Authors' response to the Referee 2 comments on tc-2023-142: Updated Arctic melt pond fraction dataset and trends 2002 – 2023 using ENVISAT and Sentinel-3 remote sensing data

by L. Istomina et al.

The authors thank the referee for their valuable comments, which allow us to improve the manuscript and make the text so much more concise and readable. Please find our point-by-point response to the comments below. The reviewer comments are highlighted with bold face font, and the authors' response follows in a normal font.

1. The treatment of Sentinel-2 derived MPF as ground truth raises its own potential problems since this is another satellite derived dataset (although at higher spatial resolution) and is subject to its own retrieval limitations. Despite referencing the Sentinel-2 algorithm, the authors do not provide enough information on the algorithm and its limitations in the current paper to enable an effective intercomparison of the two products, or to build confidence that it should be assessed as a "truth". More detail needs to be provided. As well the Sentinel-2 MPF should not be identified as ground truth.

The authors agree that the Sentinel-2 comparison dataset is not an *in situ* measurement and therefore should not be referred to as "ground truth". We will correct this in the future version of the manuscript and use term "comparison dataset".

However, Sentinel-2 MPF stems from data where melt ponds can be clearly recognized by shape and in some cases even counted manually. In comparison to OLCI data where each pixel inevitably contains a subpixel surface mixture – a situation prone to complications as shown in Section 3.2, - Sentinel-2 MPF with the spatial resolution of 10 m offers a drastic increase of dataset quality. The spatial resolution of 10 meters together with unprecedented spatial coverage gives a valuable addition to the earlier presented validation effort (Istomina et al., 2015a) and thus allows us to significantly improve our understanding on the MPD algorithm performance as compared to the previously published validation (Istomina et al., 2015a). Therefore, the authors insist on presenting this comparison. Niehaus et al., 2023 presents successful validation and claims robustness of the retrieval used to produce the Sentinel-2 validation dataset. Although we agree that more details should be added on the Sentinel-2 dataset to aid better understanding of the manuscript and will do so in the future version of the manuscript, we do not see any faults in this peer-reviewed publication or in the Sentinel-2 MPF dataset which would prevent a quality comparison to OLCI MPF.

Details on the Sentinel-2 dataset will be added, as well as the "ground truth" expression will be exchanged throughout the manuscript.

2. Similarly, the comparison between Sentinel-2 and 3 done in Section 3.2 is too cursory in that it is a global comparison of the all overlapping data from the two datasets. The authors should provide a more detailed analysis that considers the ice condition (ice type) and some indication of the temporal component, i.e. how OLCI and MSI MPF compare in different seasonal phases of melt pond coverage when the spectral properties of the snow, ice, and ponds are different (but perhaps typical to some degree). In this context, is good performance of the MPD MPF product realized for first half of the melting season (June–July), as speculated on Line 360? The authors could use one or more of the already cited papers on melt pond evolution, to provide some structure to seasonal component of MPF evolution, e.g. as opposed to calendar months (Eicken et al., 2004; Polashenski et al., 2012). On the other hand, the spectral mixing analysis in Section 3.2 is lengthy and hard to follow in parts, and should be improved. It important to be clear as to what observations from these results

were used to make changes to the current MPD, versus what are being used to highlight possible error sources or identify areas for future iterations of the algorithm.

Indeed, the comparison of the entire Sentinel-2 dataset has been limited to gridded data only, to illustrate the performance issues of the MPD retrieval at a global scale. The more detailed comparison of the same dataset to MPD MPF on the original OLCI resolution is presented in Niehaus et al., 2024, which uses the Sentinel-2 dataset by Niehaus et al., 2023, to improve the MPD retrieval presented here and to include 3 surface retrieval (sea ice-melt pond-open water). The scope of this manuscript is not the improvement of the MPD algorithm, but MPD performance assessment in addition to existing validation and the long-term trends MERIS+OLCI. In the next version of the manuscript, we will take extra care to highlight this context and make sure that the references important to its understanding are included (Istomina et al., 2015; Niehaus et al., 2024).

Unfortunately, we cannot retrieve ice type or the phase of the melt evolution in this version of the MPD retrieval. Moreover, Section 3.2 particularly deals with the question why optical data from OLCI or MERIS (or MODIS) is not sufficient to perform such a retrieval, so that using melt phase instead of weekly trends is prone to high uncertainties and is not used. Instead, we adopt the already published (Istomina et al., 2015) approach to present weekly trends of the combined dataset, as a direct continuation of the earlier presented MERIS trends and as improvement on the past MERIS dataset. The newly presented MPF trends have changed significantly with the addition of the OLCI part of the dataset, and the authors like to preserve this comparison which might be of interest to the scientific community.

However, we agree that details on ice type and melt evolution can be beneficial for MPF retrieval. This approach is realized in the recently published companion paper Niehaus et al., 2024, which presents an improvement on the MPD retrieval. They include temperature history of a given ice parcel, so that more information on the ice type can be assumed. Their approach, however, cannot be directly applied to MERIS data, so no long-term trends are possible with the new 3-surface MPD retrieval by Niehaus et al., 2024. To obtain long-term trends from 2002 till present, the initially published version of the MPD retrieval (Istomina et al., 2015a; Zege et al., 2015) needs to be used, which is the focus of the presented manuscript.

In the next version of the manuscript, we will add the details on the temporal performance of the MPD retrieval and once again proof-read the Section 3.2 for readability. The above-mentioned details as well as reference to Niehaus et al., 2024, which has been submitted later than the current work and was therefore not yet included, will be added as well. Also, we will take extra caution to highlight that in the present manuscript, the MPD algorithm was not modified and is the same as presented in Istomina et al 2015, with the exception of a uniform cloud screening applied to both parts of the dataset. Therefore, the data comparison and the spectral mixing clarification in Section 3.2 as well as the examples shown in the Section 3.1 can be seen as performance assessment of the original 2-surface MPD retrieval, e.g. when the long-term MPF dataset is used as input to climate models.

3. The authors use terminology regarding seasonal stage that isn't consistent with the literature, especially melt onset, which most often likely means pond onset i.e. formation of melt ponds that occurs some time after melt onset, when there is enough meltwater that flooding is possible. This will need to be addressed throughout the paper.

The terminology regarding melt stages which used in the manuscript is largely adopted from Eicken et al., 2002. The authors agree that it should be updated and are grateful for this remark. Indeed, there are some cases where melt onset and onset of ponding have been used

interchangeably, which is of course inconsistent. We will proof-read the manuscript for consistency of usage in the next version of the manuscript.

Minor Comments

L17-19: Clarify the ranges ("small" and "middle" are ambiguous).

Here "small" means "0-0.2" and "middle" means "0.2-0.8". This will be changed in the next version of the manuscript.

L18: The snow would not be saturated if it is before melt onset. Is this supposed to pond onset?

Yes, thank you for highlighting this case. This will be changed to "pond onset" in the next version of the manuscript.

L28: Again the term melt onset is confusing here as it was not analyzed, but the onset of ponds was, so perhaps "pond onset" is more appropriate.

Yes, here the onset of ponding is meant. It will be changed accordingly in the next version of the manuscript.

L34: 2016-2023.

At the time of writing, the year 2023 was not yet finished. In the final version, this sentence will be updated accordingly.

L35: "...world (Rantanen et al., 2022), the..." (delete "and")

Will be deleted in the next version of the manuscript.

L38: It would be better to say that it is due to the ocean being darker than the sea ice, not the other way around.

Will be changed accordingly in the next version of the manuscript.

L43: What is meant by surface melt in the context of a sea ice ECV? How would it differ from the albedo, which changes due to melt?

The melt pond fraction is not directly linked to the sea ice albedo, as same fraction of melt pond can have very different albedo depending on the pond type, or better, on the thickness of the underlying sea ice. So that in an extreme case there may be a 100% melt pond fraction on thick ice, with albedo so high that it is similar to 0% melt pond fraction on a wet, large grain sea ice, which is in turn darker than the regular sea ice. Similar albedo, but very different melt situation. Therefore, MPF ECV data should ideally be separated from the sea ice albedo ECV.

L46-54: Briefly provide some detail on what is affecting the different remote sensing methods (e.g., PM emission is affected by the presence of open water from melt ponds on sea ice, etc.).

Indeed, we will provide corresponding physical context on how summer conditions affect PM SIC, altimeter-based SIT and PM sea ice drift retrievals, in the next version of the manuscript.

L51: "A PM based sea ice drift product..."

Will be changed accordingly in the next version of the manuscript.

L55: "GCMs"

Will be changed accordingly in the next version of the manuscript.

L59: "forecasts"

Will be changed accordingly in the next version of the manuscript.

L61: Update the references (e.g. MOSAiC melt pond studies).

The following references on MOSAIC melt pond studies will be added:

Webster et al., 2022; Light et al., 2022.

L62: Do you mean "climate conforming"? It is unclear.

Here the datasets of global coverage and high quality which can be used as climatology datasets are meant. Will exchanged for "high quality" in the next version of the manuscript.

L64: Use "MPF" instead of "melt pond" for consistency.

"MPF" will be used at this point in the next version of the manuscript.

L69: delete "of"

Will be deleted in the next version of the manuscript.

L79: add space after "1.4 GHz,"

Will be added into the next version of the manuscript.

L80-84: The link between penetration depth and MPF estimation is unclear. Is it not more-so the emission differences between ice and melt pond that enable MPF retrieval, and the presence of open water along with melt ponds that confuses the MPF retrieval because melt pond and OW have similar emission characteristics (regardless of penetration depth)?

The penetration depth is essential here because the underlying sea ice in the pond ("pond bottom") cannot be recognized due to low penetration depth, that is, melt pond cannot be distinguished from open water. This will be added into the next version of the manuscript.

Line 86: Add "synthetic aperture radar"

Will be added into the next version of the manuscript.

L88: Melt pond and open water could have equally high backscatter in windy conditions.

Indeed, this is also the case and will be added into the text. Still, the point stands: melt ponds and open water cannot be reliably distinguished using SAR only backscattered signal (but could be potentially distinguished using shape and image analysis).

L93: Clarify what Terra and Aqua are (platforms each with MODIS sensors).

The clarification will be added to the manuscript.

L93: data "are"

Indeed, this should read "MODIS data are…". We will correct this.

L94: Start a new sentence at "important …"

The sentences will be separated in the next version of the text.

L99-102: Sentence "In addition, …" is not clear and could probably be broken up into two sentences.

The sentences will be split in the next version of the manuscript.

L103: "…a MPF dataset"

Of course, this typo will be corrected in the future version.

L105: "…of an earlier…"

Currently the article "an" is missing, it will be added in the future version of the text.

L120-123: The information listed should be written out and presented more clearly or summarized in a table.

Reference to Table 1 will be added also in L. 119 and the text on L.120-123 will be checked for clarity.

L134: "…and the absorption coefficient…"

Of course, we will add "and" into the text at this point.

L137-139: Provide some more information on the ice sampled here, given the importance of the dataset (types, melt pond conditions e.g. depth, etc.).

The PANGAEA dataset referred to in this sentence contains spectra of bare ice of various grain sizes, snow, dark and light melt ponds with or without the ice lid, blue ice without the scattering layer, for a range of ice thickness from 30cm to 2.5m within the melt ponds. These details will be added into the future version of the manuscript.

L142: "The MPD has been…."

We will exchange "have" for "has" in this sentence.

L159: change to "swaths" and change "overflight" to "overpass"

Will be changed in the next version of the manuscript.

L175: change to "swaths"

Will be changed in the next version of the manuscript.

L183: acronym SIC should be defined earlier

Indeed, we will define the sea ice concentration – SIC – on P2 L47.

L183: "Examples of the daily …."

Of course, as there are two examples, we will use multiple here.

L184: "…are shown"

Also this will be corrected, corresponding to multiple examples as mentioned above.

L186: Use "SIC"

Will be used in the next version of the manuscript.

L189: See general comments. It is not correct to call the Sentinel-2 data "ground truth".

This will be corrected here and throughout the manuscript.

L190: In Fig. 1 it is confusing to have 0% MPF and no-data as both white color.

We do not have any MPD data with exactly (numerically) 0% MPF, therefore this choice of the colorbar.

L202: Use italics for "in situ"

Will be done in the next version of the manuscript.

L205: "mixtures"

Will be used in the next version of the manuscript.

L210: Clarify what is meant by "within ice surface types".

Here the main feature of the melting ice as opposed to white ice, namely the decreased near infrared reflectance, is exploited, thus making it possible to only use a ratio of two channels to, in the first approximation, separate melting and non-melting sea ice. This clarification will be added into the manuscript.

L219: "MPF"

Will be used in the next version of the manuscript.

L229: As mentioned before, this should be pond onset not melt onset.

Will be changed in the next version of the manuscript.

L242: "… a high fraction of ridges…"

Will be used in the next version of the manuscript.

L259-260: "darker water saturated sea ice" could be better described. Is this blue ice and/or optically thin ice?

It can be both thin ice or blue ice, or subnivean ponds, we do not have information to distinguish these surfaces as the spectral ambiguity plot in Fig. 7 is pointing out. This clarification will be added at this point of the manuscript.

L274: "…a translucent scattering"

Will be corrected in the next version of the manuscript.

L292: Clarify what is meant by typical MYI. There is MYI north of the Canadian Archipelago, even within the Archipelago, due to it ending up there after drifting in the area during summer. Depending on where the ice transitioned to MYI before drifting to its imaged location, it may be typical (which also depends on the authors' definition of typical).

Typical MYI in the sense that it is rougher than the FYI, so that this increase in sea ice relief will lead to decrease of the maximal possible MPF on this sea ice. We will clarify this in the next version of the text.

L316: Insert comma after Fig. 5

Will be done in the next version of the manuscript.

L317: "...in (Fig. 7)" doesn't need brackets around Fig. 7 as done on Line 320. Note on Line 323 the text "Figure 7" is used. Be consistent with style used for identifying figures in the text here and elsewhere.

We will check the style for consistency.

L323: "...melt pond type..."

Indeed, here only one melt pond type is meant – dark melt pond – this will be explained in the next version of the paper.

L330: "... favorable condition"

Line 330 reads as intended "..., thus biasing an otherwise favorable for the MPF retrieval situation". No condition is meant here. We will correct this sentence for more clarity: "..., thus biasing even this favorable MPF situation of two surface classes only."

L332: "...MPD MPF"

The double MPF will be corrected to MPD MPF as advised.

L334: "... SIC is shown as color-coding of the data points"

Thank you for this suggestion, we will reformulate the original sentence to the advised version.

L335: "...bright sea ice surfaces"

We will pluralize "surface" in the next version of the text.

L338-343: It is hard to follow if these solutions are implemented in the current algorithm or not. Use of text "can still be accommodated" and "can be accounted for" makes it unclear if these ideas are for future consideration or not.

Indeed, these are ideas for future consideration which have been already realized in the companion publication by Niehaus et al. 2024. At the time of writing, the paper by Niehaus et al. 2024 has not yet been submitted. But now, as it has been already published, we will include the reference to Niehaus et al., 2024 and correct the text here for more clarity.

L343-344: pluralize "version" and use MPF for "melt pond fraction"

We will do so in the next version of the paper.

L355: There is not water saturated sea ice before melt.

Here the onset of ponding is meant, will be corrected in the future version of the manuscript.

L366-367: Used "averaged" and "analyzed" i.e. past tense for methods implemented.

We will implement past tense here.

L385-390: change descriptions of past methods to past tense

Also here, past tense will be implemented.

L397: See general comment about melt onset (above).

The reviewer means the stages of melt occurring on FYI, with the first stage of melt being "1. Melt onset" and being ambiguous. We suggest to correct it like following:

"1. Melt onset followed be onset of ponding". This brings the most clarity, although deviates from the original Eicken et al., 2002 formulation.

L451: Add spaces each side of "–"

Will be added into the next version of the manuscript.

L453: "A significance hemispheric…"

Indeed, we will insert the article "A" in the text at this point.

L454: "The last three weeks…"

Here as well, we will insert the missing article "the" in the text.

L456: Add spaces each side of "–"

Will be added into the next version of the manuscript.

L483: "…for the middle MPF range"

The missing article "the" will be inserted at this point.

L533: Is there a statement regarding the Sentinel-2 MPF dataset?

Indeed, this has been overlooked here and will be included in the next version of the text.