

Title: High-resolution Antarctic sea-ice thickness and snow depth from drift-aware multi-mission altimetry

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5 Reviewer 3 - global comment

This paper presents and validates a unique sea ice thickness and snow depth dataset based on multi-mission altimetry, with particular consideration of the effect of ice drift on the gridded data. Overall, the manuscript is well-written and provides a clear introduction to the new dataset. However, further discussion and more comprehensive comparisons with other widely used sea ice thickness and snow depth products are needed to better demonstrate the advantages of the proposed approach. Furthermore, the manuscript is quite lengthy, and at the beginning it is not easy to distinguish new methodological developments in the present work from those approaches already carried out in other studies. The authors should clarify and highlight more the new contributions of the present work.

Below are some specific comments which need be addressed by the authors before publication in The Cryosphere.

Answer to Reviewer 3 - global comment

15 *We would like to thank the reviewer for his careful reading of the manuscript, for this positive feedback and for the relevant and constructive remarks that have helped to improve the quality of the manuscript. In order to fit with your comments, we have made a revision of the manuscript that should have corrected the textual issues and well improved the readability of the document. We hope that these modifications will meet your requirements. Please find below the details on how your specific comments have been taken into account.*

20 *Before addressing the individual comments, we note that the dataset has been updated following the correction of an issue in the along-track filtering procedure. Although some reported values differ slightly from the original submission, the scientific conclusions and overall interpretation of the results remain unchanged.*

In this document, the referee's comments are in bold type, the answers are in italic type.

25 Answers to Reviewer 3 : specific comments

There are already several sea ice thickness and snow depth products for the Southern Ocean derived from both altimetry and passive microwave radiometry. The authors should provide a brief overview of these existing products, including their characteristics, known limitations and uncertainties.

30 The introduction should also provide a more explicit motivation for applying a drift-aware approach to Antarctic sea ice thickness data. In particular, the specific characteristic of ice drift in the Antarctic compared with the Arctic, including differences in drift speed, spatial variability, and seasonal behaviour as well as the main benefit achieved by the application of this method in the Arctic which is demonstrated in another paper.

We thank the reviewer for this comment. We agree that the introduction did not sufficiently describe the existing Southern Ocean snow-depth and sea-ice-thickness products. Following this comment, and similar suggestions from other reviewers,

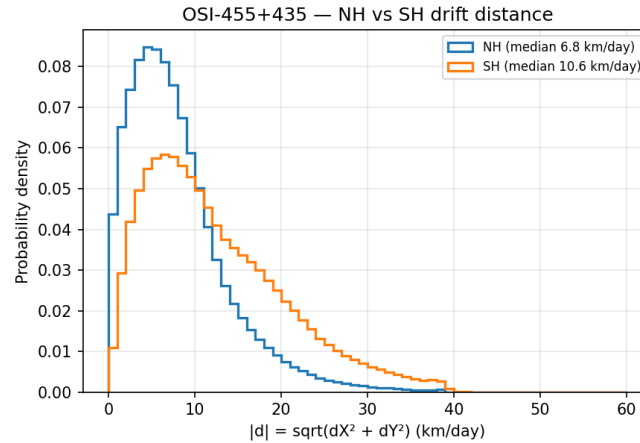


Figure 1. Histogram of the Sea-ice motion for both hemisphere during 2018-2025 from the products used by the study (OSI-455,OSI-435)

we have expanded the introduction to provide a more comprehensive overview of the currently available products and their respective limitations.

Regarding the drift-aware framework, its motivation is independent of the specific characteristics of Antarctic versus Arctic sea-ice drift. As demonstrated by Ricker et al. (2025), accounting for sea-ice motion improves the consistency of the comparison between observations acquired at different times. The objective is not to correct a specific Antarctic drift pattern, but rather to account for the displacement of sea ice between observations and thereby reduce spatial mismatches during the compositing process. This is also important when combining measurements from multiple missions with different temporal sampling and orbital characteristics, it is mostly a matter of collocating the observations.

Antarctic sea ice is highly dynamic and the drift distances substantial (Fig. 1), and higher than in the antarctic, with higher frequency of high drift, further supporting the relevance of a drift-aware approach. The spatial impact of this framework on the final product was illustrated in the Figure 11. This figure has been splitted in two, with one part now in the appendix and the other put earlier in the manuscript to better support the message we want to convey with the DA processing.

Page 6 Line 162-164: You are already assigning a constant 2 cm uncertainty to SLA, why do you need to set a maximum SLA uncertainty of 10 cm? The uncertainty of freeboard should be the sum of the other two?

Thanks for this comment, the sentence at this line is inconsistent, we apology. The uncertainty of the SLA is the sum of two terms, 2 cm and a term computed using the distance to the closest lead. If the lead is further away from 100 km, then the maximum value of the uncertainty is set to 10 cm. This paragraph have been rewritten accordingly.

Page 6 Line 165-170: Is the correction scheme of freeboard using electromagnetic wave velocity in snow is the same as in the Arctic, or have you considered the different snow characteristics in the Antarctic?

We thank the reviewer for the question. The parametrization is identical to the one used for the Arctic Ulaby et al. (1987). However, it depends on the snow density which using a seasonal Antarctic-specific parameterization based on Fons et al. (2023). This is already described in the current version of the manuscript.

60 **Is the approach used to derive snow depth in this study a new methodology, or is it adapted from other previous work? If so, it would be helpful to mention other studies (e.g. Kwok et al, 2020) carried out in this area to derive snow depth from Laser and Ku-band altimetry and highlight what is new in this snow depth product.**

65 *The approach to derive the snow depth is based on the method described in Kwok et al. (2020) later adapted for the Southern Ocean by Kacimi and Kwok (2020). This study extends the method even further by combining Ku-band freeboards from three radar altimetry mission and using the Drift-Aware module to collocate measurements in space and time before merging. The merged Ku-band freeboard is then compared with the Drift-Aware total freeboard from ICESat-2 laser altimetry to retrieve snow depth. So although the original concept was introduced by Kwok et al. (2020), accounting for the drift to compare the freeboards makes the method intrinsically more consistent.*

We added the corresponding references in this Section and clarify the additional value coming from this study.

70

Figure 3: It is interesting to see that the sea ice thickness and snow depth have different spatial distributions in Weddell Sea, whereas in the other regions they follow similar pattern. Any explanation for this?

75 *We thank the reviewer for this observation. While snow depth and sea-ice thickness generally show similar large-scale spatial patterns, a weaker correspondence is observed in the Weddell Sea. This difference may arise from several factors. On the retrieval side, complex snow and ice conditions, changes in the radar scattering horizon, and the presence of highly deformed sea ice may affect the estimated snow depth and sea-ice thickness. However, a physical decoupling between the two variables is also possible, as dynamic processes such as ice convergence and ridging can increase sea-ice thickness without a proportional increase in snow depth. Given the available observations, it is not possible to determine whether the observed difference reflects retrieval limitations, geophysical processes, or a combination of both.*

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Figure 7: Please explain the negative sea ice thickness and snow depth values shown in the figure. Are they excluded from the statistical analysis? The mean monthly biases differ substantially from those shown in the upper panels.

85 *During the compositing step, negative Ku-band freeboard, laser freeboard, and sea-ice thickness values were removed. Snow depth, however, is derived from the combination of the filtered freeboards and was therefore not subjected to an additional filtering step.*

The statistics reported in the histograms and maps differ slightly because they are computed differently. The maps show the temporal mean at each grid cell, and the reported mean corresponds to the spatial average of these temporal averages. In contrast, the histogram mean (μ) is calculated using all individual observations contributing to the dataset.

The negative value process as been added to the manuscript and we improved the clarity on the statistics.

90

Figure 9: Why are the CSAO and Fons 2023 products excluded from the comparison? This section is rather brief, and additional information about the ASPECT-BIO data set is needed to better understand and interpret the mismatch between the two data sets.

95 *We thank the reviewer for this comment. We do not believe that adding the CSAO and Fons (2023) products to Figure 9 would substantially improve the analysis. The objective of this section is not to provide a comprehensive intercomparison of sea-ice thickness products, but rather to place the MMS estimates in the context of the available ASPECT-BIO in situ observations. Comparisons between MMS and other large-scale satellite-derived products are already presented in the subsection above.*

Including additional products here would therefore increase the complexity of the figure without directly addressing the purpose of this comparison.

100 *We agree, however, that additional information on the ASPeCt-BIO dataset is required to better interpret the observed differences. The manuscript has been revised accordingly.*

Section 6 Discussion and Conclusions

105 **In contrast to the Arctic sea ice thickness product, which has large limitations during the summer melt season, the dataset presented in this study covers all seasons. Are there any specific limitations or caveats associated with the melting processes? Do you apply additional quality control during the melting season?**

110 *We thank the reviewer for this comment. No additional quality-control procedure is applied during the melt season. While melt ponds are generally less widespread over Antarctic sea ice than in the Arctic, summer conditions may still affect the retrievals. In particular, snow metamorphism, flooding, and snow-ice formation can alter both the physical properties of the snowpack and the radar scattering horizon. Furthermore, part of the snow cover may be converted into snow ice, making the distinction between snow depth and ice thickness less straightforward. These processes remain a potential source of uncertainty in the summer retrievals.*

We have expanded the discussion of these limitations in the revised manuscript, as also suggested by other reviewers.

115 **In the introduction, the authors discuss several sources of uncertainty in the sea ice thickness and snow depth retrievals associated with the specific snow conditions in the Antarctic. However, it is not clear from the manuscript whether any adjustments or corrections have been applied to account for these specific snow properties. Please clarify this in the discussion.**

120 *We thank the reviewer for this comment. No specific correction is applied to account for Antarctic-specific snow processes such as flooding, snow metamorphism, or snow-ice formation. However, the retrieval remains physically consistent, as snow depth and sea-ice thickness are derived from a common freeboard framework. The main caveat is that the retrieved snow depth should be interpreted as an altimetric snow depth, which may differ from snow depth measured in situ. In particular, when part of the snowpack is transformed into snow ice, the distinction between snow and ice becomes less clear, and a fraction of the snow mass may be incorporated into the retrieved ice thickness rather than the snow depth. We have clarified this point in the*
125 *discussion and further elaborate on this limitation in the conclusions also related to the previous comment.*

References

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