested and further labeled more clearly the different waterbodies. The figure has been regenerated at high resolution (at least 300 DPI) to ensure clarity in print and digital formats. Additionally, we have added a north arrow (compass rose) to the map. See new figure and caption **on lines 112-117**.

Line 121 — Photograph of the Self-Built Chamber
Reviewer Comment: *"Line 121: 'We used a self-built cylindrical chamber made of semi-transparent plastic' I can barely imagine what your chamber looks like, but it will be very helpful if you don't mind uploading a picture of your equipment, since it is self-built. This is more like a suggestion rather than request."*

Response: We appreciate the reviewer's interest in the chamber design. In response, we have included a photograph here in the point by point of the self-built chamber used in 2023.

However, we have left it out of the manuscript as the Boosted Regression analysis and determination of emission drivers were based on data collected using the industry built West Systems Chamber seen in Figure A2 of the appendix. However, we make clear that despite differing construction the median fluxes between the years were identical at 5.0 nmol $m^{-2}s^{-1}$. We clarify this point **on lines 131-133**.

Line 135–138 — Rationale for Control Period Measurement Change
Reviewer Comment: *"Line 135 ~ 138: What is the major reason for changing the measuring object for the control period?"*

Response: The reviewer is correct that our approach to "control" measurements differed between 2023 and 2024. We now explicitly clarify our rationale **on lines 143-147**:

> *"*In 2023, we measured isolated meltwater pools during the thaw to represent control conditions (water not yet connected to the lake or streams). In 2024, to capture an even earlier baseline, we conducted chamber measurements on top of snow and lake ice prior to thaw onset, providing a true pre-thaw control period.*"*

Line 173 — GAM Application for 2023 vs 2024 Data
Reviewer Comment: *"Line 173: Since you have certain different treatment on equipment between 2023 and 2024, are you fitting a general GAM for both years or one for each year separately?"*

Response: We thank the reviewer for this comment. As stated **on lines 161-163** in Section 2.3 of the manuscript, the same GAM-based flux calculation algorithm was applied uniformly to individual chamber measurements. However, to clarify we controlled for the different chamber construction we added the following text **on lines 163-165**:

"The flux calculation procedure was applied identically to each chamber time series for both 2023 and 2024, while controlling for different chamber construction."

In addition, we clarify **on lines 187-188**:

"…the *concentration time series* is then fit to a GAM (i.e. gam($CH4_{moles}$ ~ s(time, k = gam_knots))…"

Line 202 & 223 — Section Numbering Corrections
Reviewer Comment: *"Line 202: Shall be section 2.4"* and *"Line 223: Shall be section 2.5"*

Response: Thank you for catching these section numbering errors. We have corrected the section headings.

Line 203 — References & Validation for Metabolic Flux Estimates
Reviewer Comment: *"Line 203: There're a bunch of assumptions you used for estimating different metabolic fluxes, can you put some reference or available 3rd party data to validate your results?"*

Response: We thank the reviewer for raising this important point. The methods used to estimate NEP, GPP, and ER closely follow established and widely adopted protocols and DO assumptions from previous studies (e.g., Garcia & Gordon 1992; Cole & Caraco 1998; Mulholland et al. 2001; Winslow et al. 2016; Hall & Madinger 2018). However, we now clarify the uncertainty related to DO measurements **on lines 234-235**:

"…(DO) collected at a one-minute frequency during chamber measurements (DO sensor accuracy: ± 0.1 mg L^{-1}; resolution 0.01 mg L^{-1})"

Furthermore, we have added more references which specifically estimated NEP, GPP, and ER from Arctic and Boreal lakes and streams **on lines 249-252**:

"Nonetheless, the approach captures broadly the metabolic trends in lake and stream metabolism observed in other Arctic and Boreal waterbodies (Mulholland et al., 2001; Rocher-Ros et al., 2021; Ayala-Borda et al., 2024; Klaus et al., 2022; Myrstener et al., 2021) and is useful for comparing fluxes across aquatic biomes."

Our NEP, GPP, and ER results fall well within the values reported in the cited literature.

Line 220 — Data Smoothing and Temporal Resolution
Reviewer Comment: *"Line 220: This also depends on how you can smooth your collected data to a coarser temporal resolution."*

Response: We thank the reviewer for this comment. To clarify, DO data used in our metabolism calculations were collected natively at one-minute intervals using a water sonde see added DO uncertainty **on lines 234-235**. No additional smoothing or aggregation was applied.

Line 236 — Typographical Error in Statistical Test Name
Reviewer Comment: *"Line 236: 'Kurskal-Wallis test' shall be 'Kruskal-Wallis test'?"*

Response: Thanks for catching this. We have corrected "Kurskal-Wallis" to "Kruskal-Wallis" in the text **on line 268.**

Line 250–253 — Measurement of Environmental Variables (Instrumentation)
Reviewer Comment: *"Line 250 ~ 253: I'm not sure how you obtained these measurements? What equipment did you use to measure these variables?"*

Response: Thank you for your attention to this detail. We state **on lines 162-167** in *Section 2.2 (Data Collection),* which device was used and/or where the water, meteorological, and soil parameters come from. We state:

"We simultaneously measured water temperature using Truebner EC-100 RS-485 EC/Temperature sensors in 2023 and a suite of water parameters were collected in 2024 using an AquaTroll 600 water sonde (see section: Decoding Methane Drivers). Meteorological data and soil characteristics were collected from nearby meteorological stations maintained by Aarhus University which are part of the

Greenland Ecosystem Monitoring Database (Greenland Ecosystem Monitoring, 2025a-d) (see section "Decoding Methane Drivers" for list of variables used)."

Line 256 & Fig. S7 — Soil Temperature Depth and Relevance to Aquatic Fluxes

Reviewer Comment: *"Line 256 & Fig. S7: How do you account for the soil temperature depth for stream and lake? Start from the bottom of the lake? In line 256 you mentioned using soil temperatures 'at 40 cm' to analyze correlation to surface water CH_4 fluxes, which seems to be quite irrelevant if it means 40 cm below lake bottom."*

Response: Thank you for the question. Please see the next response as we have combined this comment with the next as they are addressing the same issue.

Line 245–267 — Clarification of Variables Measured for Lake vs Stream vs Upland
Reviewer Comment: *"Line 245 ~ 267: This paragraph shall clarify what different variables you measured for lake, stream and upland separately. If all variables are measured, shall explain if any different treatment is applied. For example, soil volumetric content seems not to be a measurable variable for lakes?"*

Response: We apologize for the confusion here and thank you for pointing this out – the soil temperature at 40 cm is measured in terrestrial soil within the catchment at a nearby climate station, not under the lake or stream bed. Soil characteristics, temperature and VWC, were included to gain an understanding of how catchment hydrogeological conditions indirectly effect fluxes from surface waterbodies within the catchment. We have clarified where the suite of predictors come from, and why they were included in the models to ensure there is no misunderstanding **on lines 283-301**:

"To characterize fluxes we assembled a comprehensive set of predictors including; (a) aquatic variables measured in-situ with a water sonde at each chamber deployment (e.g., Conductivity (µS/cm), pH, redox potential (mV), dissolved oxygen (mg/L), oxygen saturation (%), water temperature (°C), and fluorescent dissolved organic matter (FDOM; RFU)) (Figure S6), (b) catchment soil characteristics collected at nearby climate stations (e.g., soil volumetric water content at 10 cm and soil temperature at 40 cm), and (c) meteorological variables collected from a nearby climate station (e.g., Surface air temperature at 2 cm (°C), Air temperature (°C), relative humidity (%), air pressure (mbar), precipitation (mm), PAR (µmol $m^{-2}s^{-1}$), and mean wind speed (ms^{-1}) and direction (°)) (Figure S6). Lake water levels (mm) were included to characterize the effect of changing hydrologic conditions and its influence on lake CH4 fluxes. Catchment soil characteristics were included to capture the hydrogeological conditions surrounding the catchment. We used catchment soil temperature at 40 cm to represent subsurface active-layer conditions that influence deeper thermal dynamics, groundwater inflow, and delayed soil heat retention through the thaw season. Soil volumetric water content (VWC) at 10 cm was included to gain an understanding if dryer, or wetter soil catchment conditions effect surface water CH_4 fluxes, and to act as a substitute for water level in the lake early in the season as these two share a Pearson's correlation of $r = 0.93$. Additionally, we used VWC at 10 cm depth because it was the most complete and continuous dataset across the measurement depths, and highly correlated with VWC at 20 cm, 30 cm and 40 cm."

In short, we have made it clear that the soil temperature at 40 cm is not measured beneath the lake or stream, but rather in an adjacent terrestrial environment, and we justified its inclusion for capturing broader catchment-wide hydrogeological effects.

Line 277 — Choice of a Low Bag Fraction in BRT
Reviewer Comment: *"Line 277: A more popular range of bag fraction is 0.5 ~ 0.8, while here authors*

chose a relatively low bag fraction, it might make sense that authors expect more smoothed time series rather than over-fitting since the measured methane might be quite non-linear. Suggest explaining your choice."

Response: The reviewer is correct that our chosen bag fraction for the BRT models was on the lower end (we tested 0.30, 0.40, 0.50, as noted in Section 2.6). We have added an explanation of why we chose these bag fractions **on lines 314-318**:

*"*While bag fraction values in the range of 0.5–0.8 are more commonly used, a lower bag fraction increases stochasticity in tree construction, which helps reduce overfitting—especially important for modeling noisy and highly non-linear CH_4 flux data. This conservative approach favors identifying robust general patterns rather than fitting noise or outliers.*"*

Figure 4 — Relating Emission Classes to Map (Figure 5)
Reviewer Comment: *"Fig. 4: Is it possible to show the relative locations of different lake and stream classes in Fig. 5?"*

Response: This is a good point, also brought up by the other reviewer, and rather than linking Figure 4 and 5, we added some clarifications to figure 1 to give a better idea of where the different water body classes are. **See lines 112-119**.

Line 286 — Calculation of Deviance in BRT Models
Reviewer Comment: *"Line 286: How did you calculate deviance?"*

Response: Good point. We have added clarification of this calculation **on lines 326-330**:

"We further calculated the percent deviance explained for each fitted BRT model using the formula: % deviance explained = 100 × ((null deviance − residual deviance) / null deviance), where the null deviance represents the deviance of a model using only the mean response, and the residual deviance is from the fitted BRT model."

Figure 7 — Explanation of Shaded Areas in Partial Dependence Plots
Reviewer Comment: *"Figure 7. I assume the shaded area represents standard deviation, but authors shall add explanation."*

Response: We have updated the Figure 7 caption to explain the meaning of the shaded areas in the partial dependence plots. The caption now includes a sentence **on lines 483-484**:

> *"*The grey shaded area around the line represents ±SE (0.02 - 0.2).*"*

Line 389 — Rephrasing Sentence about Flux Dissipation Through Season
Reviewer Comment: *"Line 389: 'Fluxes dissipated through the season until fluxes were isolated to the warm spring inlet and the eastern inlets (Figure 5).' I find it hard to interpret this sentence. Can you rephrase it?"*

Response: We have rephrased the sentence in the **Discussion** to make the meaning clearer. The original intent was to convey that as the summer progressed, methane emissions decreased everywhere except in a couple of specific locations (the warm spring inlet and the eastern inlets to the lake, which continued to emit CH_4). See revised sentence **on lines 430-431**:

> *"*As the summer season progressed, CH_4 fluxes declined across most of the catchment, becoming largely confined to the warm spring inlet and the eastern inlet streams (Figure 5).*"*

Line 429 — DOM vs Nutrients Terminology
Reviewer Comment: *"Line 429: 'The distribution of nutrients, i.e., dissolved organic matter (DOM),' DOM is not nutrients, but an indicator. Please correct."*

Response: You are absolutely correct that dissolved organic matter (DOM) is not itself a nutrient; referring to it as such was a misstatement on our part. We have corrected the wording in the Discussion to eliminate this confusion. See revised sentence **on lines 469-473:**

> "The distribution of nutrients on the island has been shown to be linked to snowmelt and hill slope topography (Westergaard-Nielsen et al., 2020), which is likely playing a role during the early part of the season, but especially later in the year as DOM, *a proxy for nutrients*, becomes the primary limiting factor in predicting higher fluxes (Figure 7b-c) (Olid et al., 2021, 2022)."

Line 494 — Clarification of pH/Oxygen Influence on CH_4 Emissions
Reviewer Comment: *"Line 494: 'that increasing pH and oxygen saturation as a result of primary production drive CH_4 emissions down through the growing season (Figure 7c-d and Figure A1).' This conclusion is not precise. Suggest to say 'increasing pH and oxygen saturation as a result of primary production and providing a vibrant aerobic environment, thus favored methanotrophic activities and then drive CH_4 emissions down through the growing season (Figure 7c-d and Figure A1).'?"*

Response: We appreciate this suggestion and have adopted a revised wording very close to what the reviewer proposed to more precisely explain the mechanism by which higher pH and O_2 lead to lower CH_4 emissions. The sentence now reads **on lines 536-539**:

> "Here we show that increasing pH and oxygen saturation, as a result of primary production, create a aerobic environment that favors methanotrophic activity, thereby driving CH_4 emissions down through the growing season (Figure 7c-d, Figure A1)."

Supplemental Material, Line 21 — "Least Mean Deviance Standard Error"
Reviewer Comment: *"In supplemental material, line 21: I feel really hard to interpret 'least mean deviance standard error'."*

Response: We have revised the wording in the Supplementary Material to clarify this phrase. It was originally intended to describe the minimum mean deviance and its standard error from the BRT cross-validation (related to selecting the optimal number of trees). We realized the phrasing was confusing. See revised sentence **on line 21** of the Supplemental Material:

> *"…the lowest mean deviance…",*

Once again, we thank the reviewer for the thorough examination of both the main text and supplemental material. All the above changes have been incorporated in the revised manuscript and supplement, which we believe significantly improves clarity and accuracy. We trust that we have addressed all concerns, and we are grateful for the opportunity to improve our work based on Reviewer 2's insightful comments. Please let us know if any further clarifications are needed.