Response to reviewer 1

We thank the Reviewer for the careful and constructive comments. The suggestions and corrections have greatly improved the quality of this manuscript.

We have responded to all comments. The line numbers provided refer to the track changes document.

Review of "First Arctic-wide assessment of SWOT swath altimetry with ICESat-2 over sea ice" by Müller et al.

Summary:

This study evaluates the performance of the SWOT mission's swath-based sea surface height observations in the Arctic by comparing one year of data (March 2023–April 2024) with ICESat-2 measurements at ~550 crossover locations. Results show good overall coherence, with mean standard deviations of ~8 cm (6 cm over leads), but reveal systematic offsets between left- and right-swaths (up to 50 cm) and higher deviations during the early melt season and in complex regions such as the Canadian Archipelago.

General Comments:

This paper will be helpful for future studies using SWOT data over sea ice, and helps to better understand the complexity of the SWOT data. However, in its current form, it sometimes lacks clarity. Some figures are difficult to interpret and require close attention. I therefore recommend **major** revisions, although the scientific content appears sound. The main issues concern presentation and clarity."

I have some general comments that hopefully help to improve the paper:

1. The introduction lacks a clear statement of the study's main goals. It should also emphasize that SWOT is a predecessor of Sentinel-3 NG, which will carry a similar sensor, making the results valuable for the upcoming mission.

   We have further emphasized our research objectives (see Introduction, L53 - L57) and added some information about Sentinel-3 Next Generation Topography (S3NG-T) in the introduction L23-27) and the conclusion (L309-311).

   These are the new paragraphs:

   L23-27: It is the first altimetry mission, which provides 2D samples of the ocean topography. Moreover, SWOT's promising observations have motivated future missions, such as the upcoming Copernicus mission Sentinel-3 Next Generation Topography (S3NG-T). This mission, planned for launch after 2030, will adopt the swath altimetry concept and bring it to an operational level. It will consist of two satellites, each carrying an across-track interferometer and a nadir-looking synthetic aperture radar (SAR) altimeter. The results of this study will help to prepare for this future mission.

   L53-57: Our study presents an assessment of SWOT-KaRIn surface heights in the Arctic sea-ice regions. Due to a lack of sufficient in-situ data, a comparison with ICESat-2 laser altimetry is performed. Besides an Arctic-wide assessment, we cover a long period of time, including different seasons and both SWOT orbit phases. With this, we extend the work of Kacimi et al. (2025).

L309-311: For the first time, spatial, 2D height information for sea ice thickness or freeboard determination can be provided. We should try to learn as much as possible from the SWOT mission in order to pave the way for the future S3NG-T mission, which includes the cryosphere as a secondary objective and will extend the monitored area to a geographical latitude of 81.5°N.

2. I find the usage of SLA for heights in this paper slightly misleading. My understanding of SLA refers to open water only, not including sea ice. I would suggest to refer to surface heights/elevations instead.

   We see the point and decided to use the terms **surface elevations** (instead of SLA) and **surface heights** (instead of SSH) – even if the SWOT data is also named "ssh_karin" in the official products. Please find the changes in the track change manuscript at various locations.

3. Figures and text can be improved in clarity. For example, Figure 4 lacks labels, and the link between the different panels demands some attention. I made suggestions and comments below.

   Please find our answers to this comment below.

4. Can you make a suggestion how to correct for the SWOT cross-track errors? Have you tried?

   An improved cross-calibration correction is far beyond the scope of this paper. To minimize the impact of this systematic error on the comparison results, we have reduced the offset between SWOT and IS2 for both swaths individually when generating the quantitative numbers. Please find a more detailed discussion about this topic below (comment 177-179).

Specific Comments:

L9: Throughout the paper, it is referred to "Sentinel-1 grey-scale values". Is it related to sigma0? It might be clearer to refer directly to the backscatter coefficient.

We clarified "Sentinel-1 grey-scale values" and rephrased the sentence.

L9-10: Visual comparisons of SWOT and ICESat-2 with Sentinel-1 backscatter (i.e. σ_0), converted to 8-bit grey-scale values, reveal clear coherence.

L34-42: The ICESat-2 description is maybe a bit lengthy and part of it could be moved to the Data section, especially technical details like footprint etc.

We agree and moved some ICESat-2 related information to the Data section. Please find the text in "Data", sub-section ICESat-2 in the track change document.

L106-108: ICESat-2 samples the ocean topography in a particular dense observation pattern due to a laser beam split into 6 individual beams, a small footprint size of 11 meters (Magruder et al., 2020), a high measurement frequency of 10 kHz (i.e. 70 cm observation point distance) and a 91-days orbit repeat cycle (Neumann et al., 2019).

In context of this, we also added a few lines below:

L112: Depending on the number of reflected photons, which is influenced by the surface reflectivity and cloud conditions, the spatial […]

L38: Different values for the ICESat-2 footprint can be found in the literature; a commonly cited estimate is 11 m, as reported by Magruder et al. (2020).

We followed the suggestion and changed it to 11 m. The reference has been added. Please see the comment above.

L41: Leads are sometimes not so easy to track with ICESat-2, in contrast to radar altimetry where we receive specular waveforms. However, I would add here that ICESat-2 ice well suited to detect ridges and surface roughness (e.g., Farrell et al (2020)., Ricker et al. (2023))

In radar altimetry, leads are equally difficult to identify due to a larger footprint and possible off-nadir effects. There are numerous different methods for determining leads using radar altimeters. However, we agree with the reviewer and have added the above information including references.

Please see in the introduction:

L43-47: ICESat-2 aims to monitor ice sheet melting, detect ridges and provide information about surface roughness. Moreover, ICESat-2 provides the opportunity to observe small-scale features of the sea ice surface, for example small leads or water openings within the sea ice cover to support sea ice freeboard or thickness computations (Farrell et al., 2020; Kacimi and Kwok, 2022; Petty et al., 2023, Ricker et al., 2023).

L95: "ICESat-2 latest SLA segments from ATL07 Release". I believe "surface heights" are meant here? The usage of SLA is slightly confusing.

We changed SLA to "surface elevation" (see general comment 2).

L111: Here it is referred to "SSH", SLA and SSH are not the same, see also comment above. Please clarify.

Please find our comment in the "general comments" section above.

L102-104: "Tests have shown that no significant differences exist between the two laser beam types." Does it mean tests that have been done in the framework of this study? Or is it referring to earlier studies? If the latter, a reference is needed.

Initially, we created the study based on all six beams but were unable to detect any significant differences between the strong beams and the neighboring (~90-meter spacing) weaker beams. We therefore decided to use only the strong beams.

We removed the last sentence of this section.

L146: I find it hard to see the "good agreement" here. Instead of the zoom-in area, an along-track line-plot with SWOT and ICESat-2 heights might be better suited (like Figure 5). In any case, is the figure relevant? See my comments on the figures below.

The main focus of this figure is on showing general problem areas of SWOT, e.g., at the swath edges, which are removed in the later plots. Please find details on this in our comments below (reviewer comments for Figures 3 and 4). To better emphasize this, we rephrased the description of Figure 3.

L168-174: Figure 3 shows an example of a SWOT - ICESat-2 crossover in the northern Kara Sea near Novaya Zemlya Island. Sea ice surfaces and detached ice floes show up in the SWOT swath data mostly as elevations in relation to the lower lying leads and open water patches. Towards the outer edges of the swaths, especially in the last 5 km (both far-range and near-range), increased, dominant noise and erroneous surface heights become visible. These areas are thus excluded from the quantitative analysis (see Section 2.1). Additionally, artifact-like structures are observed near the *island's coastline. Besides these deficiencies, the surface elevations observed by ICESat-2 and SWOT show similar variabilities, particularly in the three narrow, lead-shaped structures (highlighted area).*

L163-164: “In some regions, sea ice surfaces appear not to be represented in the SWOT heights or show no particular elevation structure compared to other sea ice surfaces” This sentence is unclear, what is meant with “sea-ice surfaces are either absent” ?

We rephrased the sentence:

L191-193: In some regions, certain sea ice surfaces visible in the radar image are apparently not represented in the SWOT elevations or do not have a particular elevation signature compared to other sea ice areas.

164-165: Why are the stars not in the upper left figure? This would make the comparison easier.

Please find our answer below (reviewer comments for Figures 3 and 4).

172-177: This part is not entirely clear to me. What is meant here? What are the line-like height differences? Linear kinematic features? Perhaps it can be marked in the figure.

Our investigations in connection with Figure 6 should indicate that the observed differences in surface elevation in the regions of potential leads and ridges cannot be clearly attributed to the actual presence of these structures. We rephrased the sentence and added arrows to Figure 6.

L197-206: In the case of Sentinel-1, such conditions can cause strong backscatter (i.e., bright grey-scale values), which usually represents sea ice ridges, but can also indicate leads (Müller et al., 2023; Murashkin et al., 2018). […] Figure 6 shows some examples of this effect (see purple arrows). In the Chukchi Sea region in January 2024, an almost homogeneous sea ice surface is visible, only interrupted by some leads or ridges, which cause distinct height signatures in the SWOT elevations. However, the observed surface elevations cannot always be unambiguously attributed to the correct surface type (i.e., clearly defined as a lead or a ridge). The full explanation of what directly causes these line-like height uncertainties remains unclear. Rather …

177-179: this cross-track error looks like it could be at least reduced with a relatively simple gradient correction? Have you tried to correct for it?

Before we compute the standard deviations between SWOT and ICESat-2 we reduced the offsets for both swaths separately. This is reducing a large part of the error. This also holds for the along-track height plot shown in Fig. 5. It is beyond the scope of our study to develop an improved cross-calibration correction for the Arctic.

L186-189: Have you checked the behaviour using the individual ICESat-2 beams? There might be also small differences/biases between the three beams.

There are various studies that deal with offsets within the six ICESat-2 beams (e.g. Luthcke et al., 2021). However, greater attention is paid here to differences between the strong and weak beams. The resulting findings have been incorporated into the new ICESat-2 data releases (including release 6 of ATL07). Strong-only beam offsets have not yet been considered in ATL07. Studies such as Fair et al. 2024 and Smith et al., 2025 indicate systematic calibration offsets under ideal (flat, ice/snow) conditions of up to 5 cm; biases can be larger in high noise, rough, or high-scattering environments.

L194-195: “i.e. it is less sensitive to changes in height than ICESat-2” … which makes sense given the small footprint (~11 m) of ICESat-2

We agree.

L245: “The precision reduces to 6 cm”. Is it not an improvement in precision? Do you mean the standard deviation?

We changed “precision” to “mean standard deviation”.

L251: “Compared to SWOT, this indicates that the LR dataset…” … but LR is SWOT, no? Please clarify.

We removed “compared to SWOT”.

Figure 3 & 4: I find Figure 4 (in combination with Fig. 5) very informative, but using the same colormap for both SWOT and ICESat-2 makes it sometimes difficult to separate. May be use different colormaps like in Figure 3? On the other hand, I wonder if Figure 3 is actually needed. Is there something in Figure 3 that cannot be explained by Figure 4 + 5? However, in Figure 4, I suggest to use “a)”, “b)”, etc, and moreover, it would be good to use arrows starting at the black boxes, pointing to the respective bottom figures.

Here are our responses to the various comments on Figures 3, 4 and 5:

Figure 3 (now updated due to an upload error) shows a SWOT pass without prior mean centering and application of outlier detection methods, which is the biggest difference compared to Figures 4 and 5. The image, especially on the left, shows artifacts and problems at the edges of the SWOT swaths. Since the motivation for this plot is to show the high noise in the outer edges of the swath and not a detailed along-track comparison of the heights. This is now more clearly indicated in the text (see comment above). An additional plot, similar to Fig.5, does not contain new information above the one shown in Fig. 5.

Figure 4: We agree to add labels for the different panels. However, we would like to avoid additional arrows and stars, as we believe that arrows crossing the images would overload them. We think that the rectangular markers clearly show where a larger ice floe and lead can be found. With regard to the stars in the left-hand image, we would prefer to do without additional stars, as these would obscure the effects we are describing. Furthermore, we would keep the colormaps to demonstrate how well the heights match each other. For detailed comparisons between the height profiles, Figure 5 is provided, which shows a direct along-track comparison enabling detailed analyses.

Figure 5: The right axis needs a label, even if these are relative units.

The figure is updated.

Figure 10: Colorbar label missing.

We are not sure what the reviewer means here. The unit of the colorbar “m“ (meter) is specified and what is shown is described in the caption. However, we added “surface elevation”.

References:

Farrell, S. L., Duncan, K., Buckley, E. M., Richter-Menge, J., and Li, R.: Mapping Sea Ice Surface Topography in High Fidelity With ICESat-2, Geophys. Res. Lett., 47, e2020GL090708, https://doi.org/10.1029/2020GL090708, 2020. a, b, c

Luthcke, S. B., Thomas, T. C., Pennington, T. A., Rebold, T. W., Nicholas, J. B., Rowlands, D. D., Gardner, A. S., and Bae, S.: ICESat-2 Pointing Calibration and Geolocation Performance, Earth and Space Science, 8, e2020EA001494, https://doi.org/https://doi.org/10.1029/2020EA001494, 2021.

Magruder, L. A., Brunt, K. M., and Alonzo, M.: Early ICESat-2 on-orbit Geolocation Validation Using Ground-Based Corner Cube Retro-Reflectors, Remote Sensing, 12, 3653, https://doi.org/10.3390/rs12213653, 2020.

Ricker, R., Fons, S., Jutila, A., Hutter, N., Duncan, K., Farrell, S. L., Kurtz, N. T., and Fredensborg Hansen, R. M.: Linking scales of sea ice surface topography: evaluation of ICESat-2 measurements with coincident helicopter laser scanning during MOSAiC, The Cryosphere, 17, 1411–1429, https://doi.org/10.5194/tc-17-1411-2023, 2023.

Smith, B. E., Studinger, M., Sutterley, T., Fair, Z., and Neumann, T.: Understanding biases in ICESat-2 data due to subsurface scattering using Airborne Topographic Mapper waveform data, The Cryosphere, 19, 975–995, https://doi.org/10.5194/tc-19-975-2025, 2025.