General comments

This manuscript describes the use of observations of sea ice and melt features and examines the relationships between the presence of melt ponds, ice type, ridging and age.

This manuscript addresses a critical and persistently under-quantified component of Arctic sea ice evolution: the relationship between surface morphology, e.g. ridge fraction, ice age, and the geometric characteristics of melt ponds. The authors use a combination of high-resolution optical imagery and coincident airborne altimetry to assess melt pond distribution and shape across a 70 km^2 section of ice north of Greenland. The paper's structure is clear and the results are well exposed and supported by the data analyzed.

I recommend the publication of this paper provided that the authors address a few points.

> Thank you for your thorough review of our manuscript. Your comments have helped us improve the study. We are please to read that you support its publication. 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.

Specific comments

The introductions contains all the right concepts, but it is often presented in a very fragmented way with very short phrases and paragraphs not properly linked to each other. The authors could improve it by grouping some of the very short phrases (e.g. lines 20-25), and making the links between the concept presented more explicit.

> 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. We have added the revised version of the introduction at the end of this document.

The methodology (between paragraphs 2.3-2.6), could be moved to an appendix and more details could be added. A much shortened version describing it could be added in the main manuscript.

> You bring up a valid point! We recognize that the Methods section takes up a lot of space in the manuscript. Before submitting the initial manuscript, we thoroughly thought about moving (parts of) the Methods to the Appendix, but we decided to include them in the main part of the manuscript because almost all of the subsections include new methodology and, in our opinion, are thus worth being incorporated into the main part. Upon your and the editor's approval, we would prefer to keep the structure as it is.

In particular, it would be nice to read about the choice of algorithm: here you use Fuchs (2023a). I am not questioning your choice, but considering that several other algorithm used for sea ice, I believe that the reasoning behind this choice should be more explicit.

We completely agree that our reasoning for the choice of algorithm was missing. We now start Section 2.5 as follows:

"For the semantic classification of the images into sea-ice surface types, we use the pixel-based classification algorithm by Fuchs (2023a), which uses a random forest classifier. It was particularly developed for the applied camera systems and allows for classification of aerial images collected under clear- and overcast skies. To ensure compatibility with our dataset after the modified brightness correction (see Section \ref{sec:brightness}), we expanded the original training dataset with pixels sampled from our images and retrained the model. While a variety of sea ice surface classification for airborne images is available (e.g. Buckley et al., 2020; Wright and Polashenski, 2018), we selected this algorithm due to its tailored design for the imaging system used in our campaigns. It provides …"

Another study (Buckley et al., 2020), uses pixel classification and seems to have less limitations when sea ice concentration is low.

Please note that low sea ice concentration in individual images is no problem at all. It can become a problem for the semi-automatic image brightness correction (Section 2.2), but only if the low sea ice concentration persists throughout large parts of the flight. The classification algorithm itself is not affected by the sea ice concentration. See also the next comment for more details effect of sea ice concentration on the brightness correction.

In case you a referring to problems related to submerged ice: As mentioned in Section 3.2.3, a low sea ice concentration often introduces more brash and submerged ice. By its nature, a pixel-based approach on its own can not distinguish between submerged ice and a melt pond. This can introduce misclassification, in our case this is only a small fraction of the total melt pond class. Both Fuchs (2023a) and Buckley et al. (2020) report on misclassification due to submerged ice.

My main concern is about the amount of data analysed: It would be nice to have a feel of the total number of images acquired and how many were used: how many images were discarded because of too low SIC for example? What is the threshold assumed to discard an image (it could be more explicit I line 92-93).

Thank you for bringing this up. We realize that our wording is not precise enough, as it might sound like we can not use images with low SIC at all. As a matter of fact, all 5467 images mentioned in Table 1 are used for subsequent melt pond analysis, just not all of them contribute to the brightness assessment (see Figure 3). We changed the text to the following:

"Images dominated by open water or melt ponds are filtered out from the brightness assessment step, as explained below. These images are not discarded but are assigned a brightness value interpolated from neighboring images and are fully retained for all subsequent processing steps. It should be noted that this brightness correction method is not well suited for regions with many such images, such as the marginal ice zone (MIZ) with low sea ice concentration. "

A more thorough description of the whole campaign would be useful (there is a map in figure A1, but there is no time described).

Thank you for raising this point, as indeed the timing of the survey flights is only mentioned in Table 1. For a better overview, we included the dates (along with the names we gave to the flights) in the campaign description in Section 2.1. Figure A1 shows the same flight tracks as Figure 1 but with the entire drift trajectories to show the source areas of the investigated sea ice including its age. This is mentioned in the first sentence of Section 3.1. We now added the information that it also shows sea ice age of the surveyed ice, to avoid confusion with Figure 1.

In line 113 you mention that there is no need to find references for the brightness temperature more than once per flight. Is this due to the length of the flight, to the weather (see also line 79).

Our wording was not ideal here. We are referring to the method itself, which makes sure that reference areas from images across the whole brightness spectrum are being used. We write this more explicitly now. We also changed the phrasing to make more clear that this means finding reference areas for a total of 10 images per flight. We now write:

"The described method ensures that the selected images used for calibration span the full range of brightness conditions encountered during a flight. As each image is assigned to one of 10 brightness categories, we determined that it is sufficient to identify reference areas in just one representative image per category, resulting in a total of 10 images assessed per flight.

This revised approach significantly reduced the manual labor involved in analyzing optical imagery from long flights over Arctic sea ice, relying solely on the images themselves."

In paragraph 3.4, Could you please add a comment on the reliability of the statistics: the area covered by the three flights (70km2), is not huge. Could you make a comment on how representative your conclusions are? When devising a new melt pond parameterization this would be an important information to consider.

We agree that we should include more information about this. We added the following paragraph to Section 3.4, after line 440:

While the total surveyed area of ~70 km^2 may seem limited, the dataset spans a broad geographic range and includes diverse ice conditions. The 5467 analyzed images are non-overlapping and spaced at mostly regular intervals along the flight tracks, thereby keeping the observations statistically independent. Over 1.2 million individual ponds were identified in total, including 268,511 ponds larger than 1 m^2. These provide a strong statistical foundation, particularly for small- to medium-sized ponds, which are the focus of this study. This extensive, varied dataset allows for a robust evaluation of the relationship between melt pond geometry and the presence of pressure ridges, and, to our knowledge, represents the first observational study capable of directly linking these two features at high resolution, while covering such a wide geographic range.

Technical corrections

Line 4: "coincided laser altimeter data": correct to "coincident laser altimeter data"

Changed to "coincident".

Line 44-46: too many interruptions for refs: please move them to the end of the phrase if the journal allows it.

Done.

Caption - figure 2: "examplary images": correct to "example of images". Also in line 480.

Done.

The pink circles in this figure are either too big, too close or too many: they look like a line.

The individual measurements are so close together that they can be difficult to distinguish. We now use short horizontal lines, a compromise between making sure the markers are big enough to be seen at all and thin enough to be seen individually.

Line 68 – 70: subsections 2.2 on brightness correction and 2.3 on the removal of the tow cable introduce novel approaches and are therefore described in detail. Pls review punctuation for clarity.

Done.

Line 84: " by determining the modal value of the sum of the R, G, and B channel rightness per image (modal RGB sum), as..': in the first part of the phrase pls write in full Red, Green and Blue.

Done.

Line 100: "...along each flight track" (if multiple are referred to) rather than "Along the flight track".

We agree that this wording might have caused confusion. As suggested by Reviewer #1, we omit the description of the figure at this location in the main text, as this kind of description belongs in the figure caption. The sentence you are referring to is thus not included in the manuscript any more. In the figure caption we explicitly state that these are the images along the Western flight track.

Line 102: what is an expected modal RGB sum value?

> 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 #1 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 20,000 to over 50,000 (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 107: "histogramm stretch approach": correct to "histogram stretch approach"

> Changed to "histogram".

Line 126: First rather than firstly

> Changed to "First"

Line 146: the camera timestamps are precise only to 1 second": pls consider rephrasing to "…are only precise to one second".

> Changed to "… are only precise to one second"

Line 188 and following: Could you please explain the 3.9% and 17.5% more clearly? Why these numbers?

> Thank you for pointing this out. These values correspond to the quantiles mentioned in the sentence before. We added a sentence after the one mentioning the threshold values to make this more clear. The paragraph now reads:
>
> "In other cases, the classified images were grouped into three ridge fraction categories: low, medium, and high, based on quantiles of the observed ridge fraction distribution across all images. This means the lowest third of the distribution, comprising ridge fractions below 3.9%, is categorized as "smooth ice", while the highest third, comprising ridge fractions above 17.5%, is categorized as "rough ice". Specifically, these thresholds represent the 33rd and 67th percentiles of the observed ridge fraction range, respectively."

Line 235: the colon is probably not appropriate. Pls also consider to have three subsections for the three chosen flights.

> We replaced the colon by a period, but decided to keep the three flights in one subsection, in order to keep the flow of the text.

Line 244: fewer?

Changed to “less melt”

Line 338: Perhaps the ref to Horvat 2020 should come to the end of this phrase, since their study is based on the hypothesis that the distribution of pond is of fundamental importance for the distribution of light and energy under the ice.

Thanks for spotting this. We moved the reference to the end of the next sentence, as suggested.

Line 123, 374 and 419: Capitals after colons in a few instances. Please correct throughout

We agree that it is common to start with a lowercase letter after a colon in British English. However, for other ambiguous spellings, we opted for American English, where, in our understanding, it seems to be common to start with an uppercase letter if the colon is followed by a complete sentence. To stay consistent throughout the manuscript, we use an uppercase letter here. We are happy to change this upon request according to editorial guidelines.

Others:

"preflight" and "postflight" not consistently hyphenated: pls correct in a uniform way of choice.

We assume you are referring to “pre-melt”. We have made sure that it is spelled consistently throughout the manuscript.

"behaviour" vs. "behavior”: please ensure consistency throughout.

Changed to “behavior” in all instances throughout the manuscript

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.