Response to the comments of Reviewer 2

We would like to thank Reviewer 2 for their thorough and valuable feedback. Their detailed comments allowed us to improve the structure of the manuscript and expand on several aspects, enhancing its completeness. We believe that the revised version, which integrates these suggestions, improves readability, provides stronger contextualization for the reader resulting in greater practical utility of the paper. We are grateful for the Reviewer's important contribution to strengthen this article review. Our responses to the Reviewer's comments appear below in **blue text**, positioned directly beneath each respective comment.

Review of: egusphere-2025-4480
Observational data of Arctic Sea Ice Melt Ponds: a Systematic Review of Acquisition and Processing Approaches By Aparício et al. Summary The authors provide a review of earth observation (EO) methods used in the study of sea ice melt pond properties. Systematic melt pond property observations using EO are challenging and there are no high quality observations (e.g., ECV or CDR type datasets) despite importance for observing sea ice evolution, making proxy estimates such as albedo or light transmittance, and for predicting sea ice conditions. The paper requires some improvements, as per the major and minor comments provided here, and by others, before consideration for publication in The Cryosphere.

Major Comments

1. Given that the paper is a synthesis, the abstract should contain some statements relating to the outcomes of the synthesis. As it is, there only a statement about EO data gaps, along with an outline of the paper's intentions and some motivation statements.

We thank the Reviewer for this feedback. We agree that the abstract should better reflect the key outcomes from our synthesis rather than giving a stronger focus on the intentions and motivations. Following Reviewers' feedback, the abstract now provides the reader with a clearer understanding of what this synthesis revealed about melt ponds observations and it reads as follows:

'*This review synthesizes current methods for acquiring and processing Earth Observation (EO) data relevant to Arctic sea ice melt ponds (MPs), pools of meltwater that form on the ice surface during the polar summer. By reducing albedo, MPs amplify the ice–albedo feedback and alter the sea ice surface energy budget, exerting a strong influence on the Arctic climate system. Despite their importance, melt pond parameterizations remain underdeveloped in many sea ice models, and robust observational records are essential for improving sea ice predictions in a rapidly changing polar environment.*

We review the main EO methods used in MP studies, including active and passive optical sensors (multispectral and LiDAR), and microwave instruments (synthetic aperture radar, radiometers, radar altimetry, and scatterometers). We synthesize melt pond signatures across the electromagnetic spectrum, distill the underlying physical mechanisms governing sensor responses, and outline the strengths and limitations of each sensor type. In situ observations from field campaigns, together with key processing techniques, are discussed alongside available MP datasets from satellite missions and ground-based campaigns.

Our synthesis reveals that optical systems currently dominate pan-Arctic melt pond fraction (MPF) products despite their limitations (e.g. light availability and cloud presence), while microwave systems face fundamental challenges despite their all-weather capabilities. Data processing has evolved from statistical approaches to spectral unmixing, physics-based algorithms, and machine-learning techniques. Intercomparison of pan-Arctic datasets reveals discrepancies during peak melt season and pronounced regional variability. Trade-offs exist between pan-Arctic datasets, which provide continuous monitoring at coarser resolutions, and high-resolution regional products offering meter-scale accuracy but limited coverage.

EO data gaps remain a major challenge: while major field campaigns have provided temporal and spatial snapshots of Arctic conditions they offer limited geographic coverage. Conversely, satellite remote sensing provides pan-Arctic coverage but validation datasets remain concentrated in coastal areas and first-year ice, leaving central Arctic and multi-year ice zones less well documented. Temporal constraints hinder capturing rapid melt transitions, and the lack of standardized classification and validation limits algorithm development and intercomparisons.

This review provides the first side-by-side overview of melt pond datasets, sensors, processing approaches, and field campaigns, highlighting spatio-temporal patterns of in situ coverage and enabling direct comparison of coverage, uncertainties, and accessibility that are otherwise scattered across sources. By compiling existing datasets and methods, identifying knowledge gaps and outlining priority research needs, this review paper provides a state-of-the-art review of melt pond observations, designed to support refinement of parameterizations and the development of multi-modal modeling approaches, crucial for closing observational gaps and advancing the understanding and prediction of Arctic change".

2. It would be advantageous for terminology relating to EO to be tightened up. The authors are focused on what they refer to as the "main" EO methods, which appear to be airborne and satellite-based remote sensing. But in section 3, EO is also used to describe some in situ methods to, which is fine since buoys, weather stations, etc. are EO tools too. The term EO is dropped for remote sensing in the main text – is that distinction intended?

We appreciate that the Reviewer has highlighted this important terminological inconsistency, which can be potentially confusing. We have revised the manuscript to establish clear and consistent terminology throughout. We now explicitly define our scope in the introduction, we use '*Earth observation'* as the broader term encompassing all observational methods for monitoring melt ponds, including both remote sensing (spaceborne and airborne platforms) and in situ measurements (ship-based observation and field campaigns). When we refer specifically to satellite and airborne sensors we use '*remote sensing*' or spaceborn/airborne observations to be precise.
The term 'main EO methods', in our original text referred to the primary remote sensing approaches (optical & microwave sensors on satellite and airborne platforms), but we acknowledge this was unclear given that Section 3.2 discusses in situ methods, which are also forms of Earth observation.

For clarity and consistency, we have restructured Section 3 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*' which apply to both. We believe that these revisions (which are listed below) eliminate the terminological ambiguity and make our scope and distinction clear throughout the manuscript.
Regarding the specific revision made:

- The introduction now explicitly defines scope and terminology
- Section 3 title is now revised to: '*Earth observation methods for melt pond detection and monitoring*'
- Section 3.1 is revised to '*Spaceborne observations*'
- Section 3.2 is revised to '*In situ and field campaign observations*'
- Finally, through the text we now use '*remote sensing'* when referring specifically to satellite/airborne sensors and 'Earth *observation*'

3. The paragraphs on Lines 59-74 needs improvement since some passages are hard the follow. More specific information is needed. How are melt ponds related to a shift in this Arctic sea ice spring predictability barrier? What is the barrier exactly? It can be stated better than "melt ponds …predict …September minimum" since melt ponds can't make predictions. More detail should be given on how melt ponds are parameterized in GCMs, especially given the sensitivity, and the overall theme of the paper. What is the link between GCM parameterizations and the Spring predictability barrier, as suggested on Lines 66-67? Overall, seasonal prediction and climate model projections, as they pertain to melt pond properties should be much better described. Otherwise, the motivation statements on Line 87 and Line 100 are not well backed-up.

In reference to the comments regarding Lines 59-74 and Lines 66-67, we have described in more detail the influence of melt ponds on both seasonal prediction and climate predictions, and clarified all our statements. We apologise for confusion caused, and awkward wording (for instance that melt ponds themselves 'predict'). Furthermore, we have added more detail on how melt ponds are parametrized in GCMs, addressing all the comments here which we are grateful for. We have also modified statements on L87 and L100 and incorporated the changes as suggested.

4. The seasonal evolution of melt pond properties in Section 2, including Figure 3, needs to better differentiate between first-year ice and multiyear ice. There is mention of the influence of ice types in the context of topography, which is good, but there still needs to be seasonal stages in terms of melt pond formation and evolution, and expected melt pond albedo or fraction, defined by ice type. E.g., Stage 4 (freeze-up) rarely occurs for first-year sea ice since the ice melts away / disintegrates during summer.

We thank the Reviewer for this important observation. We agree that the seasonal evolution should be more explicitly differentiated between FYI and MYI, as these ice types follow distinct pathways. In the revised version, for instance, Section 2 has been updated to address ice-type-specific characteristics at each stage of evolution, including typical albedo ranges, defined by ice type. We have further updated our manuscript to note that Stage 4 (freeze-up) is primarily a characteristic of MYI. Furthermore, this revision has also been reflected by updates to the Figure 3 caption and throughout the seasonal discussion.

5. It is generally hard to follow what satellite missions are current or past. Information about data products availability comes later in Table 2, but prior to that there are many missions discussed without enough detail regarding status.

We agree that addressing this lack of information will improve the clarity regarding current data availability for users. For this reason, we have revised Section 3.1 to include the operational status and temporal coverage for each satellite mission when first mentioned. Specifically, we now indicate: (i) mission status, i.e. whether it is operational or has been discontinued; (ii) the operational period and (iii) data availability status. These additions now appear before Table 2 in order to provide the readers with essential context about mission status as they read through the technical descriptions of each sensor system.

Moreover, this section was further revised to include an additional family of sensors (as discussed in the response to comment 6) and to address our response to comment L194 (in the minor comments section).

6. Optical (laser) altimetry is addressed but radar altimetry is not. Radar altimetry should be included.

Following the Reviewer's suggestion, we have given radar altimetry its own dedicated section, following the same structure as other satellite missions (i.e. it includes its way of operating, signature, mission examples, and data availability). We have included relevant studies, such as Dawson et al. (2022), Landy et al. (2022) and Kwok et al. (2018), and additionally, for the sake of consistency, we also include this family of sensors in our Figure 4, dedicated to the overview of melt pond signatures and parameters across the different remote sensing systems. Refer to our response to comment L174 to view the updated image and caption.

7. In Section 3.2, more emphasis needs to be placed on the salient findings from these campaigns, in the context of melt pond property information retrieval from EO data, where possible. In some cases there are just descriptions of data collected and some observations made (e.g., ICE212). In other cases the descriptions aren't clear (e.g., MOSAiC contributions to spatiotemporal studies – what was learned?).

We have revised Section 3.2, to ensure a consistent structure and level of detail for each campaign, while specifically including how each of these campaigns advanced our understanding of melt ponds. In response to the Reviewer's suggestion, the revised section now includes the key findings from each campaign: MOSAiC (e.g., its contributions to understanding melt pond evolution patterns and relation between pond depth and the use of MOSAiC data for validation and algorithm improvement); SHEBA (e.g., its contributions to findings regarding the albedo-pond coverage relationship); ICE212 (e.g., its relevance to spectral differences between bright and dark melt ponds and the usage of data for melt pond validation purposes); HOTRAX (e.g., comprehensive documentation of pond fraction across a broad transect of ice conditions); IceBridge (e.g. the relevance of a multi-sensor approach to demonstrate the importance of sensor complementarity for characterising pond depth, extent and bathymetry); THINICE (e.g. how observations revealed pond formation and drainage patterns, which provided new insights ingto melt pond behaviour under extreme weather).

Additionally, in response to Reviewer 1's suggestion, a new figure has been generated illustrating the tracks and locations of the campaigns.

Minor Comments

- L20: "… sensor type."

Fixed.

- L48-50: Recommended text: "(Right) True colour composite image of Arctic sea ice melt ponds from the Copernicus Sentinel-2 satellite (illustrating the large variability of melt pond, lead and open ocean reflectance). Acquired on 17th June 2024 off the Northeastern coast of Greenland.".

Added.

- L75: Add mention that SHEBA and MOSAiC are summarized later on.

The mention was added, referring to the section where it happens.

- L78: Change "struggle to" to "do not".

Changed.

- L93: "…melt pond studies…"

Was fixed (also on L434 and L635).

- L96: Refer to "… passive microwave" since radar used microwaves too.

Fixed.

- L103: Add a description of the basic outline of the sections of the paper.

The description was added at the end of Section1/Introduction as follows:

'Section 2 reviews essential melt pond optical properties and their seasonal evolution. Section 3 covers Earth observation methods, including spaceborne sensors across the electromagnetic spectrum (3.1), in situ and field campaign observations (3.2), and post-processing techniques (3.3). Section 4 compiles available datasets (distinguishing between pan-Arctic satellite products (4.1) and high-resolution regional datasets (now Section 4.2). Section 5 discusses current knowledge gaps (5.1) outlines the role of melt ponds on future cryospheric research, and highlights potential future research trends (5.2). Section 6 concludes with key findings and emphasises the importance of enhanced melt pond observations for advancing Arctic climate research.'*

*This section number is different from the original manuscript due to changes on its structure.

- L114-118: Bare ice is referred to as both stable and changing (as melt progresses). Clarify.

We apologise for the confusion, the text was revised as follows:

"Bare ice (light orange curve in Figure 2) has a substantial surface scattering layer that provides characteristically high reflectance in the blue-green region of the spectrum (0.75-0.8 at 450-500 nm) (Perovich et al., 2002). While the spectral signature remains relatively stable for this surface type, the magnitude of reflectance gradually decreases as melt progresses (Smith et al., 2022), primarily due to increasing snow grain size associated with rising liquid water content (Warren, 1982, 2019)."

- L121: “radiometric” doesn’t fit here.

Removed.

- L127: “ice surface features” should be changes to “ice properties” since ice surface and volume properties are important (as is described).

Changed.

- L134-135: Are the timings (by month) always appropriate when Arctic sea ice extends across about 40° latitude?

We expanded the text to address this question as follows:

"Melt ponds typically begin forming in late spring to early summer and develop to cover large portions of the sea ice in the Arctic. They then deepen and expand, and refreeze by late Summer to early Autumn. The exact timing varies depending on latitude and regional climate conditions, with earlier onset taking place in lower-latitude seasonal ice zones."

- L136: Here and in Figure 3 the melt onset should be “pond onset” since melt onset precedes the formation of ponds through meltwater accumulation. See, e.g.: https://doi.org/10.1038/s41597-023-02760-5 and L142: See major comment 4. The seasonal peak in pond fraction for first-year ice can be at the initial flooding stage, before drainage pathways open up. The Polashenski et al., 2012 paper shows this too.

We thank the reviewer for this observation. We have revised both the text and Figure 3 to reflect the ice-type-specific differences in pond fraction evolution. The text now clarifies that for first-year ice (FYI), the seasonal peak in pond fraction can occur during the initial flooding stage (Stage a), before drainage pathways open, whereas multi-year ice (MYI) typically exhibits its peak pond fraction later in the season after drainage and interconnection

(Stage c). Figure 3's caption and stage descriptions have been updated to explicitly describe the differences between FYI and MYI, with reference to Polashenski et al. (2012).

- L159: Delete Earth Observation since “(EO)” was defined earlier.

Deleted.

- L160: Be consistent with “in situ” being italicized or not, here and elsewhere.

Fixed

- L162: “... .considerations of associated …”

Corrected.

- L164: “addresses” (change the tense)

Fixed.

- L168: In the Section 3.1 heading “ponds” should be “pond”

Fixed.

- L174: Describe how the main applications were determined. In figure 4, “measured parameters” is used; are these the same thing? And L179: The Figure 4 caption is incomplete. In the figure, it is unclear if there is a difference between “detection of onset” and “timing of onset”. It is odd that melt pond fraction is not mentioned.

We have updated the text to explain that the main applications were determined through our systematic literature review (which can be found in Appendix C - previously Section 4.2). To better clarify the distinction between parameters used and main applications we made considerable changes to Figure 4’s layout and caption. This allows for a clearer and more intuitive understanding of the difference between parameters (i.e. directly measured physical quantities) and the main applications (i.e. higher-level derived applications). Figure 4 was further revised with the inclusion of radar altimetry, a clearer distinction between the signatures and applications rows, and the caption was updated.

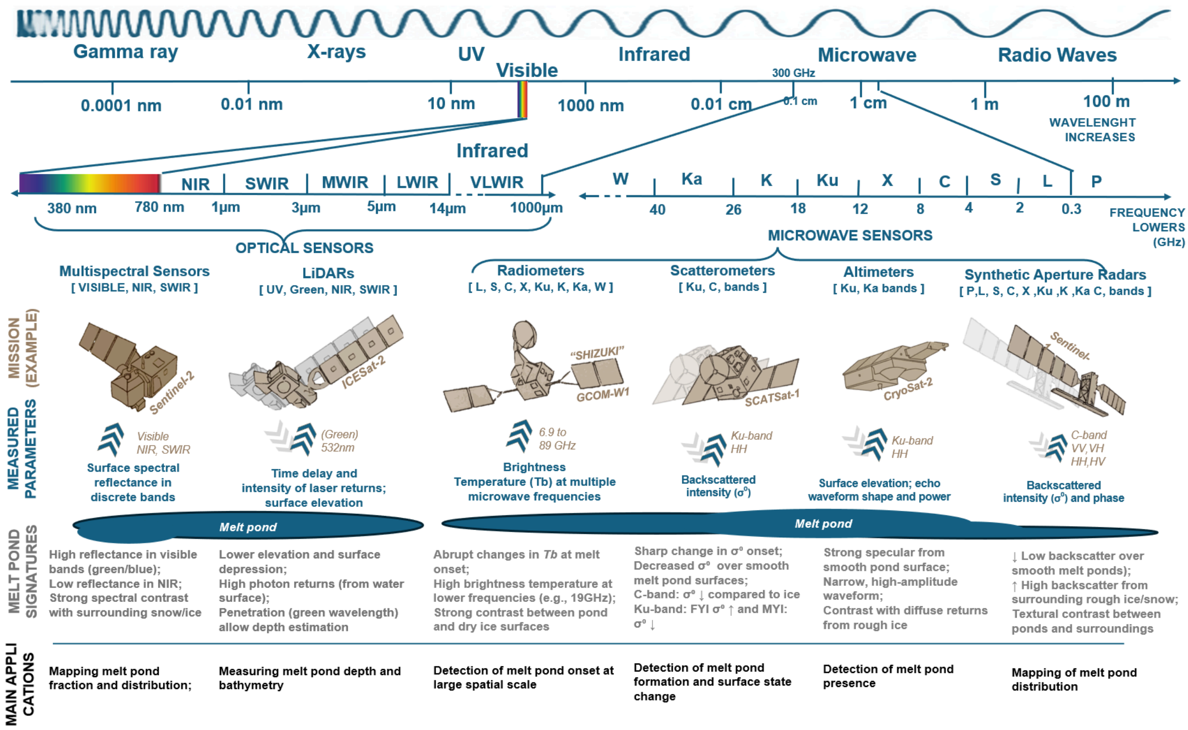

Figure 4: Overview of Earth observation methods for melt pond detection across the electromagnetic spectrum. The figure shows six sensor types (multispectral sensors, LiDARs, radiometers, scatterometers, radar altimeters, and synthetic aperture radars) organized by wavelength range (optical and microwave). 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.

- L183: Name the spaceborne mission.

The mission has been named.

- L186: It should be "EM spectrum".

Updated.

- L194: "instruments" L183-205: Some of these missions are still operational, and others are defunct. Some clarity in this regard is needed. With regards to high-resolution imagery, is WV referenced as an example only? There have been others used; e.g. Webster et al. 2015 used data from the NTM satellites.

Regarding the operational status, we have added: operational dates and current status for all satellite missions mentioned in section 3.1, clearly indicating which missions are currently operational versus discontinued ones. These additions appear throughout section 3.1 providing readers with immediate context about mission status as they encounter each sensor system, as clarified in our answer to major comment 5.

About high-resolution imagery, the Reviewer is correct in that WV was referenced as an example (which we clarify in the text also), and we acknowledge that other high-resolution commercial satellites have been used in melt pond studies. The high-resolution imagery text was revised as follows:

‘For very high-resolution imagery, commercial satellites from the DigitalGlobe's WorldView (WV) constellation (2007–present, multiple satellites), which is an example that has enabled local analyses of melt pond properties and classification (Wright and Polashenski, 2018), providing finer spatial insights that complement the broader-scale insights provided by coarser-resolution data. Other high-resolution platforms, including governmental satellites, have also contributed to melt pond studies, as documented in the literature compiled in Appendix C (e.g., Webster et al., 2015).’

- L222: State why Landsat is not suitable, and if that is for a specific Landsat mission or all of them.

The text was revised to explain the unsuitability statement regarding Landsat missions, which will include mentions of: (i) swath widths; (ii) limitations associated with cloudless opportunities, (iii) and Landast-7-specific additional limitations caused by the Scan Line Corrector failure in 2003, which created persistent data gaps and affected ~22% of each scene (as described in Markus et al., 2003).

- L223: Sentence “Additionally, for high resolution…” should be re-written for clarity. Are there no data for coastal waters, or limited data?

We have rewritten this sentence for clarity. Sentinel-2 MSI is restricted to coastal waters within 20 km of the shore, meaning that data coverage is limited rather than absent in these regions. The revised text now clearly states this spatial limitation and its implications for monitoring melt ponds on sea ice.

- L226: Remove “Similarly”. The commercial restriction associated with those platforms is not similar to Sentinel-2.

Removed.

- L230-234: This should be made clearer. It is unclear how fresh snow mimicking melting ice leads to misclassification. What is classified/mis-classified? If it is melt pond fraction or pond/ice, aren’t fresh snow or melting ice basically the same class (i.e., not melt pond)? It is also unclear why freeze ponds (refrozen ponds or freezing ponds?) lead to melt pond fraction overestimation.

We agree that the misclassification mechanism requires a clearer explanation. The revised text addresses both misclassification examples asked by the Reviewer, explaining how/why they can be misclassified (i.e. the spectral mechanism leading to the misclassification) and the result (which is overestimation in both cases).The revised text now reads as follows:

"Fresh snow with high liquid water content exhibits increased NIR absorption similar to wet melting ice, making both surfaces spectrally similar to shallow or bright melt ponds in certain band combinations. When classification algorithms rely heavily on NIR reflectance characteristics, these wet snow or melting ice surfaces can be incorrectly classified as melt ponds, leading to MPF overestimation (Istomina et al., 2025). Similarly, refrozen melt ponds (ice-lidded ponds) retain low NIR reflectance similar to liquid melt ponds despite their frozen state, as the thin ice lid does not substantially alter the spectral signature. Classification algorithms based on reflectance alone cannot distinguish between liquid and ice-covered ponds, resulting in ice-lidded ponds being classified as active melt ponds and thus contributing to MPF overestimation, particularly during early-season refreezing events and late-season freeze-up (Xiong and Ren, 2023)."

- L240: Sentence on LiDAR should be “LiDAR laser pulses are composed of photons typically emitted at one or both of these wavelengths.”.

Updated.

- L245-248: Mention is made of pond depth and presence, in terms of research. But only pond depth is mentioned in relation to operational products. What about presence?

The parameter ‘pond depth’ received particular attention since, amongst the multiple pan-Arctic data products on the presence of melt ponds or MPF (as summarized for instance in Table 2), none focused on depths. Regarding ICESat-2 mission, its capabilities remain at research level, with no operational data products providing automated melt pond presence classification or depth measurements. With regards to presence, we revised the text, to acknowledge this distinct difference on data availability and operational products, while also inviting the reader to consult Appendix C, showcasing numerous studies involving the development of products.

- L249: “…consist of laser penetration…”

Fixed.

- L249-252: Add detail on how melt pond presence affects existing ICESat-2 data products for sea ice, and what those products are, if known. Are melt pond areas masked out, or generally unreliable in sea ice data products during spring/summer conditions?

The revised text now addresses how the presence of melt ponds affects ICESat-2 data products and further discusses the limitations of this type of sensor. Specifically, it now refers to relevant ICESat-2 data products (e.g., ATL03, ATL10) and explains how melt pond-covered areas are treated in sea-ice products during the spring and summer seasons, following, for example, Tilling et al. (2020) and Buckley et al. (2023).

- L254: Add a comma after “particles”.

Added.

- L262-264: The statement about liquid water in snow needs correcting. Snow effects do not create the low signature of melt ponds, since melt ponds are water bodies and their backscatter is dependent on wind/wave roughness.

We thank the Reviewer for this remark. The text has been revised to focus exclusively on melt ponds, and it clarifies that their lower backscatter under calm conditions is primarily controlled by specular reflection from the smooth water surface, with the returned signal being sensitive to wind- and wave- induced roughness (in addition to radar configuration).

- L272: Clarify what you mean by early melt detections, in the context of X-band suitability over other frequencies.

The clarification has been added as follows:

‘Comparatively, X-band SAR systems like TerraSAR-X (9.65 GHz, 3.1 cm) provide higher spatial resolution (0.25-40 m) and enhanced sensitivity to fine-scale surface features compared to C-band (5.6 cm) or L-band (23.5 cm) systems. This is because radar backscatter is most sensitive to surface roughness features with scales comparable to the wavelength. For this reason X-band can detect smaller-scale surface changes such as initial ponding, and subtle surface roughness variations that characterize melt onset and early pond formation (Fig. 5), making it particularly suitable for detecting the initial stages of melt pond development (Kern et al., 2010; Fors et al., 2017).’

- L274: Correct “melt onset” if necessary. I.e., if this is pond onset.

Corrected.

- L275: Change “on” to “for” and make “signatures” to “signature”.

Corrected.

- L297: Get rid of the empty space. Also it should be “… poorly distinguishable from smooth sea ice.”.

Corrected.

- L301: Provide detail about the swath widths. Smaller than what?

We have provided the actual swath widths adding clarification on size comparison.

- L304-306: The statement about X-band is hard to follow. Optimal performance for deriving what melt pond related information? MYI monitoring of what melt pond related information?

We revised the text in order to improve its readability while clarifying the two points, as follows:

‘The optimal incidence angle for X-band melt pond observations depends on the specific application and ice type. For melt pond fraction (MPF) retrieval on first-year ice, Fors et al. (2017) found optimal performance at 29-40° incidence angles using TerraSAR-X single-pol data. For multi-year ice, Han et al. (2016) demonstrated that TerraSAR-X dual-pol data performs best at 20-30° incidence angles for discriminating melt ponds from surrounding ice and monitoring pond evolution.’

- L306-307: Backscatter should not increase due to specular reflection.

Corrected.

- L316: “pond onset”

Corrected.

- L311-322 and 311-313: It is hard to follow what melt pond properties are being observed/retrieved here. E.g., optimal retrieval of what melt pond information?

We have restructured this paragraph to explicitly state what is being retrieved.

- L326 and L350: The section on scatterometers should be shortened since most of the current focus is on melt onset, which precedes pond onset. Focus should be placed on melt pond properties. As for scatterometers, the discussion of melt effects in this section should be shortened and more emphasis placed specifically on melt pond related properties.

The scatterometer discussion was condensed to focus on melt pond properties as suggested.

- L376: Low penetration depth also applies to scatterometers and SARs since they operate in the microwave range. It should be noted above too.

We agree on its importance, and we added this clarification earlier in the SAR section (around L265-270) as follows:

"It should be noted that low penetration depth into liquid water (~1 mm at frequencies ≥6 GHz) is a fundamental constraint across all microwave sensors operating in these frequency ranges, including SAR, scatterometers, and radiometers (Ulaby et al., 1986). This physical limitation prevents sensors from distinguishing seawater from meltwater in ponds and affects all microwave-based melt pond observations."

We then referenced this earlier statement in the radiometer section (L376) rather than introducing it for the first time there.

- L390: Provide some detail on what criteria were used to include these campaigns, and (potentially) exclude others that have studied melt pond properties and detection techniques.

The criteria were included when introducing Table 1 as follows:

"Table 1 summarizes field campaigns that contributed significant melt pond observational data, selected based on the following criteria: (1) campaigns that acquired spatially extensive in situ melt pond measurements (coverage, depth, albedo) or high-resolution imagery suitable for melt pond mapping; (2) datasets that have been widely used in the literature for algorithm development or validation (as documented in Appendix C); and (3) multi-instrument campaigns providing complementary observations relevant to remote sensing validation. Campaigns focused solely on ice thickness, oceanographic, or atmospheric measurements without melt pond-specific data collection were excluded. This selection represents the most significant melt pond observational efforts but is not exhaustive of all Arctic field campaigns."

- L488: “named”

Corrected.

- L506: “that geophysical inversions” doesn’t make sense. Please clarify.

The revised sentence now reads as follows:

"Microwave data processing employs distinct methodologies that include 1) geophysical inversions to retrieve surface properties, 2) conversion of backscatter coefficients to MPF and empirical relationships, and 3) correlations between co-polarization ratios and compact polarization metrics (Yackel and Barber, 2000; Scharien et al., 2014; Li et al., 2017)"

- L514: In Figure 8, there is mention of compact polarization but there was no mention of that in the earlier section on SAR approaches.

We have updated an earlier section (SAR section, around L262-290) to include a mention of compact polarization.

- L515-517: Some of the mentioned studies focus on melt pond fraction prediction, where spring MPF is predicted from winter SAR imagery, e.g., Howell et al., 2020. Others focus on direct estimation of MPF, Tanaka and Scharien, 2022. This should be clarified here, and in the earlier SAR section.

In order to clarify this important distinction, the 515-517 text was revised as follows:

"Since 2014, two distinct approaches for MPF retrieval using multiple sensors have emerged: (1) direct estimation methods that use correlation and regression to relate coincident or near-simultaneous microwave signatures to optical-based MPF (Mäkynen et al., 2014; Tanaka et al., 2016; Fors et al., 2017; Scharien et al., 2017; Ramjan et al., 2018; Tanaka and Scharien, 2022), and (2) predictive methods that forecast future MPF from earlier-season SAR data, such as predicting spring/summer pond conditions from winter SAR imagery (Howell et al., 2020). These fusion methods link microwave and optical-based MPF and are well-suited for integration since they are essentially empirical mappings that can incorporate information from multiple sensors."

Given the relevance of this clarification, it will also be reflected in the earlier SAR section (around L287-290) with the following revised text:

"While most SAR studies focus on contemporaneous melt pond detection during the melt season, recent work has demonstrated the potential for predictive applications, using winter and early spring SAR characteristics to forecast subsequent melt pond development (Howell et al., 2020)."

- L522: It would be helpful to know if more advanced techniques like ANN represent any increase in efficacy compared to traditional techniques.

The impacts on the efficacy of more advanced techniques were added as follows:

"Deep learning methods have generally demonstrated improved performance over traditional techniques. For MPF retrieval, ANNs achieved RMSE values of 0.05-0.10 (Lee et al., 2020; Ding et al., 2020; Peng et al., 2022) compared to 0.10-0.18 for spectral unmixing approaches (Rösel et al., 2012; Zege et al., 2015). For classification tasks, CNNs achieved accuracies of 92-96% (Wright and Polashenski, 2018) versus 85-90% for traditional supervised classifiers (Fetterer et al., 2008; Divine et al., 2015). However, these improvements come at the cost of requiring large labeled training datasets and reducing skill in physical interpretation. The performance gains are most pronounced when training data are abundant and representative of diverse conditions."

- L526: “converged”

Corrected.

- L530: MPF was defined earlier.

Fixed.

- L532: “melt pond” (singular).

Corrected.

- L580: Statistically significant “difference”.

Corrected.

- L581: Use “MPFs”.

Corrected.

- L598: “datasets”

Corrected.

- L631: Use “MPF”.

Corrected.

- L698: “5. Discussion”

Corrected.

- L757: It is unclear why SAR-based methods are specifically identified as lagging in situ methods when, presumably, other satellite-based methods would be similarly lagging. This also comes up on L867.

We agree this phrasing was unclear. All satellite-based methods, including both optical and SAR, suffer from limited in situ validation data relative to the spatial and temporal scales needed for comprehensive algorithm development and validation. The revised text now clarifies that the distinction for SAR is not about lacking in situ data per se (which affects all remote sensing methods), but rather about SAR-based methods facing additional fundamental challenges in retrieving MPF at operational scales (L287-294), including: difficulty distinguishing melt ponds from open water due to similar backscatter characteristics; strong dependencies on environmental conditions and sensor parameters; and limited validated correlations beyond smooth FYI surfaces (Mäkynen et al., 2014; Scharien et al., 2014; Li et al., 2017).

While available in situ validation datasets are predominantly optical in nature (aerial photography, visual surveys, albedo measurements from field campaigns, Section 3.2, Table 1), this alone does not explain why SAR has not achieved the same level of operational MPF product development as optical methods (Table 2). The key point is that SAR faces signal interpretation challenges that have proven more difficult to resolve than those encountered by optical methods, despite SAR's theoretical advantages of all-weather, day-night capability.

The text at L757 and L867 has been revised to focus on this comparison between satellite-based approaches rather than on comparing satellite methods to in situ observations.

- L765: Use “MPF”

Corrected.

- L780: CAA was defined earlier. Use “CAA”.

Corrected.

- L821-822: Elaborate what these schemes are, as well as schemes in general as they pertain to melt pond representation in models. This will make this section of the review more accessible to readers focused on in situ and satellite studies.

We appreciate this valuable recommendation, and agree that revising the text will make it more accessible. We have therefore revised the text in order to: (i) add the explanation of the meaning of melt pond 'schemes', (ii) add a brief description of the main categories of melt pond schemes, followed by (iii) the need for specification of explicit schemes and (iv) the importance behind of the choice of scheme regard impacts on models outputs.

- L850: Elaborate on why specifically pond depths, pond fraction, snow cover and type. Is ice topography and permeability less important?

Thank you for pointing this out. We revised the discussion of topography, noting that it can be observed remotely and validated, and added a remark highlighting other equally important parameters (e.g. sea-ice permeability) that do not meet these same criteria. The revised text now reads as:

"Quantifying the physical processes driving melt pond fraction evolution remains a key challenge: understanding the interplay between the main ponds characteristics (pond depth and pond fraction) and the sea ice surface characteristics (e. g. snow cover and type, topography) would improve the comprehension of the links between surface physics and MPF variability. Emerging efforts to couple remote sensing observation with sea ice components of GCMs, hold the potential of improving and simulating pond onset, evolution and refreeze states. The significant influence of physical features like snow cover (Webster et al., 2015) or snow depth (Kim et al., 2018; Toyoda et al., 2024) underscores the importance coupling these parameters in a modeling framework to resolve inconsistencies between MPF datasets and improve melt onset detection. The parameters listed can be directly observed (either remotely or in field campaign) and validated, and can be used in model simulations. Other parameters, such ice permeability, while crucial for drainage processes (Polashenski et al., 2012), remain difficult to observe directly or validate systematically and must therefore be represented through process-based parameterizations."