Response to the comments of Reviewer 1

We thank Reviewer 1 for their relevant feedback. Their detailed comments have led to substantial improvements in the manuscript's organizational logic, focus and clarity. Following their advice, we added significant details that drastically improved the quality, readability and utility of the paper, and these suggestions have strengthened and enhanced this review article.

Our responses to the Reviewer's comments are provided below in **blue text** and are positioned directly beneath each corresponding comment.

This manuscript aims to provide a comprehensive review of observational approaches for quantifying melt ponds on Arctic sea ice. Given the central role of melt ponds in ice-albedo feedback and the difficulty of obtaining consistent observations, a systematic overview comparing the strengths, weaknesses, and future potential of various methods is highly relevant and well-motivated.
However, the current version of the manuscript lacks the focus and structure expected for a review paper. The organization makes it difficult to follow the line of reasoning between sections, and the conclusions remain unclear. The manuscript should better clarify the current state of sensing capabilities and offer practical guidance on which products or methods are best suited for different applications.

Major Comments
Organization and Focus

- The manuscript is often repetitive, particularly in sections discussing general motivation for melt pond observations. In contrast, the technical comparison of methods lacks sufficient depth.

We thank you for your comment and have made substantial revisions to address potential redundancy and structural issues throughout the manuscript. The Introduction (Section 1) now explicitly defines scope and terminology, consolidates the primary motivation, and clearly outlines the structure of the manuscript. Section 2, which presents the main characteristics of melt ponds and their evolution, is now supported and cross referenced to Appendix C, which has been expanded to include a comprehensive analysis of over 40 studies. Section 3 has undergone many changes. For example, it was restructured with clearer headings that distinguish: (3.1) '*Spaceborne observation*' for satellite remote sensing, (3.2) '*In situ and field campaign observation*' for ground-based and ship-based measurements, and (3.3) '*Post-processing techniques*'.

These sections now focus exclusively on technical sensor capabilities, and include new and improved images following advice of the Reviewer. Regarding technical comparison of methods which was addressed by the Reviewer, Section 3.1, provides enhanced technical specifications for each sensor (physical principles; measured parameters; missions status, data availability; MP signatures and detection mechanisms); Section 3.2, was revised to ensure consistent structure and level of detail for each campaign, while including specifically how each of these campaigns advanced our understanding of melt ponds. Section 3.3, examines methodological approaches; algorithm types, and their applicability to different sensors. We maintained the technical comparison details primarily in updated appendixes to enhance article readability while providing comprehensive depth for interested readers.

Furthermore, if the Reviewer feels specific sections of the appendix should be moved to the main body or any topics therein, we would be happy to hear them.

Section 4 underwent a considerable change as it now focuses exclusively on existing datasets. Section 4.2, following the Reviewer's concern on being beyond scope, was placed entirely as an Appendix, where it provides complementary information that cross references and bridges Section 2, 3 and 4.

Finally, Section 5 was revised to exclude any redundancy, with motivations for melt pond studies now stated exclusively in Section 1. Section 5 now focuses solely on identifying key knowledge gaps and outlining directions for future research. Section 6 remains as the Conclusions section which has undergone its own updates.

- Section 3 should begin with a concise synthesis of overarching challenges common across observational platforms, including:
    1. Temporal coverage (limitations due to clouds, daylight, and repeat time),
    2. Spatial resolution, and
    3. Discrimination and identification of pond boundaries.

    These challenges are especially critical for melt pond fraction (MPF) retrievals.

We agree with the Reviewer that these are important topics. Following the Reviewer's advice, we have added a synthesis that previews these major challenge categories and forward-references where each is addressed in detail, guiding the reader more effectively through the structure progression.

All challenges pointed by the Reviewer are addressed extensively for each sensor type throughout Section 3. Namely, temporal coverage limitations are discussed at lines 206-214* and 249-252, for passive and active optical sensors, respectively and at lines 294-295 for microwave systems. Spatial resolution constraints (and resolution coverage tradeoff) are covered at lines 194-229, for optical sensors and at lines 267-294 for active and passive radar systems, respectively. Finally, pond boundary discrimination challenges are addressed at lines 230-235, for optical sensors and at and 294-322 and 371-386 for active and passive microwave systems. We have also updated this Section now to include another family of sensors, namely altimetry, and it follows the same structure as others, contributing to the completeness of Section 3.

*Please note that the line numbers provided here correspond to the original manuscript. Since substantial revisions were made, the line numbers will differ in the updated version. We hope this clarifies the changes.

4. **Scope and Content**

- It is unclear what the extent of observational datasets that the manuscript aims to include are. The section describing field campaigns should clarify which are included and why. Focusing on those most relevant for benchmarking or validation would strengthen the section. A map of campaign locations could help illustrate spatial biases.

We thank the Reviewer for their useful feedback, particularly regarding the need to clarify the scope/extension of the observational datasets considered and the suggestion to focus on those most relevant ones (for benchmarking and validation). We have made the following substantial changes:

- We added to the Introduction (Section 1), a clarification stating that the article includes observational datasets derived from spaceborne platforms, airborne campaigns and major field campaigns that have contributed to melt pond research; it also states that we focus on datasets that provide (i) melt pond specific measurements; (ii) that have been widely used in literature for algorithm development, validation or (iii) constitute standalone research products, generated through dedicated methodological or algorithmic developments (e.g., pan-Arctic melt pond fraction estimates). We hope by including those most relevant for benchmarking and validation it strengthens the section accordingly.
- At beginning of Section 4, where observational datasets are described, we synthetize its structure cross referencing the two families of datasets: pan-Arctic, multi-year satellite products (Section 4.1.1, Table 2), and high-resolution regional datasets (Section 4.1.2, Appendix B).
- Section 4.2 was moved to support Appendix C, so that Section 4 is exclusively dedicated to datasets and products.
- With respect to the field campaigns, we have revised the introduction to the campaign section to clarify both the intent of the section and the rationale behind the selection of the listed observational campaigns. The revised section now explains that the campaigns were chosen as key reference field studies that have provided significant in situ melt pond datasets, which are discussed later in the manuscript in the context of their application for validation activities. In particular, the selection criteria are now explicitly stated as (i) substantial contribution to the understanding of melt pond processes, (ii) accessibility and scientific use of the datasets for model and satellite product validation, and (iii) their representation of different observational platforms, regions, and temporal scales. This section itself was also revised, and it now achieves better balance regarding how descriptive each campaign is, while including specifically how each of these campaigns advanced our understanding of melt ponds.
- Finally, following the suggestion of the Reviewer, a map of the campaigns was created and added. We appreciate the originality of showing in a visual manner the spatial biases, and thank the reviewer for this suggestion.

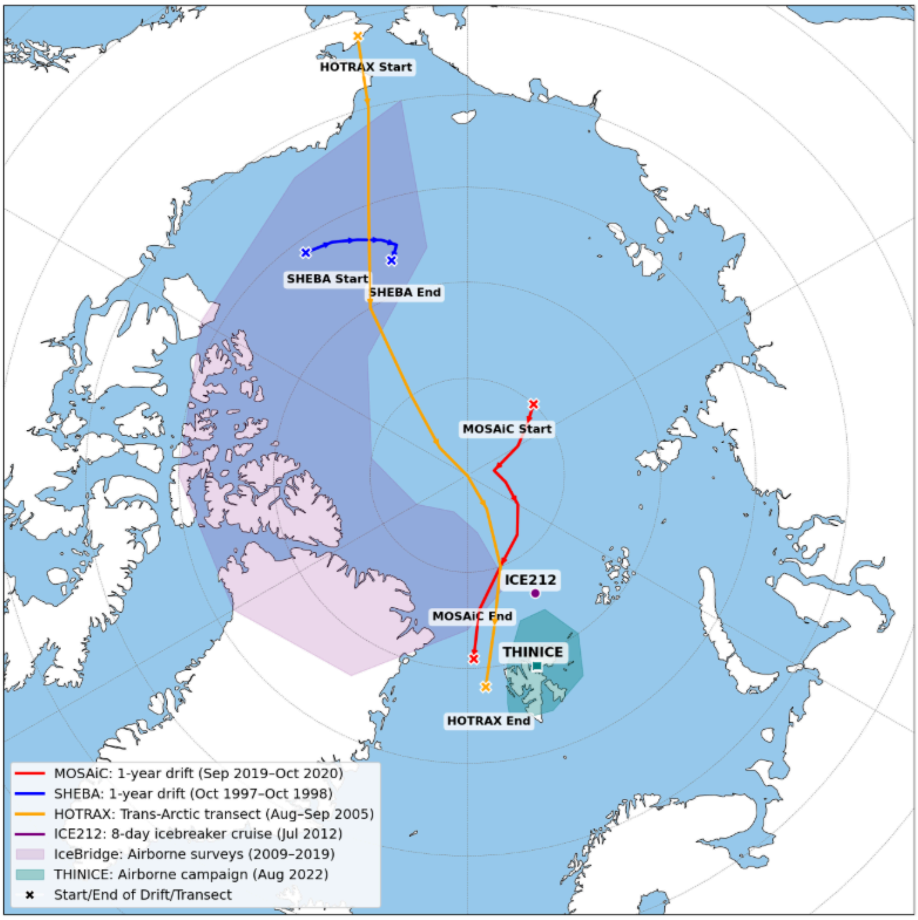

Figure: Arctic sea ice melt pond-relevant campaigns and expeditions

- Although the focus is on Arctic sea ice, some mention of Antarctic melt ponds is warranted. A short discussion of their sparse observations, unique challenges, and potential for future monitoring would improve completeness.

We appreciate the Reviewer's suggestion to include a mention of Antarctic melt ponds to improve completeness of the manuscript. We included some mention of Antarctic melt ponds addressing their sparse observation, unique challenges and trends accordingly, while noting the larger role that melt ponds play in the Arctic.

- The section on parameterization in global climate models seems beyond the scope of this review. It could instead be reframed as part of the motivation or discussion of future directions.

We thank the reviewer for this suggestion and have reframed it as part of the motivation section accordingly.

- **Key Variables and Definitions**
- Introduce the key melt pond variables early in the manuscript, ideally in a table. These should include MPF, depth or volume, connectivity (and open vs. lidded), and melt onset.

We introduced the key melt pond variables accordingly (around L157). It now explicitly lists and describes the key observable variables, furthermore forward-referencing where their measurement or retrieval approach is discussed in detail.

- Methods for measuring parameters beyond MPF (e.g., pond depth or volume) need greater attention (see Buckley et al., 2023; Fuchs et al., 2024).

We thank the Reviewer for raising this important point about methods for measuring pound depth and volume, giving greater emphasis to these, going beyond MPF. We have added clarification and extra detail to our text that now highlights other parameters measurements - including substantially about pond depths. We have also included volume, for example to our bathymetry discussion.
Moreover, we included the Reviewer's suggested literature, and incorporated additional relevant studies (e.g., Xiong and Li, 2025). Section 5.1 has been revised accordingly and now explicitly addresses these parameters, emphasizing their critical importance and the fact that they remain under-measured.

- Figures and Tables
- The choice of figures should be revisited. A meta-analysis figure summarizing validation efforts or comparisons of MPF products would be valuable. Notably, a figure showing typical seasonal cycles should be included.

We thank the Reviewer for this comment. We added a synthesis of available validation and intercomparison information making clear links to the MPF datasets (with cross references 4.1.1 and to Table 2). We have moreover revised Figure 3 showing the seasonal development of melt pond formation, by adding MPF-related aspects (such as increase of %). These illustrate the typical seasonal cycles of MPF and its differences between MYI and FYI.

- Consider adding:
    - A consolidated table summarizing pros and cons of each remote sensing method for MPF (the current figure does not allow easy comparison).

      We have updated Figure 4 to reflect this under *main applications* for optical systems.

    - Example images comparing different types of retrieved melt pond products and A space–time diagram quantifying temporal and spatial coverage, or the percentage of usable data for each platform.

      We thank the Reviewer for suggesting we could consider adding such images. As we wish to provide a methodological synthesis, we feel this is potentially beyond the scope and aim of our paper. We therefore focus on summarizing reports capabilities and limitations from the literature and improve substantially on these aspects such as through all our updates as provided here.

Specific Line-by-Line Comments

- L52: Pond color has been shown not to strongly depend on pond depth. Revise or list last.

Corrected - now listed last.

- L66–67: The statement that melt ponds can break the spring predictability barrier lacks clear supporting evidence.

We thank the Reviewer for pointing this out. We did not intend to suggest that melt ponds definitively break the spring predictability barrier, but more that some studies have hinted they could help in improving such seasonal predictions where forecasting has been imperfect and faced challenges. We have amended the text accordingly.

- L68, L70: Reconsider the choice of references (e.g., Driscoll et al., 2024; Polashenski et al., 2012).

These have been replaced and more suitable references have been chosen.

- Figure 2: If retained, the text should better explain why this observation is relevant.

We have amended our text for further clarification. We thank the Reviewer for highlighting this as it improves our text.

- L123–124: Repetitive—streamline.

Streamlined.

- L137–142: Provide references for albedo values and ensure consistency across lines.

References provided (Perovich et al., 2002; Grenfell and Perovich, 2004; Polashenski et al., 2012), and we have addressed consistency issues when addressing albedo ranges across different surface types and melt pond stages, throughout the manuscript.

- Figure 3: Consider annotating observable variables and how features such as refreezing or lidding affect retrieval.

Figure 3 was updated in order to enhance its utility following Reviewer's recommendation. The modifications include an enhanced caption explicitly identifying observable variables from remote sensing (e.g.pond area/coverage; surface color; ice lids); they also include subtle visual indicators to panels b) and c) highlighting observable figures that affect retrieval accuracy.

- L155–157: Add references.

References added.

- L172: Typo—merge sentences.

Sentences are now merged.

- Figure 4: Well prepared, but note limitations (e.g., LiDAR also requires cloud-free conditions). Clarify whether each method detects or times onset.

We thank the Reviewer for these important suggestions. Figure 4 has been revised to clarify onset-related applications. Regarding limitations cloud and other environmental conditions; melt stage dependencies; and ice type impacts on signatures, these are not included in the figure itself but are comprehensively discussed in Section 3.1 for each sensor type. The updated figure incorporates several additional improvements: (i) inclusion of radar altimetry as a distinct sensor category; (ii) clearer visual distinction between measured parameters (directly observable quantities) and main applications (derived products); and (iii) an expanded caption that describes the figure's structure and content.

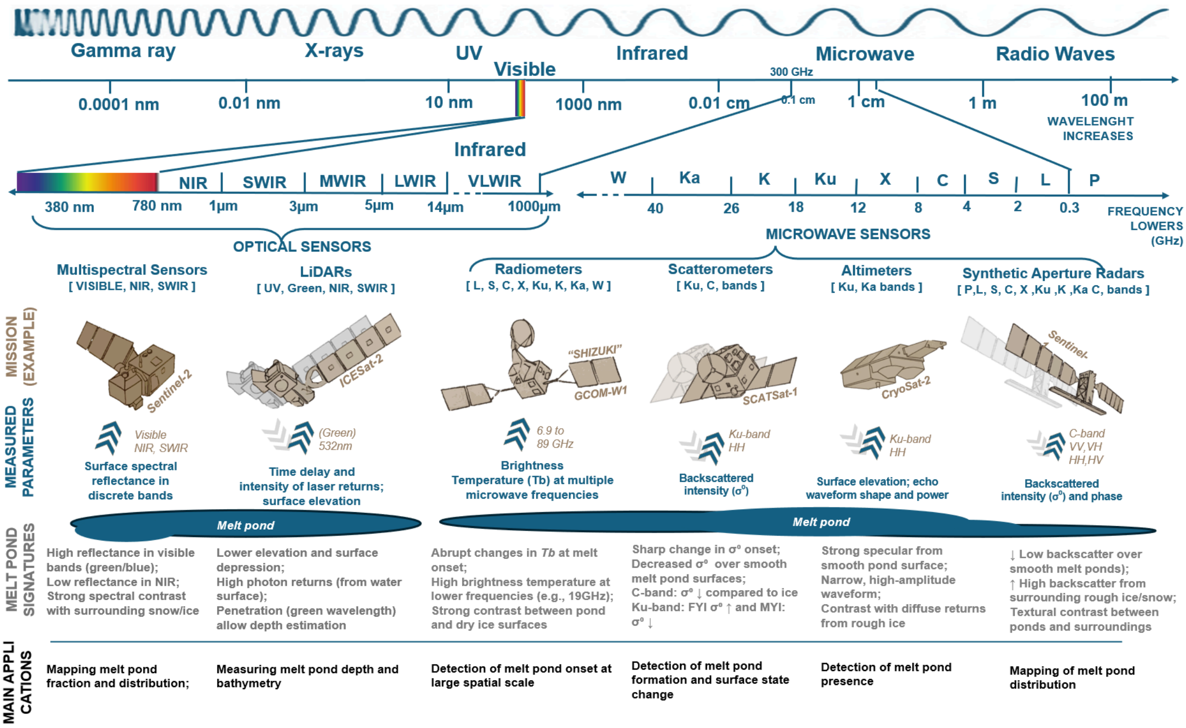

Figure 4: Overview of Earth observation methods for melt pond detection across the electromagnetic spectrum. The figure shows six sensor types (multispectral sensors, LiDARs, radiometers, scatterometers, radar altimeters, and synthetic aperture radars) organized by wavelength range (optical and microwave). For each sensor type, the figure presents: (top row) example satellite missions and operating wavelengths; (middle row) measured parameters and physical principles; (second last row) characteristic melt pond signatures and (bottom row) main applications.

- L255: Replace "capabilities" with "utility."

Replaced.

- L277: Clarify whether “liquid melt pond fraction” differs from MPF used elsewhere; ensure consistent terminology.

Fixed to melt pond fraction.

- L320: Clarify whether sensor sensitivity differs for FYI vs. MYI, and introduce this distinction earlier.

We thank the Reviewer for this. Accordingly, this distinction has been introduced earlier in Section 3.1.2 when discussing SAR signatures. The text at L320 now explicitly references these ice-type-specific sensitivities. We have clarified that sensor sensitivity indeed differs between FYI and MYI due to their distinct surface roughness, dielectric properties, and melt pond morphologies.

- L366: “Firn” is not relevant for sea ice melt ponds—remove.

Removed.

- L387: Clarify intent and scope of listed observational campaigns.

We have clarified the intent and scope of the listed observational campaigns by revising the text preceding Table 1. The updated text now explicitly states the selection criteria we applied. Specifically, we have emphasized that these are key field campaigns that have significantly contributed in situ melt pond datasets to the scientific community. These campaigns were selected based on their substantial contribution to melt pond observations, data accessibility, and their representation of various observational platforms and temporal scales.

- Figure 6: Consider removing or supplement with date, location, and retrieved pond parameters.

We thank the Reviewer for this suggestion. As a result, we have supplemented Figure 6 with the relevant date and location information. The retrieved parameters are also introduced in the text preceding the figure, following the same convention used for the other images in this section.

L425–434: Reorganize to emphasize what was observed, derived products, and how data were collected.

The entire SHEBA description has been reorganized as suggested. It now emphasizes: (i) the observations made, (ii) the derived products, and (iii) their main applications, while directing the reader to the table where the related products are listed. The section concludes with a description of how the data were collected.

Additionally, this section has been revised to provide more balanced descriptions of each campaign, highlighting specifically how each one advanced our understanding of melt ponds by incorporating key findings from each campaign.

L468, L474: Minor wording edits ("melt pond"; "specifically").

Edited

- L480–484: Redundant—streamline.

Streamlined

- L484: Consider starting a new section; summarize datasets and melt pond variables.

We agree that summarizing datasets and melt pond variables is important for guiding the reader. Following the Reviewer's suggestion, we added clear forward-references after L484 directing readers to Section 4.1, where all available melt pond datasets are systematically summarized: Section 4.1.1 covers pan-Arctic satellite-based MPF datasets (Table 2), and Section 4.1.2 addresses high-resolution regional products (Appendix B).

Section 3.3: Difficult to connect with sensor overview. Suggest merging with Section 4 and organizing by wavelength/sensor type.

We thank the Reviewer for this helpful structural suggestion and agree that strengthening the connections between sensor types will enhance readability. In response, we have reinforced the links between Sections 3.1 and 3.3 to more clearly connect each sensor type with the corresponding processing techniques. These relationships are now also clarified in Figure 8 and its caption. Additionally, we have included a transition between Section 3.3 and Section 4, which now better explains its role as a bridge between the processing techniques (based on sensor characteristics) and the resulting datasets discussed in Section 4. We believe these revisions establish a more explicit connection between sections, based on sensor type, and improve the overall flow of the text.

- L526: Replace "convergent" with "converged."

Corrected.

- L538: Table 4 missing—add or renumber.

Corrected.

- L547–549, L553: Typographical and introduction issues—revise.

Revised.

- Table 2: Clarify whether "MERIS-ZEGE" is identical to MPD1; include sensor type for consistency.

We thank the Reviewer for this. We clarify that *MERIS-ZEGE* is a dataset, whereas *MPD1* refers to an algorithm; they are not the same. Naming convention for datasets was clarified at Table 2, and MPD1 algorithm is now introduced and clarified in Section 4.1.1.

Section 4.2: Scope too broad—consider omitting or condensing to future directions.

We thank the Reviewer for this. Therefore, Section 4.2 is now moved to be part of Appendix C where it can provide some linking information between sections without being in the main part of the narrative.

L666–697: This list adds little—remove or condense.

Lines 666–697 were part of Section 4.2, which has now been moved to Appendix C in response to the previous comment. As a result, this list no longer appears in the main manuscript.

L671: Incomplete sentence—revise.

Revised.

- L714: Clarify meaning of “sensor-based constraints.”

We changed this to ‘sensor-specific limitations’.

- L734: Highlight the importance of seasonal transitions more clearly.

We thank the reviewer for this. Therefore we revised the text to do this as follows:

"Capturing rapid seasonal transitions, particularly pond onset, drainage events, and freeze-up, is critical for understanding melt pond evolution and validating model parameterizations, yet current observational capabilities frequently miss these short-lived but crucial phases. Airborne campaigns have demonstrated..."

- Section 5.2: Possibly redundant—merge with earlier priorities.

We thank the Reviewer for this note. We feel Section 5.2 builds on 5.1 (dedicated to the identification of knowledge gaps), but is intended to address a different purpose within the manuscript architecture: it synthesizes implications beyond the description content of Section 3-4 (since Section 5 is dedicated to Discussion). We have made an effort to clarify this in the text, and we have also addressed the Reviewer note on the possible redundancy.

- L794–800: Serves as general motivation, not melt pond–specific—condense.

We thank the Reviewer for this. We have condensed it. The new condensed revised motivation now reads as:

‘Instruments such as AMSR-E and SSMIS provide near-daily SIC data essential for climate monitoring and modeling. However, melt ponds significantly degrade SIC retrievals during the melt season by lowering surface emissivity, causing algorithms to misinterpret pond-covered ice as open water and systematically underestimate SIC (Cavalieri et al., 1990; Comiso and Kwok, 1996), with additional uncertainties arising from changing snow and ice surface properties. These limitations highlight the need to account for melt pond

influence in SIC products, particularly during summer, to improve the accuracy of sea ice monitoring and data assimilation.'

- L801 onward: Repetitive—edit for conciseness.

We thank the Reviewer for noting this issue. To address this, the revised version now reads as:

'Multiple studies quantify this impact: Kern et al. (2016) found that at 40% MPF, SIC is underestimated by 14-26% depending on the algorithm, though underestimation becomes negligible below 20% MPF. Kern et al. (2020) compared 10 passive microwave SIC products against MODIS and ship measurements, revealing significant melt-pond-related discrepancies. Zhao et al. (2021) analyzed 60 Arctic cruises (2006-2020) and found that at 50% MPF, SIC was underestimated by 7-20%, but MPF-based corrections significantly reduced this bias. These studies demonstrate that improved characterization of melt pond brightness temperature signatures and their explicit inclusion in retrieval algorithms are essential for advancing satellite-derived SIC accuracy during melt seasons.'

References
Buckley, E. M. et al. (2023). Observing the evolution of summer melt on multiyear sea ice with ICESat-2 and Sentinel-2. The Cryosphere, 17(9), 3695–3719.
Fuchs, N. et al. (2024). Sea ice melt pond bathymetry reconstructed from aerial photographs using photogrammetry: a new method applied to MOSAiC data. The Cryosphere, 18(7), 2991–3015.

We thank the Reviewer for the suggested references. These studies are featured in the Appendix C, and are also now used more extensively in relation to bathymetry studies.