Review of: Buth et al., Characterizing sea ice melt pond fraction and geometry in relation to surface morphology

This study utilizes airborne imagery and altimetry captured on three flights over melting Arctic sea ice. The authors look to identify the link between melt pond fraction and the presence of sea ice ridges but find a complex relationship. The methodology is well described and the discussion topics were well chosen. It is a very interesting paper with a strong analysis. There are many minor comments and revisions for clarity and a few major points that would benefit from further analysis and/or longer discussion. Please find my general and specific comments below.

Thank you for your thorough review of our manuscript. Your comments have helped us improve the study. We are please to read that find it interesting. In the following, we address your comments one by one. Our replies are in blue. Line numbers are always referring to the first submitted version of the manuscript.

General:

The introduction reads like a list of references. It doesn't tell a cohesive story. Although the references included are good sources, I recommend a rewrite to make it flow better. Especially the paragraph starting at line 29- you flip back and forth between first year and multiyear ice and include landfast ice and it is all very confusing.

Thank you for this feedback. We rewrote parts of the introduction and added some links between topics, while taking into account your and the other reviewers' comments.

In particular, we have changed the structure of the paragraph formerly starting in line 29, as suggested. We believe that with the new order, the paragraph is more intuitive and easier to understand. We have added the revised version of the introduction at the end of this document.

The discussion on pond geometry needs some clarification in the methodological description. How are ponds that intersect with image borders handled? What are the minimum and maximum pond sizes that can be observed in the flights at varying altitudes with the range of pixel sizes and images sizes. Perovich et al., 2002 has a good way to determine these values:

Perovich, D. K., Tucker III, W. B., & Ligett, K. A. (2002). Aerial observations of the evolution of ice surface conditions during summer. Journal of Geophysical Research: Oceans, 107(C10), SHE-24.

We agree that this is an important topic to include.

We added the following text to the methods, in section 2.5, now named "Surface classification and geometric considerations", after line 160:

"While the minimum observable pond size is defined by this threshold, the maximum size is limited by the image dimensions. Due to the relatively low flight altitude required for sea ice thickness retrieval, the classified images are small, and larger ponds are increasingly likely to extend beyond image boundaries. As stated by Perovich et al. (2002), the probability that a circular pond with radius R is fully contained within an image of width W and length L is given by:

$$p(R) = \frac{(L-2R)(W-2R)}{LW + 2LR + 2WR + \pi R^2}$$

Using this equation, we estimate that the probability of fully capturing a circular pond with an area of 50 m² —a threshold that will be relevant relevant in our analysis— is about 76% for the Western flight and 74% for the Central and Eastern flights. As pond size increases, this probability decreases, and larger ponds are more likely to be cut off at image edges. As a result, the dataset predominantly captures smaller ponds in full, while larger ones may only appear partially. In such cases, we treat ponds intersecting image borders as if they were whole. Consequently, our observations are inherently biased toward smaller ponds, and this constraint shapes the scope of our analysis, focusing on small to medium-sized melt ponds."

In Section 3.3.1 about the ponds size distribution, we already discuss the introduced bias towards smaller ponds.

We account for the effect on pond circularity in Section 3.3.2, by adding the following text in line 377:
"Additionally, ponds that are only partially captured within an image may appear less geometrically complex than they actually are, as portions of their shape are not visible.
This phenomenon is most evident in larger, more irregular ponds, where the removal of branches or extensions can lead to a reduction in the perceived complexity and in particular on the calculated circularity value. For ponds of smaller, rounded proportions, the impact is negligible. The ponds are already not perfectly circular due to the pixel-based classification process; therefore, an image edge does not significantly alter their shape. The intersection of ponds with image edges thus introduces a bias towards rounder ponds, corresponding to lower circularity values.
Nevertheless, within the context of this study, the same methodology has been consistently employed, and the same limitations apply, allowing for valid comparisons of circularity among ponds within our dataset."

Specific:
Line 6: what do you mean by high melt pond fraction (quantify).

Indeed, it was not clear what we mean by "high" melt pond fraction. What is considered high depends on many aspects, including in our case which flight we are looking at (see Fig. 6a). With the sentence we wanted to express that pond fractions can be as high on ridged ice as they are on smooth ice, we therefore changed the respective sentence to:
"Our results reveal that melt pond fractions on heavily deformed multi-year ice can reach values comparable to those on smooth ice, with similar distributions observed for both."
This should make more clear what we want to emphasize.
We also considered writing an absolute number e.g. "higher than 30%" (see histogram in Fig. R1.1 below), but we think this might be more confusing to the reader, as they might compare it to Figure 6a, where such high numbers are rare due to the used resampling method.

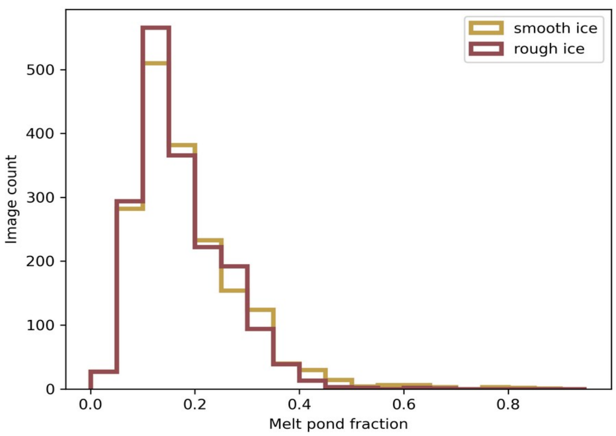


Figure R1.1: Histogram of melt pond fraction per image for smooth and rough ice, as defined in Section 2.7 of the manuscript, before resampling and including data from all three flights. (Figure not included in manuscript)

Line 29: how do snow dunes affect pond formation- mentioned but not explained

We rewrote this part to better explain how meltwater collects in low-lying areas between the elevated features such as snow dunes. See attached revised introduction for details.

Line 33: for the Eicken et al reference- how does the topography influence pond formation?

Thank you for the question. We wanted to mention the influence of previous melt seasons here, with some melt ponds reappearing at the same location as in the previous summer. Your comment made us realize that we accidentally referenced a different Eicken paper, it should be Eicken et al. (2001). We corrected this and added two more references that fit the topic. For details see revised introduction.

Line 34: Doesn't the presence of ridges on multiyear ice limit the spread of pond water as well? This is a confusing sentence

Yes, it limits the spread, but this does not necessarily mean that it limits pond fraction as well. In the cited study, this difference between FYI and MYI is mentioned. We believe that this aspect is now better presented in the revised introduction.

Line 40: which parameterizations in which models is this study referring to? This is a very broad statement.

We now explicitly mention these specifications when citing the study. See attached introduction for details.

Figure 1 caption: can you describe the source of the drift trajectories and indicate the way that they are marked (semi transparent dot marked every day?) And does the color correspond to the days since continuous melt onset at the date of the flight or does it change over the course of the drift trajectory? Potentially interesting information, but needs to be described better in the caption.

Thank you for pointing this out. The NASA Arctic Sea Ice Melt product provides the first day of continuous melt as a "day of year" value on a grid. Thus we cannot use it to determine the exact number of continuous melt days that a drifting region has experienced along its path. For this reason, we calculated the average number of days along the shown summer drift path. The

color represents this average value with respect to the day of the survey; therefore, it is constant within each trajectory. The approach to derive this value is also described in Section 2.9. We changed the figure caption to the following:
"Map showing the flight tracks (circles) of the Western (W), Central (C), and Eastern (E) flights, along with the satellite-derived ice drift trajectories for the 70 days prior to each survey (Krumpen et al., 2018). Trajectories are shown as semi-transparent dots, with one dot per day. Flight tracks and the corresponding drift paths are color-coded by the average number of continuous melt days along each trajectory until the survey time, based on the NASA Arctic Sea Ice Melt product of the respective year (2018 for W, 2016 for C and E)."

Table 1: does typical mean average or median or what?

Thanks for catching this! We indeed mean "mean image size" and "mean ground sample distance". We corrected it in both instances.

Table 1: What does ground sample distance mean? It is not described in the text.

We added a short explanation to the paragraph starting in line 64 of the original manuscript. The paragraph now reads:
"Altitude variations during the measurements were minimal, mostly within 2.5\,m, with maximum variations of about 5\,m. These differences in altitude, together with the fixed camera specifications, affect the ground sample distance (GSD), defined as the distance between adjacent pixel centers on the ground, which in turn determines the surface area covered by each image. As a result, the surface area per image varies slightly throughout and, more noticeably, between the flights."

Figure 2: Can you use a different color for the cable lines in a/d/g and the altimeter measurements in b/e/h?

Done.

Line 88: what is a typical RGB sum that corresponds to the surface type? Can you give an average?

Thank you for raising this point as indeed this was a bit unclear in the previous version of the manuscript. As the modal RGB sum is varying along track, there is no typical or expected value for the snow/ice class. Reviewer #2 had a similar comment. To account for both we included the following text in the Section 2.2, in line 88 of the previous manuscript:

"However, the RGB sum of each surface type varies significantly along each flight, depending on the prevailing brightness conditions. For instance, values for snow and ice during the Western flight range from below 20000 to over 50000 (see Fig. 3). Given this variability, there is a need for a relative rather than a fixed reference. That is why the following approach does not rely on a single expected brightness value for snow or ice, but instead dynamically adapts to observed conditions and thereby ensures consistent correction across a broad spectrum of light conditions."

Line 100-102: I think this text is more valuable as a figure caption and does not need to be in the main text

Indeed, we already describe this in the figure caption and don't need to do so again in the main text. As suggested, we now omit the figure description in (formerly) line 100 and only leave the sentence "Figure 3 illustrates the process of assigning brightness values and categories to each image."

Line 108: histogramm → histogram

Changed to "histogram"

Figure 3: this figure is a little blurry- I recommend increasing the dpi. The smoothed & filtered dots look more like a line, so I would just call them that in the figure caption

We increased the dpi to 600 and changed "circles" to "line".

Line 146-150: Can you provide a few more details on how the time offset for the camera is refined based on the altimetry?

Sure! The paragraph now reads:

"To address this issue, a two-step approach is employed. Initially, the data are matched with 1-second precision. Then, using surface profiles from the laser altimeter, the time offset for the camera is refined manually for each flight. This is done by visually identifying and matching distinctive features, such as pressure ridges and smooth ice areas, that appear in both the altimeter data and the images. By comparing the spatial alignment of multiple such features, a spatial offset is determined, which can be converted to a temporal offset. The georeferencing algorithm is then rerun using this refined time offset to improve the spatial accuracy. The results are verified by re-examining multiple locations along each flight track."

Line 152: I believe the references after e.g. should be listed in chronological order but check the style guide.

Done.

Line 160: can you remind the reader how many pixels 0.1 m^2 is?

We rephrased the sentences to the following:

"Following the classification process, neighboring pixels of the same class are combined into objects. To reduce noise, objects smaller than 100 pixels, here corresponding to an area of approximately $0.1 m^2$, are filtered out, as applied by Huang et al. (2016) and Fuchs et al. (2024). This process ensures that the classification results are robust and relevant to the scale of our analysis."

Line 244: fewer → less

Changed to "less melt"

Line 246: are the dark/light ponds identified in the classification algorithm or is this a visual qualitative assessment? If included in the algorithm- can you provide numbers?

Thank you for this question, we agree that we should have mentioned this in the text. We are here referring to a visual qualitative assessment. The subclasses "bright pond" and "dark pond"

exist in the classification algorithm (Fuchs 2023a), but we have not checked their performance in combination with the new adapted brightness correction and this dataset, nor do we use these subclasses in the later analysis. For other uses cases, it could certainly be insightful to make use of these and other available subclasses.
We added "Based on visual qualitative assessment of the images, …" to the sentence.

Figure 4: somewhere in the text can you describe why you think the observed SIC from images is so different from the OSISAF SIC?

Thank you very much for this question, it made us recalculate the SIC from the airborne imagery. Upon recalculation we realized that we had made a mistake: Instead of the sea ice concentration, we were showing the fraction of area classified as snow/ice over the total image area, not taking into account that the "pond" areas need to be included here as well. Naturally, this led to SIC values that are too low. The correct way to calculate SIC per image from the classification results is:

$SIC = (a_{ice} + a_{pond}) / a_{total}$

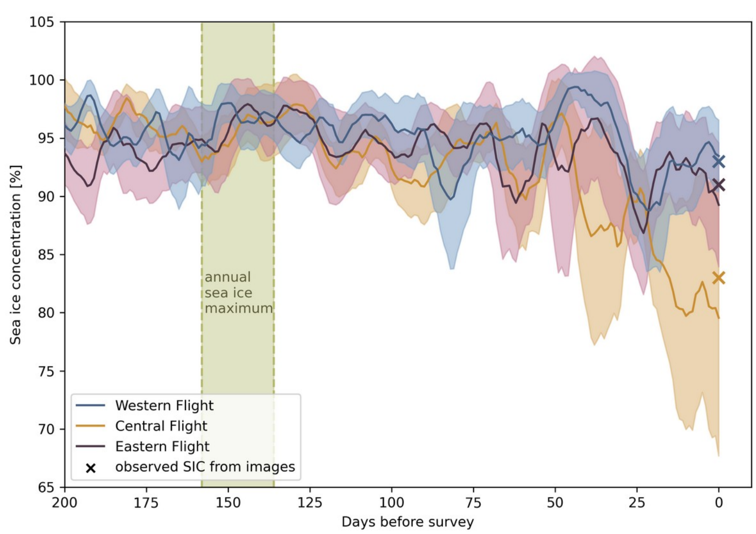
or even $SIC = 1 - (a_{ow} / a_{total})$

, with $a_{total} = a_{ice} + a_{pond} + a_{ow}$

, where a_{ice} , a_{pond} and a_{ow} denote the areas of the image covered by snow/ice, pond/submerged ice and open water, respectively.

With the correct approach, we obtain the following new mean SIC values per flight:
Western flight: 0.93
Central flight: 0.83
Eastern flight: 0.91

We have updated all instances of the SIC values in the table, the main text and Figure 4. The corrected SIC values are much closer to the mean OSI SAF values now, and all fall within their standard deviation.



Please note that we have also changed the order in which the flights appear in the legend to make it consistent with the order typically used throughout the manuscript.

Line 278: can you clarify? I think you mean that for the Western flight there is less time between the flight date and the melt onset date and that is why it is lower MPF?

Indeed, this was not phrased ideally. We intended to say that this "less time" certainly plays a role, but in particular we wanted to emphasize that it is not the only factor determining melt pond fraction. To clarify, we rephrased it as follows:

"In comparison, the melt pond fraction observed during the Western flight is lower, with an average of 0.13. This flight was conducted in a region where the melt onset occurred later and closer in time to the survey date, reducing the time available for pond formation and evolution before the overflight. However, the melt onset date alone does not determine the pond fraction at any given time. While it provides context for the visual differences in ponding during the three flights, additional factors influence pond development. Throughout the four stages of melt defined by Eicken et al. (2002), melt pond coverage evolves continuously with periods of expansion, drainage, and potential refreezing. The observed melt pond fractions in our data reflect this complex temporal variability of ponds."

Line 330: Snow depth and distribution is also a factor in melt pond distribution. It would be worth mentioning if not including a full discussion.

We agree to this point, but can not distinguish between different surface types from laser altimetry. To make this clear, we chose to add some sentences to the methods and discussion sections.

In the Methods, Section 2.6, after line 173, we include the following:

"Such features may be composed of ice and/or accumulated snow; however, we refer to them as ridges throughout this study, as pressure ridges are the dominant elevated features on the sea ice during these summer surveys."

We now also mention this again in the Discussion, Section 3.4, after line 432:

"Additionally, our ridge detection method does not allow us to distinguish between snow and ice in the detected surface features. As a result, elevated structures identified from the laser altimeter are referred to as ridges throughout this study, although they may in some cases include contributions from snow accumulation. This limitation should be kept in mind, as snow depth and distribution can influence early meltwater pooling and thereby the location and development of melt ponds."

Line 370: for the circularity and general pond size distribution analysis, how do you handle the ponds that are on the edges of images? Are they eliminated from the analysis (via border intersection clearing)?

See above.

Figure 8. It would be useful to plot a common shape (circle) on the pond perimeter v pond size chart? Or note what it would look like (a straight line?)

Thank you for the suggestion. We have added the line showing the perimeter-to-area of a circle to Figure 8b.

Figure 8c. I don't understand what conceptualized and simplified visualization means? Is this just what you expected? Why? Explain in the text. The text currently does not clarify what this is.

We agree that this was not sufficiently explained in the previous version of the manuscript, and that the word "simplified" and the arrowhead in the figure were misleading in this context. Our approach was to split up the rather complex Figure 8a into different conceptual figures (panels b, c and d) that each show one of the aspects we explain in the points 1 to 3 in the text. We now write this explicitly when introducing Figure 8:

"To better understand the influence of ridges on pond shapes and to clarify the observed differences among the various flights, we present Figure 8. Panel a shows the distribution of melt pond areas and perimeters for every individual pond on a binned grid. Several key trends emerge from this figure, each represented by one subsequent panel of this figure: …"

Out of these panels, panel c is meant to visualize the background trend, or in a way the "lower frequency mode" of Figure 8a, so the relationship of ridge fraction observed for ponds with both increasing size and perimeter. (Panel d could be interpreted as the "higher frequency mode".) We changed the caption of panel c to:

"Conceptualized illustration of the general trend of decreasing ridge fraction with increasing pond size and perimeter, as seen in panel a."

In the main text, we changed it to:

"2. A clear second trend is evident in Figure 8a and conceptually visualized in Figure 8c, which illustrates the background mode of the dependency between pond geometry and surface roughness: As both pond area and perimeter increase, the ponds tend to appear on ice with, on average, lower ridge fractions. "

Line 387: the description of the figure should be contained within the figure caption.

Agreed. As this information is already included in the figure caption, we simply removed these sentences (lines 387-389) from the main text.

Line 405: this paragraph (point 3) is confusing. You say high perimeter to area ratio ponds form on more ridged ice across pond sizes. Then later say that this trend is reversed for large ponds and that when the perimeter to area ratio is high, it is on smooth ice. So the statement "broad range of pond sizes" needs to be clarified.

We agree that this wording was not precise enough. We now add a specification:

"… across a broad range of pond sizes, from the smallest detected ponds up to about 10^2 m^2.$"

Line 408: Confusing comment about the fractal dimension- can you please clarify? Did you calculate the fractal dimension? With what metric? IF you are referring to another paper's finding please cite here.

Thanks for pointing out this missing information. We did not calculate the fractal dimension, instead we are referring to other studies and the shift in trend in Fig. 8b. To make this clear, we now write:

"The transition between these behaviors appears to occur at the same scale as the shift in fractal dimension reported in previous studies (e.g., Hohenegger et al., 2012), which is also reflected in the bend of our data shown in Figure 8b, though larger images (i.e. higher flight altitudes) would be required to fully capture this effect."

Revised version of the introduction:

Melt ponds are pools of meltwater that form on sea ice during the summer as a result of snow and ice melt. They are a critical component of the Arctic marine environment during the melt season as they substantially influence the energy and mass balance of sea ice. Melt ponds have a markedly lower albedo than the surrounding sea ice and snow surface (Perovich et al., 2002a). This contrast contributes to the ice-albedo feedback, a positive feedback mechanism in which the reduced surface albedo of melt ponds increases the absorption of solar radiation. This enhanced energy input accelerates surface melting, further reducing the albedo and reinforcing the feedback (Perovich and Tucker, 1997; Fetterer and Untersteiner, 1998). The increased energy absorption caused by melt ponds not only accelerates surface melting but also contributes to sea ice thinning (Popović and Abbot, 2017). During winter, their influence continues as refrozen ponds inhibit sea ice growth by forming an insulating ice lid. The pond water beneath this lid retains latent heat, which slows ice formation at the base of the underlying sea ice until the pond fully refreezes (Flocco et al., 2015). Beyond their impact on the physical properties of sea ice, melt ponds also play a role in the Arctic ecosystem by increasing light transmittance through the ice, which supports primary productivity (Frey et al., 2011; Nicolaus et al., 2012; Arrigo et al., 2012).

The timing and onset of pond formation depend on environmental conditions that trigger and sustain melting. Synoptic weather events transporting warm, moist air into the Arctic play a critical role in initiating pond formation by enhancing sensible and latent heat fluxes, which drive snow and ice melt (Skyllingstad and Polashenski, 2018). The formation of ponds is then regulated by the availability of meltwater and the permeability of the ice (Eicken et al., 2002).

The location of initial pond formation is determined by pre-melt surface height, especially by the presence of snow dunes. These represent elevated features on the sea ice surface, and as snow and ice begin to melt, meltwater preferentially accumulates in the lower-elevation areas between them. These local depressions control the initial distribution of meltwater and thus determine the spatial pattern of early pond formation (Barber and Yackel, 1999; Polashenski et al., 2012; Petrich et al., 2012). Similarly, sea ice pressure ridges constrain the lateral spread of meltwater. Rather than being driven by larger-scale topography, pond formation is primarily governed by such small-scale surface roughness features (Landy et al., 2014). The detailed relationship between ice surface morphology and melt ponds differs across ice regimes, and most studies focus on one ice type only. On first-year ice, the presence of pressure ridges has been shown to limit pond coverage (Nasonova et al., 2017). Consistently, Landy et al. (2014) observed a higher peak pond coverage on smooth landfast first-year ice compared to the previous year when the surface was rougher. On multi-year ice, however, Nasonova et al. (2017) found no strong correlation between surface roughness and the melt pond fraction. Still, topography influences pond formation on multi-year ice as well. Inherited topography from previous melt seasons influences pond formation, with some melt ponds reappearing in the same locations as in the previous year (Eicken et al., 2001). These low-lying areas often coincide with thinner ice, and their locations can be predicted from winter surface temperature anomalies and pre-melt elevation data (Thielke et al., 2023; Fuchs et al., 2025).

Melt ponds play a critical role in sea ice evolution, yet their representation in sea ice models remains challenging. If ponds are not included, ice thickness and volume can be overestimated, with simulations showing up to 40% higher sea ice volume at the September minimum compared to models that incorporate a melt pond scheme (Flocco et al., 2012). However, current parameterizations, such as the level-ice melt pond scheme in Version 2 of the Community Earth

System Model (CESM2) and the melt pond distribution conservation equation in the Marginal Ice Zone Modeling and Assimilation System (MIZMAS), tend to overestimate pond fraction compared to observations (Webster et al., 2022). Since individual melt ponds are subgrid-scale features, they cannot be explicitly resolved in large-scale models. At the same time, the sensitivity of model results to the melt pond parameterization is very high (Driscoll et al., 2023), highlighting the need for better process understanding to improve their representation.

As the frequency of pressure ridges has decreased on Arctic sea ice, the relationship between melt ponds and ridges and its implication for the albedo feedback and under-ice solar partitioning become subjects of increasing interest (Krumpen et al., 2025; Landy et al., 2015; Katlein et al., 2016; Horvat et al., 2020).

The objective of this study is to examine how the presence of ridges influences melt pond characteristics, utilizing high-resolution airborne data collected during Arctic field campaigns over sea ice, covering a variety of different ice types and deformation grades during the melt season. By analyzing simultaneous camera imagery and laser altimeter measurements, we quantify melt pond fraction, size distribution, and shape complexity across different ridge conditions. These observations provide a detailed assessment of the relationship between ridges and melt pond properties, based on a large-scale dataset, thereby establishing a foundation for refining representations of melt ponds in sea ice and climate models.

New references:

Eicken, H., Tucker, W. B., and Perovich, D. K.: Indirect measurements of the mass balance of summer Arctic sea ice with an electromagnetic induction technique, Annals of Glaciology, 33, 194–200, https://doi.org/10.3189/172756401781818356, 2001.

Fuchs, N., Birnbaum, G., Neckel, N., Kagel, T., Webster, M., and Wernecke, A.: Predicting Melt Pond Coverage on Arctic Sea Ice From Pre-Melt Surface Topography, Geophysical Research Letters, 52, https://doi.org/10.1029/2025gl115033, 2025.

Thielke, L., Fuchs, N., Spreen, G., Tremblay, B., Birnbaum, G., Huntemann, M., Hutter, N., Itkin, P., Jutila, A., and Webster, M. A.: Preconditioning of Summer Melt Ponds From Winter Sea Ice Surface Temperature, Geophysical Research Letters, 50, https://doi.org/10.1029/2022gl101493, 2023.