Point-to-Point response to Reviewer #1

We thank the Reviewer for the thorough, constructive, and insightful comments, which have significantly improved the quality of the manuscript. We largely agree with the points raised and have addressed them in the revised version of the manuscript. Below, we provide a detailed point-by-point response to each comment and describe the corresponding revisions made.

Kind regards,

Niklas Neckel

General comments

***General comment 1**: The validation of the method to retrieve freeboard, ice thickness and pond depth is limited to very few cases. A discussion on the limits of this validation would greatly improve the understanding of the usability of the methodology. Moreover, a first quantitative estimation of the retrieval uncertainty based on the case studies discussed in the paper is missing.*
Reply: we thank the reviewer for this valuable comment and for the interest in the geophysical data products. We deliberately kept the sections concise so that they serve as illustrative test cases rather than a comprehensive accuracy assessment, which would be beyond the scope of this manuscript. Nevertheless, following the reviewer's suggestion, we have expanded the discussion of the limitations of the presented validation in the revised manuscript.

***General comment 2**: I interpret that Table 2 summarizes the uncertainty on the horizontal and vertical position of the GCPs, but this is not clearly presented and explained (see the detailed comments below). Also, what are the implications of this uncertainty on the retrieved DEMs and sea ice parameters?*
Reply: we thank the reviewer for identifying this lack of clarity. We have completely revised the caption and the corresponding text referring to Table 2. We also refer the reviewer to our responses to the detailed comments below, where these revisions are discussed in more detail. In addition, we have expanded the discussion of how these uncertainties propagate into the derived DEMs and the retrieved sea ice parameters.

***General comment 3**: The used language is not always clear, and often commas are missing in the text. In the detailed comments listed below I pointed out some cases as examples, but my list is not exhaustive, and the authors are invited to carefully check each single sentence of the manuscript (nowadays many tools exist to assist in that).*
Reply: we carefully revised the language throughout the manuscript, including but not limited to the examples highlighted in the detailed comments. We also corrected punctuation and improved the sentence structure and clarity throughout the revised version of the manuscript.

Specific comments

***Line 17**: comma is missing after "trivial"*
Reply: done.

***Line 59**: "along track and across track respectively results..." should be "along and across track, respectively, results..."*
Reply: the corresponding sentence was changed accordingly in the revised version of the manuscript.

***Line 63**: comma is missing after "ocean currents"*
Reply: done.

***Line 64**: comma is missing after "for this"*
Reply: comma was added in the revised version of the manuscript.

***Line 65**: comma is missing after "Otherwise" and after "guaranteed".*
Reply: done.

***Line 66**: remove "single"*
Reply: removed.

***Line 67**: comma is missing after "prior to the flight"*
Reply: done.

***Line 68**: "pseudo Lagrangian grid mission": I think that calling the grid "Lagrangian" or "pseudo Lagrangian" is not appropriate. A Lagrangian perspective would follow the motion of a target in time, while here the time dimension is absent. Although the photos of the orthomosaic are captured at different times, they do not include any temporal variability of the targeted ice surface, the whole orthomosaic represents a snapshot of the*

ice condition at a single time. Accounting for the ice drift in the flight pattern (Fig 2a) does not make the pattern "Lagrangian", and removing the drift (Fig 2b) does not make the pattern "Eulerian". A time dimension would be needed to invoke the "Lagrangian" or Eulerian" flows.
Reply: we thank the reviewer for this comment and agree that the term "Lagrangian" may be misleading in this context. Our intention was not to describe the orthomosaic as a Lagrangian product, as it indeed represents a snapshot of the ice surface, but rather to indicate that the flight plan was adjusted to account for sea-ice motion during image acquisition. The objective of this drift correction was to keep the survey grid approximately fixed relative to the ice surface while the UAV was flying, thereby maintaining the intended survey coverage and minimizing data voids in the final orthomosaic. To avoid confusion, we have removed the terms "Lagrangian" and "pseudo-Lagrangian" throughout the manuscript and replaced them with the term "ice-fixed". We have also clarified that the flight pattern was translated according to the estimated sea-ice drift during image acquisition.

***Fig. 2 caption**: comma is missing after "mission planning" and "post-processing". The comma after (a) should become a full stop, the bracket after "arrows" should be removed, and a bracket before b) should be added. The last sentence is a bit too cryptic and hard to read: to make it clearer, I would replace "GNSS drift estimates" with "the ice drifts estimated from GNSS sensors", and I would avoid introducing the concept of "Eulerian coordinate system", which sounds ambiguous in this context (see comment above). Instead, I would precisely explain what you did, i.e. you translated the image locations to the positions in which the photographed ice was at fixed reference times.*
Reply: we agree to this point and changed the corresponding caption to: *"Scheme of pre- and post-flight drift correction of UAV camera grid flights. The ice drift (black arrow) is measured prior to the flight and is included in the mission planing, resulting in an ice-fixed grid mission **(a)**. Time is indicated by the color gradient and flight direction of the UAV by blue arrows. During post-processing, GNSS-based drift estimates are used to transform image locations to a common reference time and their corresponding geographic positions **(b)**."* in the revised version of the manuscript.

***Line 73**: comma is missing after "Before takeoff"*
Reply: done.

***Line 79**: comma is missing after "quality check"*
Reply: done.

***Line 81**: comma is missing after "flight routine" and after "For this". Add "-" in "drift-corrected".*
Reply: changed as suggested.

***Line 82**: replace "exif metadata" with "EXIF (Exchangeable Image File Format) metadata"*
Reply: we agree to this point and included: *"Exchangeable Image File Format (EXIF)"* in the revised version of the manuscript.

***Line 87**: throughout the whole paper, please add "-" between "drift" and "corrected"*
Reply: we agree to this point and included "-" btween "drift" and "corrected" throughout the revised version of the manuscript.

***Line 88**: "GNSS solutions" us unnecessarily vague: do you mean "Additionally, the GNSS solutions from our drifting reference stations at the reference times listed in Table 1 were imported into the software and were used as GCPs during the processing", To me, this sentence seems quite tortuous. To simplify it and improve clarity, I suggest to rephrase to something like "as well as the GNSS-base GCPs at the reference times listed in Table 1" and replace the full stop of the previous sentence with a comma. In fact, in Sect 2.1 you already explained that the GNSS stations were used as GCPs.*
Reply: we agree to this point and changed the corresponding sentence accordingly in the revised version of the manuscript.

***Line 90**: add a comma after "images"*
Reply: done.

***Line 92**: to improve the language, I would replace "now aided by the more precise GNSS reference solutions." with "using the GCPs".*
Reply: changed as suggested.

***Line 93**: add a comma adter "DEMs"*
Reply: done.

***Line 94**: please replace "next" with "successive" and add commas after "step" and after "generated".*
Reply: changed as suggested.

***Line 95**: add a comma after "DEM"*
Reply: done.

***Line 96**: To improve clarity, I would replace "we applied an additional fit to the data to adjust with sea level" with "we applied an additional fit to detrend the data" It would be good to add here some reference to previous*

work where this detrending fit was applied to DEMs.
Reply: we agree to this point and changed the corresponding sentence as suggested. We now cite Landy et al. (2015) and Drews et al. (2009) in the revised version of the manuscript.

***Line 97**: add a comma after "step".*
Reply: done.

***Line 107**: replace "the pond level" with "the height of the pond". Please use past tense instead of present tense in the last three lines of Sect 2.2.3.*
Reply: changed accordingly in the revised version of the manuscript.

***Line 108**: "we derive pond depth in a two-media photogrammetry approach": could you please add a brief explanation of the applied approach, so that the reader does not need to read Fuchs et al. (2024) to understand the method? That should also clarify what the "brightness correction" mentioned in Fig 3a refers to.*
Reply: many thanks for the in-depth interest in the method. We have added a short description of the brightness correction method to the text: *"We first corrected the brightness of the RGB orthomosaic (Fig. 3a) using an empirical line approach between manually determined points"* and extended the pond depth retrieval paragraph by: *"In this process, deviations caused by refraction are suppressed in the reconstruction to such an extent that it is ultimately sufficient to multiply the water depth at each pond pixel by the refractive index between air and water."*

***Line 118**: replace "a nearby" with "the" (the mobile RTK station was described in the section above so it is not a generic device). Please use past tense in the sentence.*
Reply: changed as suggested.

***Line 120**: please explain what "LAS" stands for.*
Reply: we agree to this point and changed the corresponding sentence to: *'LiDAR data were successfully acquired at ice stations ICE05, ICE07, and ICE09 and exported from the DJI Terra software in LAS (LASer) point cloud format, a standard file format for storing LiDAR point cloud data.'* in the revised version of the manuscript.

***Line 125**: add a comma after "DEMs".*
Reply: done.

***Line 126**: please replace "DEMs" with "LiDAR-based DEMs" to make clearer the distinction between the two DEMs*
Reply: changed as suggested.

***Line 128**: add a comma after "Arcwatch-2"*
Reply: done.

***Line 134-135**: "In the next step both datasets were resampled onto a common, equidistant track at 1.5 m point spacing so that each point contains both snow and ice-thickness information". This sentence is not very clear: did you mean "both datasets were resampled onto a common track of equidistant measurement points having 1.5 m spacing, so that ..." Please also remove "In the next step" and use past tense instead of present tense.*
Reply: we agree to this point and changed the corresponding sentence to: *'Both datasets were resampled onto a common track of equidistant measurement points having 1.5 m spacing, so that each point contained both snow and ice-thickness information (Kolar et al., 2025).'* in the revised version of the manuscript.

***Line 136-138**: "The clearly visible footpaths in the corresponding orthomosaics allowed for additional horizontal corrections by aligning the equidistant track files to these features." Also this sentence is not clear: do you mean that you used the GEM tracks as reference distance in the processing of the UAV photos to generate orthomosaics and DEMs? Did you align files or the data points that belonged to the GEM track and that were visible in the UAV photos? Please rewrite the sentence to clarify it.*
Reply: thank you for raising this point. We agree that the original wording was unclear. The GEM GPS data were not used during the generation of the orthomosaics and DEMs. Instead, the GEM and Magnaprobe track data were manually translated by a small horizontal offset after processing, using clearly visible footpaths in the orthomosaics as reference features to improve the spatial alignment between the ground-based measurements and the UAV-derived products. The corresponding sentence was changed accordingly in the revised version of the manuscript.

***Line 139-144**: This paragraph does not belong to this section. It should be moved to the Results section, merging it with the sentence in line 159-160. Please explain the sentence: "For this we converted the ellipsoidal DEM elevations into freeboard estimates employing the in situ freeboard measurements conducted at each GNSS station." How did you use the in situ freeboard measurements? Did you use them as vertical reference distances in the processing of the UAV photos to generate the DEMs? If so, please state it explicitly. What is the estimated uncertainty of the freeboard derived from DEMs in places far away from the GNSS stations?*
Reply: we partly agree with the reviewer's comment. However, we believe that this paragraph is appropriately

placed in the Methods section because it describes the procedure used to derive sea-ice thickness from the DEMs using the hydrostatic equilibrium assumption, rather than presenting a result. Nevertheless, we agree that the conversion from ellipsoidal DEM elevations to freeboard is not sufficiently explained in the current manuscript and we revised the text accordingly.

Specifically, the UAV-derived DEMs provide elevations relative to the ellipsoid. To obtain freeboard, we applied a constant vertical offset to each DEM such that the DEM elevation at one GNSS reference station matched the corresponding in situ freeboard measurement. This offset was then applied uniformly across the entire DEM before deriving sea-ice thickness from hydrostatic equilibrium. We included the following paragraph in the revised version of the manuscript: *"The UAV-derived DEMs provide elevations relative to the ellipsoid. To obtain freeboard, we applied a constant vertical offset to each DEM such that the DEM elevation at one GNSS reference station matched the corresponding in situ freeboard measurement. This offset was then applied uniformly to the entire DEM to convert ellipsoidal elevations into freeboard estimates."*

Since in situ freeboard measurements were only available at the GNSS stations, we cannot directly quantify how the freeboard uncertainty evolves with increasing distance from these reference points. However, the comparison with GEM-derived ice thickness along the GEM transect (Fig. 4e) provides an indirect assessment of the overall performance. The LiDAR- and photogrammetry-derived thicknesses differ from the GEM measurements by -0.06 ± 0.46 m and 0.06 ± 0.47 m (mean $\pm$ standard deviation), respectively. The small mean biases indicate that, on average, the freeboard estimates and the subsequent hydrostatic thickness retrieval are reliable across the survey area. In contrast, the relatively large standard deviations suggest that larger local errors occur, particularly in heavily ridged regions where the assumptions of hydrostatic equilibrium are less well satisfied. We have added this discussion to the revised manuscript.

Table 2.*: The table caption does not clarify the content of Table 2. In the sentence "Here we show the average deviation to all GCPs with No GCPs, 3 GCPs, All GCPs and if required with an Extra fit included in the photogrammetric processing." what "average deviation" refers to? Is the mean horizontal distance between the GCPs identified in the orthomosaics and the measured GCPs location? If so, are the numbers given in the table "horizontal distances ± vertical uncertainties"? Mixing horizontal and vertical distances/uncertainties does not make much sense to me... probably I misunderstood. Can you clarify? Also, could you explain in the text how you calculated the vertical uncertainty (1σ)? The measured freeboards at the GNSS stations were used to generate the DEMs, so those measurements could not be used for validation. What did you use then for validation?*

Reply: we apologize for the lack of clarity. The reported deviations are exclusively vertical differences between the surveyed GCP elevations and the corresponding elevations extracted from the DEM. No horizontal distances are included in Table 2. The uncertainty term ($\pm 1\sigma$) corresponds to the standard deviation of these vertical residuals. We have revised the caption and manuscript text to clarify this point.

We also agree that GCPs used during photogrammetric processing cannot serve as independent validation points. However, as only three to six GCPs were available at each ice station, all available GCPs were used in the final processing to maximize accuracy. Consequently, the values reported in Table 2 represent vertical residuals at the control points and provide a measure of internal consistency rather than independent validation accuracy.

Line 147-148*: "Final DEMs include all GCPs in the processing and were adjusted with an additional vertical fit to adjust with sea level if required." Are you here referring to the detrending fit described at the end of Sect 2.2.2? If this is the case, please remove this sentence as it is a repetition, and instead I recommend to better explain what the "Extra fit" in the last column of Table 2 is, in the caption of Table 2.*

Reply: we agree to this point and have added a reference to Section 2.2.2 in the figure caption. In addition, the entire section describing the residuals has been revised in the updated manuscript, including the corresponding sentence.

Line 176-177*: "Even under poor environmental conditions data from grid flights can be used for stitching orthomosaics making it an ideal tool for quickly generating orthorectified maps of large ice floes.": please clarify which conditions you are referring to, and please add a comma after "conditions" and after "orthomosaics". As it is now, this sentence does not sound very meaningful to me. I guess that you mean that grid flights become a doable option even over drifting ice only if the suggested pre-flight and post-flight drift corrections are applied? Please clarify.*

Reply: we thank the reviewer for this helpful comment and agree that the original wording was ambiguous. A similar concern was also raised by Reviewer #2. In response, we have added a new figure to the revised manuscript (Fig. 5; and point-to-point response to Reviewer #2) illustrating the range of environmental conditions under which meaningful results can be obtained. To clarify the intended meaning, we have revised the sentence as follows: *"Even under poor environmental conditions, such as diffuse lighting over a uniform snow surface (e.g. Fig. 5c), data acquired from grid flights can be successfully used to stitch orthomosaics, making this approach an ideal tool for generating orthorectified maps of large ice floes."*

Line 190: *"Also the wavelength of 905 nm is perfectly suited for snow and ice applications." How is this conclusion reached? Is this the wavelength of the applied LiDAR? If so, this should be mentioned earlier in the method section. Since no other wavelength has been tested in the paper, the authors should explain that the comparison with GEM observations suggested that the wavelength used in the LiDAR measurements allows retrievals of ice thickness with an accuracy of...*

Reply: we agree to this point and removed the corresponding sentence from the Discussion. Instead we included the following sentence in the Data and Methods section of the revised manuscript: *"The DJI Zenmuse L2 operates at a wavelength of 905 nm. This wavelength lies within the near-infrared region, where dry snow exhibits high reflectance, resulting in strong LiDAR return signals suitable for topographic mapping of snow- and ice-covered surfaces (Warren, 1982; Deems et al., 2013)."* As mentioned above, we also added a paragraph to the Discussion comparing the LiDAR-derived and GEM-derived ice thickness estimates, demonstrating that the LiDAR observations acquired with the 905 nm sensor provide ice thickness estimates that agree reasonable well with the GEM measurements.

Line 197-199: *"We assume that the ice at the pond bottom of the here observed melt pond has potentially lost scatterers, such as air inclusions through an increased permeability, and thus becomes more translucent, causing a reconstruction of the sub-pond bottom layer." This sentence is totally obscure because the method applied to retrieve the pond depth from RGB photogrammetry is not explained. And what is the "sub-pond bottom layer"?*

Reply: we thank the reviewer for highlighting the missing explanation. In the revised version, we will rephrase this as follows: *"The deviation exceeds previous evaluations that were based on earlier-season melt-pond observations (Fuchs et al., 2024). A plausible driver for this behavior is the increased translucency of the pond ice toward the end of the melt season. Stronger radiative transmission can reduce the optical visibility of the pond–ice interface in the image data. In particular, if the ice becomes more permeable, internal scatterers, like air inclusions, may be lost or their scattering efficiency may decrease, so that the photogrammetric reconstruction may instead latch onto optical features located deeper in the ice. Such a mechanism would readily explain a systematic offset in the absolute aerial pond depth, while leaving the overall gradient pattern largely intact, consistent with our observations. Based on these observations, we recommend further comparisons of the same ponds over the entire melt season, including an analysis of the actual reconstructed layer."*

Line 200: *"Another small part..." I invite the authors to use more proper language such "Other sources of error may have contributed to the observed discrepancy between measured and retrieved pond depth, such as..." or similar phrases.*

Reply: we greatly appreciate this recommendation and will adapt it as suggested: *"Other sources of error may have contributed to the observed discrepancy between measured and retrieved pond depth. These include an imperfect pond-level determination, either because of steeper pond walls late in the season (Fetterer and Untersteiner, 1998) or due to horizontal inaccuracies in determining where the ice is water-covered in the high-resolution image data. In addition, the spatial co-location of the in situ measurements appears imprecise. This could be improved in future campaigns by employing a tachymeter."*

Line 205: *"... error dependencies on pond evolution and morphology, and the technology used". The language used in this sentence should be improved. Does the meaning here is that future campaigns will enable a better validation of the retrieval method, and a better understanding of its limitations in different stages of the pond evolution? Please explain.*

Reply: many thanks for pointing out this ambiguity. We rephrased the corresponding sentence to: *"Future UAV deployments during upcoming field campaigns will enable us to better quantify how retrieval errors depend on pond evolution and morphology, as well as on the specific sensing technology employed."* in the revised manuscript.

References

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Fetterer, F. and Untersteiner, N. (1998). Observations of melt ponds on Arctic sea ice. *Journal of Geophysical Research: Oceans*, 103(C11):24821–24835.

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Warren, S. G. (1982). Optical properties of snow. *Reviews of Geophysics*, 20(1):67–89.