

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

Marion Bocquet, Robert Ricker, Torbjörn Kagel, Stefan Kern, Thomas Lavergne, Emily Down, and Stefan Hendricks

5 Reviewer 1 - global comment

This manuscript implements a drift-correction method to align freeboard measurements from multiple satellite altimetry missions and generate high-resolution Antarctic snow depth (SD) and sea-ice thickness (SIT) maps for 2018–2025. The manuscript is generally well written and logically presented. However, I have several comments that should be addressed before the manuscript can be recommended for publication.

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My main concern is the literature review and the justification for the selection of datasets used for validation and comparison. Retrieving Antarctic sea-ice thickness remains an important challenge for the community, particularly because of the heterogeneous snow cover and the complexity of radar interactions within the snowpack. In the Introduction, the authors mention several existing Antarctic sea-ice thickness products and studies, including Kurtz and Markus (2012), Schwegmann et al. (2016), Kacimi and Kwok (2020), and Fons et al. (2023). Some of these references (e.g., Kacimi and Kwok (2020) and Fons et al. (2023).) were used for comparisons of the derived MMS results. While some datasets used in Sections 4 and 5 (Paul et al. (2024) and CSAO) were not introduced or discussed in the Introduction.

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Therefore, I suggest that the authors provide a clearer overview of the currently available Antarctic SIT and SD products and datasets. For example, a table could summarize the existing products/datasets, the satellite missions or measurement platforms from which they are derived, their spatial and temporal coverage, and indicate which datasets are used for validation or comparison in this manuscript. This would help readers understand how the new MMS product relates to existing datasets and why particular datasets were selected.

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Related to the above point, I also suggest that the authors reconsider or better explain the organization of Sections 4 and 5.

Different datasets are introduced at different stages of the validation and comparison:

-In Section 4.1, Fons et al. (2023) and CSAO are used for intercomparison of SIT and SD.

-In Sec 4.2, OIB data are used to validate regional MMS snow depth.

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-In Sec 4.3, ASPECT-Bio in-situ measurements are used to validate MMS SD and SIT.

-In Sec 5.2, SIT and SD estimates from Fons et al. (2023) and Paul et al. (2024) are compared with MMS.

Is the intention to distinguish between pan-Antarctic and regional-scale comparisons? If so, this distinction should be stated more clearly. At present, the rationale for separating the different validation and comparison analyses is not super apparent.

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An alternative structure might be to organize the analyses according to the retrieved variables - for example, one section focusing on the validation/intercomparison of MMS snow depth and another focusing on sea-ice thickness. However, the current structure could also work if the authors provide a clearer explanation for why the analyses are organized in this way.

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For the OIB snow-depth measurements, ASPECT-Bio in-situ observations, and Sentinel-1 imagery, could the authors provide more justification for the specific regions and dates selected for validation/comparison? Since the MMS products cover the pan-Antarctic region from 2018 to 2025, I would expect that several OIB campaigns may overlap with the study period and provide snow-depth measurements. There are also ample in-situ Antarctic SIT and SD measurements from various expe-

ditions, for example through AWI or the AAPP data portal. Sentinel-1 also provides extensive spatial and temporal coverage of Antarctic sea ice.

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The authors should therefore explain why these particular dates, regions, and datasets were selected. Were the choices determined by temporal overlap, spatial coverage, data quality, availability, or other criteria? A clearer explanation would help readers assess how representative the validation results are for the overall pan-Antarctic MMS product.

50 **Answer to Reviewer 1 - global comment**

We would like to thank the reviewer for the careful reading of the manuscript and for the constructive comments, which have helped improve both the content and the clarity of the paper.

55 *We agree that the Introduction did not sufficiently present the existing Antarctic snow-depth and sea-ice-thickness products, nor clearly explain the rationale behind the different datasets used throughout the manuscript. We have therefore substantially revised the Introduction to provide a more comprehensive overview of the available Antarctic SIT and SD products, their characteristics, and their known limitations. The purpose of this overview is to better position the MMS product within the existing landscape of Antarctic sea-ice products and to provide the necessary context for the datasets used in this study, rather than to perform a comprehensive intercomparison of all available products.*

60 *We would however like to emphasize that the objective of this manuscript is not to provide a systematic intercomparison of all existing Antarctic SIT and SD products. Instead, the selected datasets were chosen to provide complementary validation and comparison exercises at different spatial scales and using different observation techniques. Our objective is therefore to evaluate the consistency and performance of the MMS product rather than to benchmark it against every available Antarctic dataset.*

65 *Regarding the choice of validation datasets and periods, the selection was primarily driven by data availability, temporal overlap, and spatial representativeness. Suitable independent observations over Antarctic sea ice during the ICESat-2 era remain limited. In practice, OIB 2018 is the only Operation IceBridge campaign overlapping the study period, while few other available observations are highly localized or restricted to coastal and marginal ice zone environments, making them less suitable for evaluating a pan-Antarctic gridded product.*

70 *Section 4 is dedicated to the quantitative evaluation of the MMS product, whereas Section 5 focuses on the interpretation of the spatial patterns and on demonstrating the impact of the drift-aware compositing framework relative to conventional gridding. The Sentinel-1 example was selected because it captures one of the most pronounced sea-ice export events identified in the study period, while the coastal ice example was chosen to illustrate that the presence of locally thick coastal ice is physically consistent with the regional ice regime. Both figures and their descriptions have been revised to make these motivations clearer.*

75 *To improve the readability of the manuscript, we have revised the presentation of the datasets and clarified the objectives of Sections 4 and 5, explicitly distinguishing between independent validation exercises and larger-scale comparisons with existing products.*

Finally, both the MMS sea-ice-thickness and snow-depth datasets will be made publicly available through SINX'S, enabling future community-led intercomparison studies using additional datasets and methodologies that are beyond the scope of the present manuscript.

80 *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.

85 **Answers to Reviewer 1 : specific comments**

Lines 160–165: There are many mathematical symbols introduced in this section. Please ensure that each symbol is clearly defined when it first appears.

We have checked the symbols and added the missing definitions.

90 **Lines 227–228:** Could the authors provide some additional explanation of how the change correction factor is applied in this study?

The change-correction factor follows the approach of Ricker et al. (2025). During the drift period, sea-ice thickness may evolve due to thermodynamic growth, melt, or dynamic deformation. The method therefore estimates a local sea-ice thickness change rate from the available observations for each parcel and uses it to adjust the thickness measurements to a common reference date before compositing (the target date). We have added some clarification in the manuscript to better explain how this correction is applied.

Line 287: Why was a three-day rolling window selected? Are the results sensitive to the selected window length.

100 *We thank the reviewer for this comment. The purpose of the rolling window is primarily to reduce noise and fill spatial gaps in the observations, particularly for ICESat-2. A three-day window was found to provide sufficient spatial coverage while preserving most of the temporal variability. Longer windows only marginally improve coverage but introduce additional smoothing, whereas shorter windows leave larger gaps in the resulting fields. We added a sentence in the revised version of the manuscript.*

105 **Lines 322–325:** The authors state that the thickest ice is observed in certain regions and that similar spatial distributions are found across the study period. Could the authors be more quantitative and specific here? For example, during which years are similar spatial patterns observed? Are the maximum thickness values also comparable between years? What are the main differences or biases between the annual results?

110 *We thank the reviewer for this comment. Our intention was to describe the persistence of the large-scale spatial distribution of Antarctic sea-ice thickness rather than to imply quantitative agreement between years. We have revised the text to more explicitly describe the recurring regions of thick ice and to acknowledge the interannual variability in thickness magnitude. In addition, monthly sea-ice thickness and snow-depth anomaly maps have been added to the Supplement, while Figure 5 highlights the mean spatial distribution over the study period.*

115 **Figure 4:** I may have misunderstood the purpose of this comparison, but I did not fully follow why comparing MMS with each of these three datasets separately, given that MMS itself is generated by merging observations from these missions. If the purpose is to assess consistency in freeboard measurements among the different missions, would it be more appropriate to use spatially and temporally overlapping observations and directly compare CS2 with S1-A/S1-B? Please clarify the purpose of this analysis and how it should be interpreted.

120 *The objective of this analysis is to verify that the merged product remains consistent with the individual input datasets and that the merging procedure does not introduce significant distortions in the sea-ice thickness distribution. It should therefore be interpreted as a consistency check of the multi-mission framework rather than an inter-mission comparison or an independent validation exercise.*

We have clarified this point in the revised manuscript to ensure that the figure is interpreted as a consistency check of the merging procedure and not an inter-mission comparison or an independent validation exercise.

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Figure 5: Is this figure showing the monthly averages calculated over the entire 2018–2025 period? Could the authors also provide monthly SIT and SD results for each individual year in the Supplementary Material? This would allow readers to assess the interannual variability that may be hidden in the multi-year monthly averages.

130 *Yes this figure shows the monthly averages over the entire period. We thank the reviewer for the suggestion and have added the following figures to the Supplementary Material.*

Line 364 (bottom of Page 16): The authors mention that processes such as flooding can increase the uncertainty. Is this conclusion based on observations in the present study, or is it supported by previous studies? It would also be useful to show the spatial distribution of uncertainty, potentially alongside the SIT and SD results in Figure 5.

135 *This statement is not based on a specific analysis conducted in the present study. Rather, it refers to the fact that flooding and snow-ice formation may modify the effective radar scattering horizon and complicate the interpretation of the radar freeboard, thereby increasing the uncertainty of snow-depth and sea-ice-thickness retrievals. We have added appropriate references and clarified this point in the revised manuscript. Corresponding uncertainties might be good alongside in this figure (5 in the manuscript), however, we think the newfigure (Fig 9) would be more difficult to read, we therefore added these uncertainties in*
140 *appendix.*

Figure 6: Section 3.3 discusses the fitting relationship between freeboard and snow depth for each month. Could the authors provide the monthly fitting results in the Supplementary Material? It would be interesting to examine the seasonal variation in the relationship between freeboard and snow depth.

145 *This figure has been added to the Supplementary Material document (see Figure 10):*

Lines 487–489: The authors state that the drift-aware approach captures distinct temporal anomalies. Could the authors identify specific examples in the figures where this improvement can be clearly observed?

150 *We thank the reviewer for this comment. We agree that the term "distinct temporal anomalies" was not sufficiently supported by the figure. Our intention was to refer to differences in the temporal variability observed in the regional mean time series rather than to specific anomalous events. We have revised the text accordingly and now focus on the differences in temporal variability between the drift-aware and conventional approaches.*

We also added a panel comparing the daily thickness change, dh/dt , with the thickness change expected from advection by the ice drift, $-\mathbf{u} \cdot \nabla h$, computed from the OSI SAF ice drift (OSI SAF and EUMETSAT SAF On Ocean And Sea Ice, 2022; Lavergne and Down, 2023). The day-to-day variability is about twice as large in the drift-aware product and is largely explained by advection ($R^2 = 0.61$, vs. 0.00 for the conventional product).

155 *Therefore, the takeaway message is that the higher variability of the local DA sea ice thickness (compare to CV) is explained by the advection term and therefore not noise.*

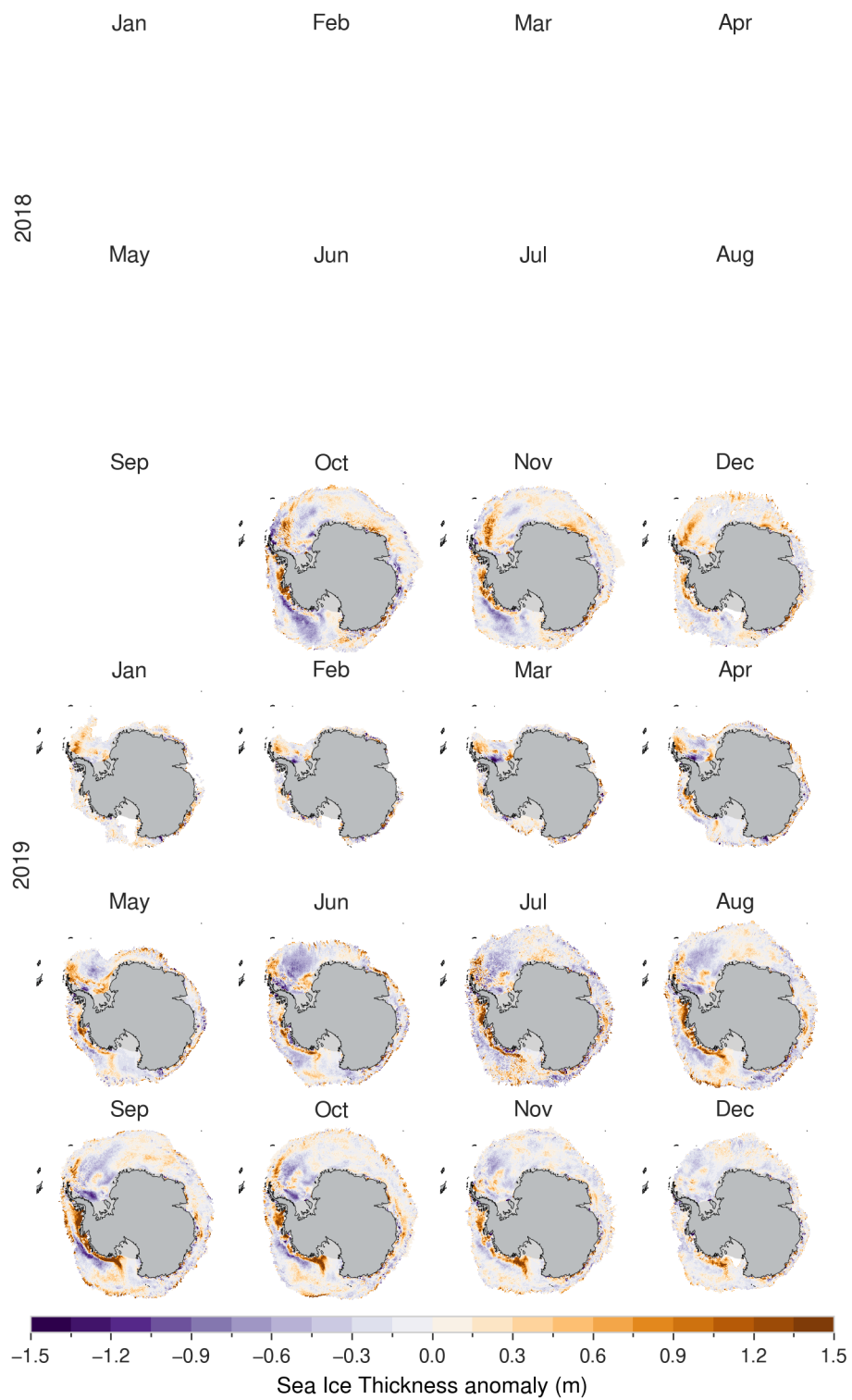


Figure 1. Monthly Sea-Ice thickness anomaly 2018-2019 in reference to 2018-2025.

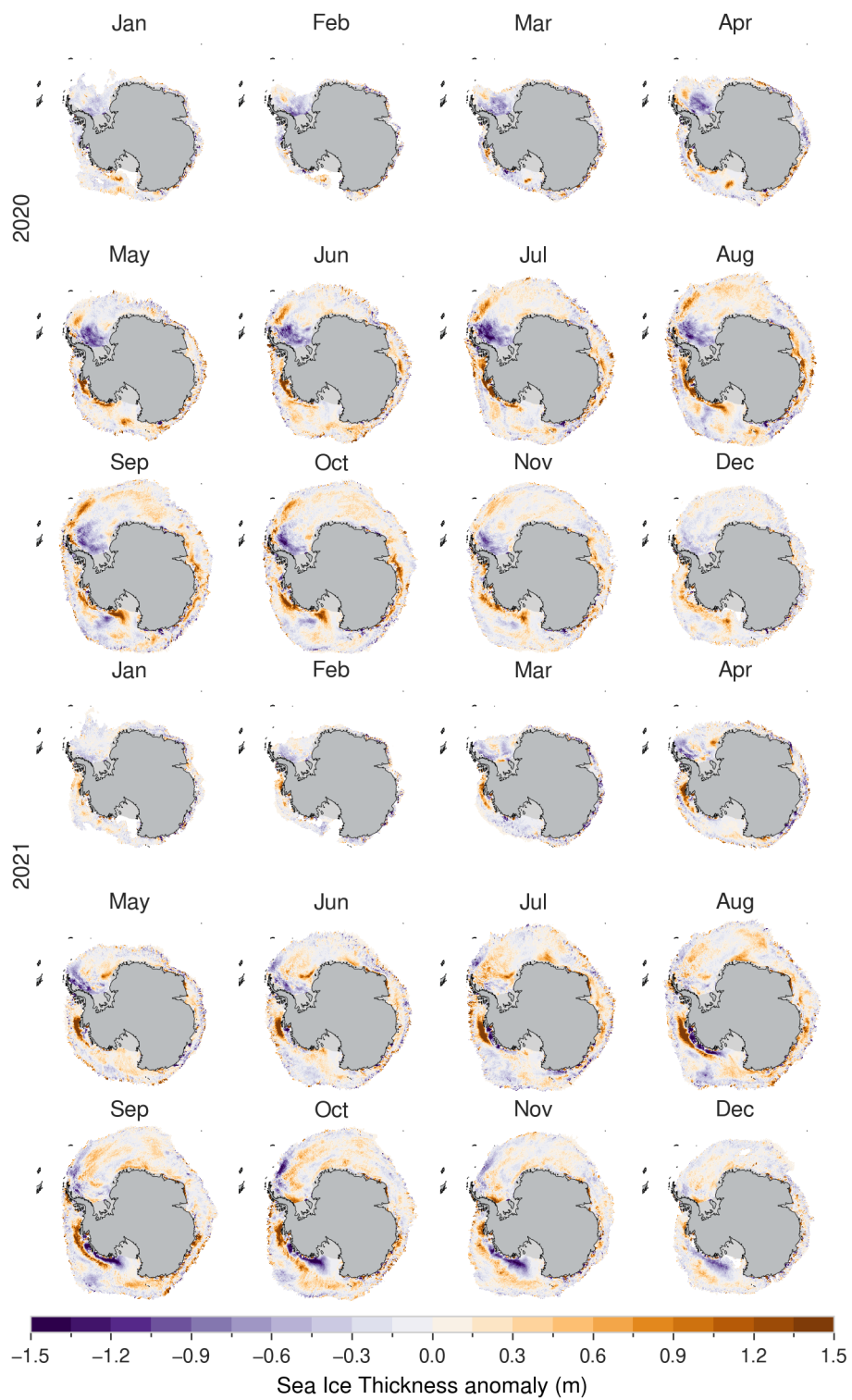


Figure 2. Monthly Sea-Ice thickness anomaly 2019-2020 in reference to 2018-2025.

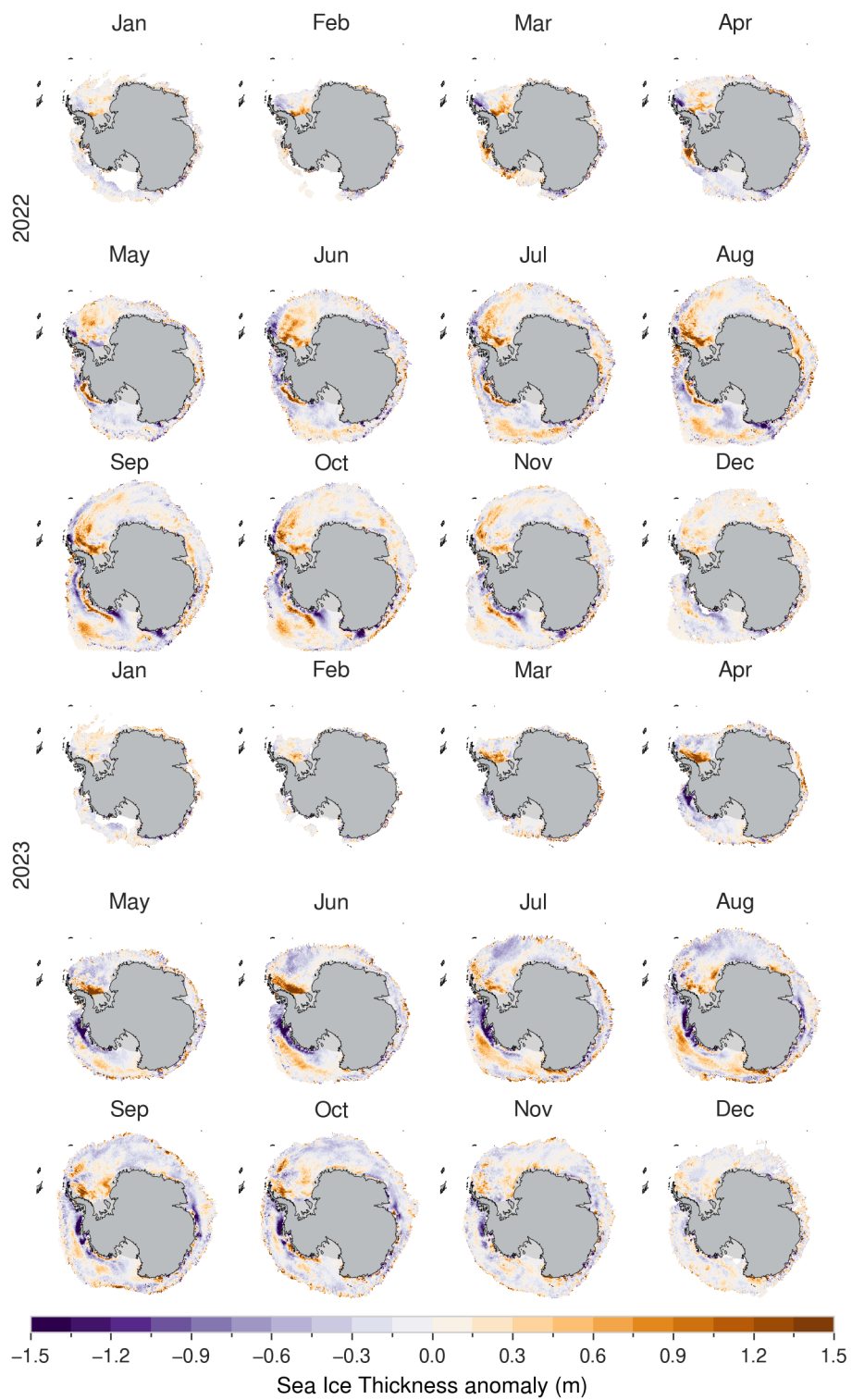


Figure 3. Monthly Sea-Ice thickness anomaly 2022-2023 in reference to 2018-2025.

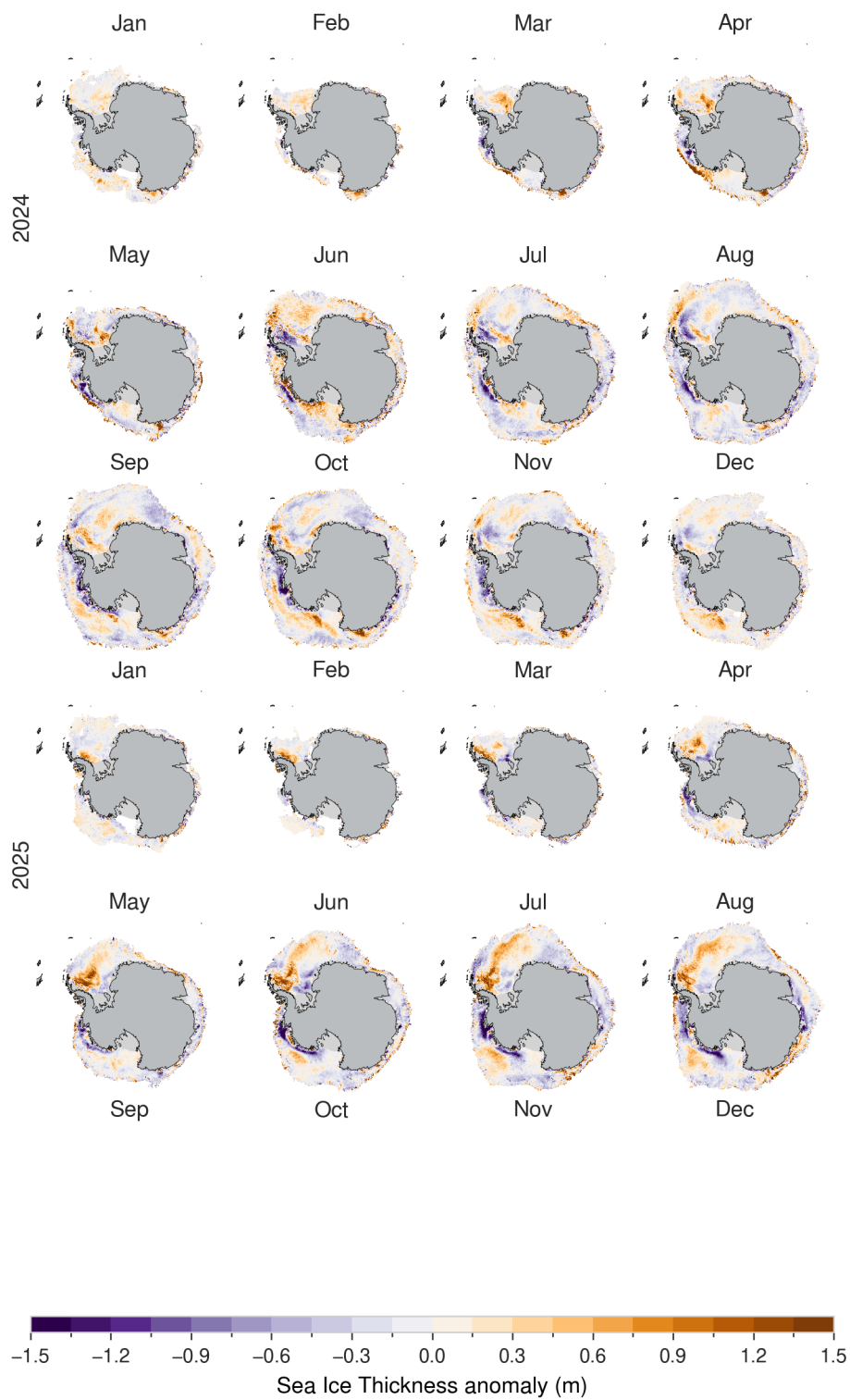


Figure 4. Monthly Sea-Ice thickness anomaly 2024-2025 in reference to 2018-2025.

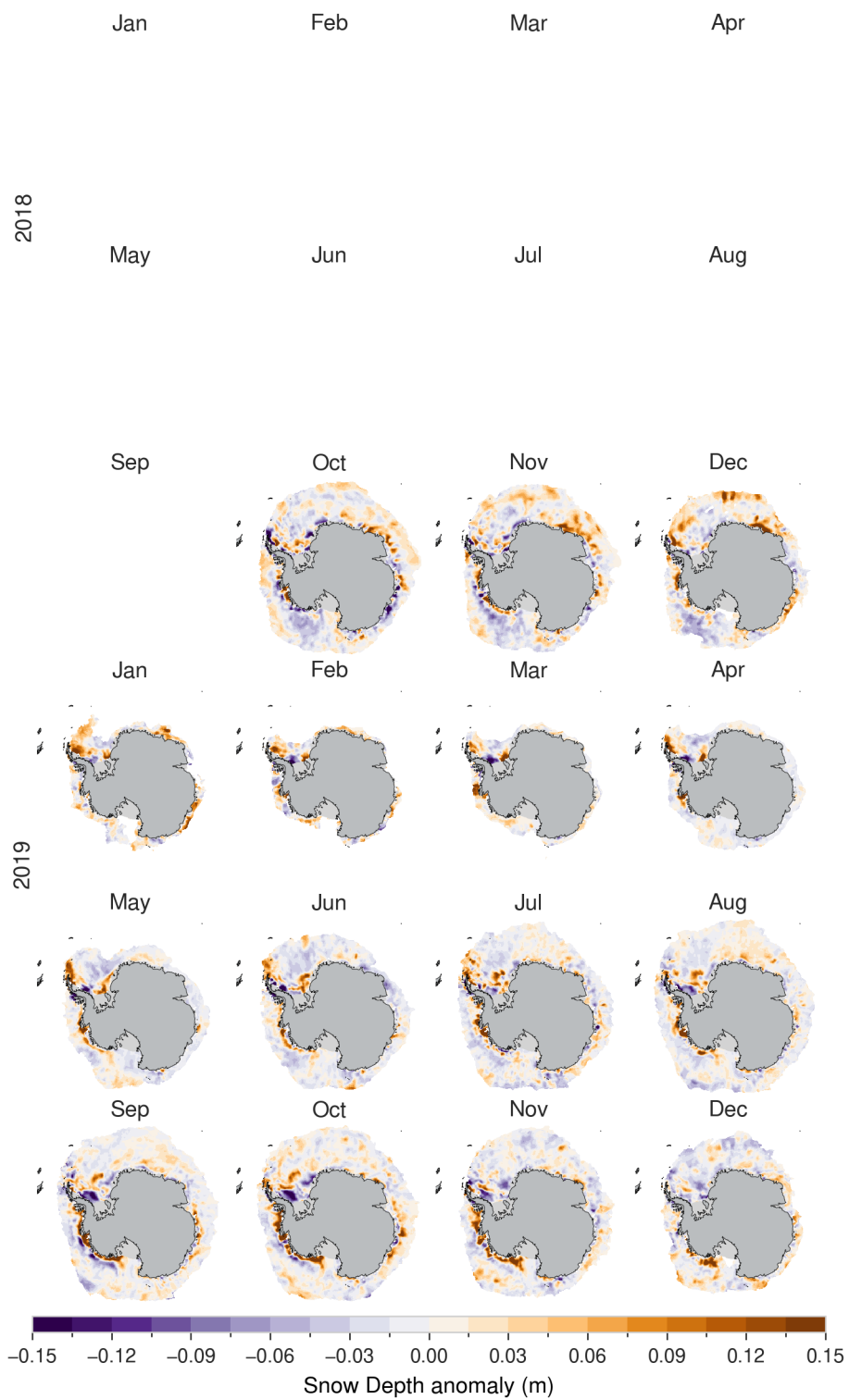


Figure 5. Monthly Snow Depth anomaly 2018-2019 in reference to 2018-2025.

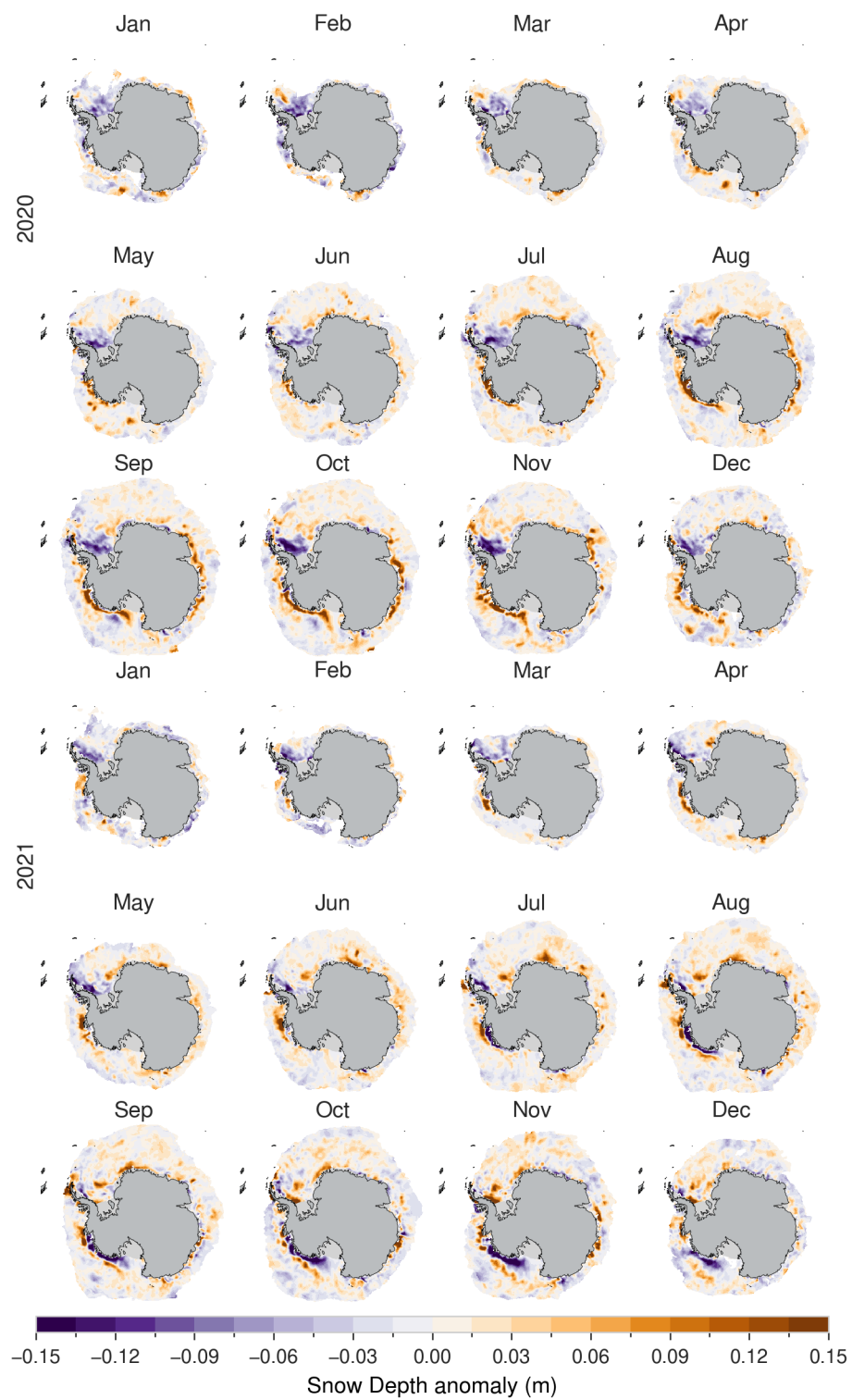


Figure 6. Monthly Snow Depth 2019-2020 in reference to 1825-2018.

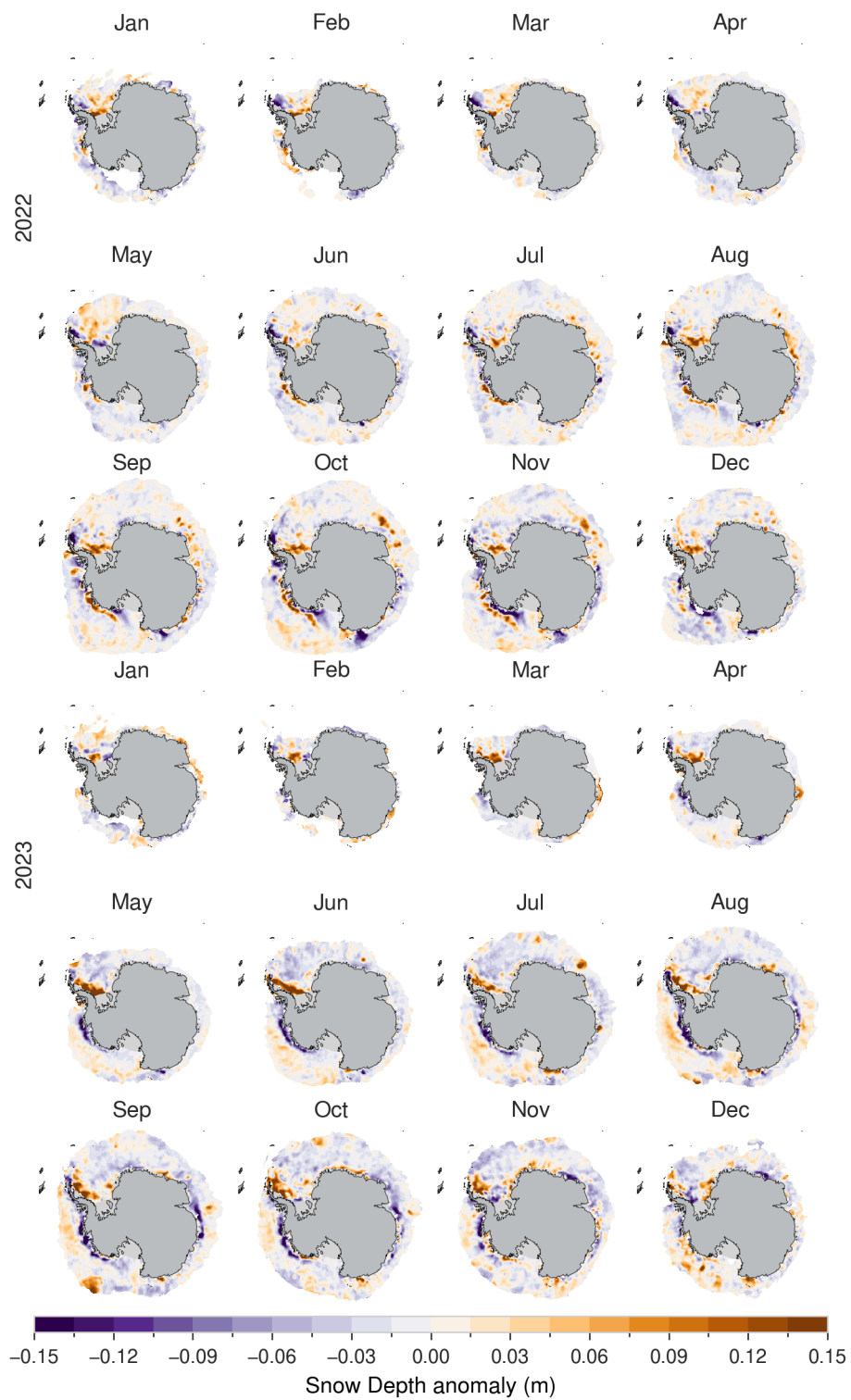


Figure 7. Monthly Snow Depth 2022-2023 in reference to 2018-2025.

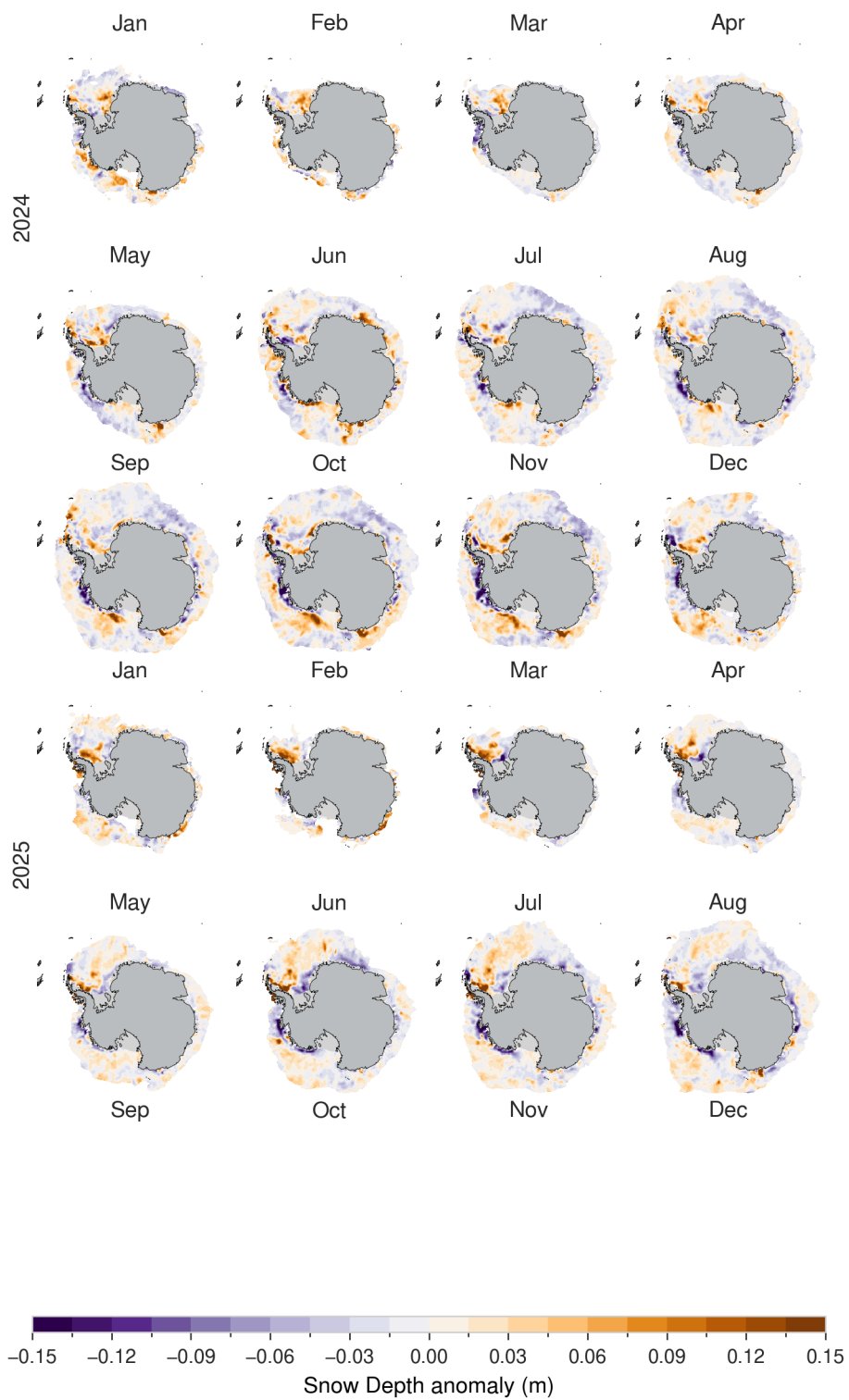


Figure 8. Monthly Snow Depth 2024-2025 in reference to 2018-2025.

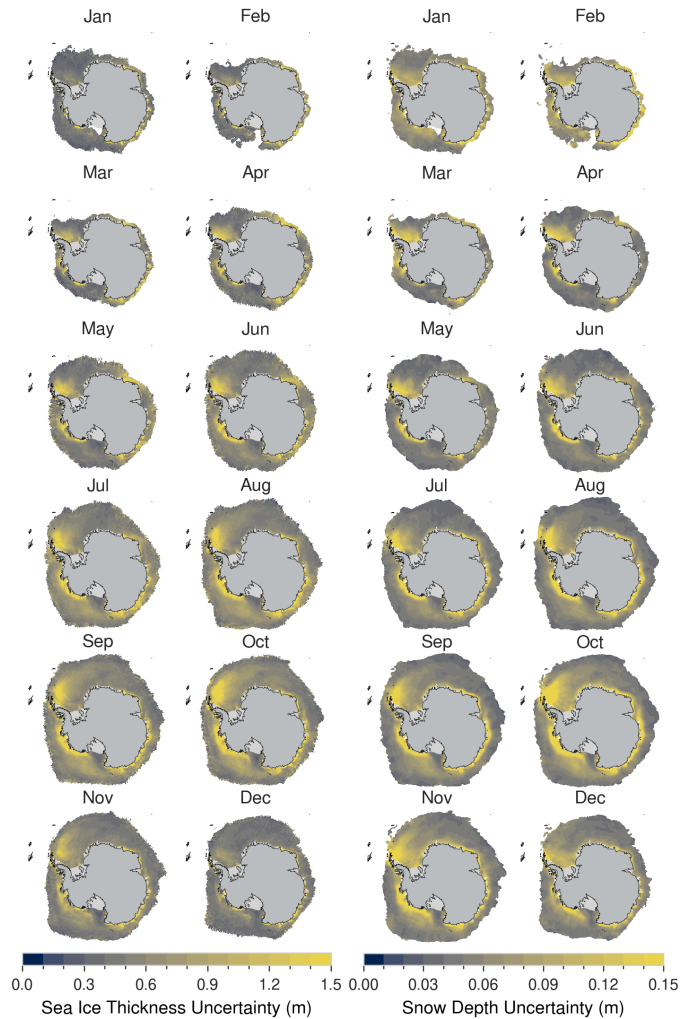


Figure 9. SIT and SD uncertainty climatology for 2018-2025.

160 **Figure 10:** For segments where the differences exceed the estimated uncertainty, could the authors discuss the possible reasons for these discrepancies and support the interpretation with relevant references where appropriate?

We thank the reviewer for this comment. The purpose of this figure was not to demonstrate a systematic improvement, but rather to show that sea-ice drift has a significant impact on the resulting signal. In a fixed Eulerian domain, the ice present within the region may be substantially different from one observation period to the next. Conventional gridding tends to smooth this variability by combining observations without accounting for sea-ice motion, resulting in a blurrier signal and a more gradual day-to-day evolution. By accounting for ice drift, the drift-aware framework better preserves the evolution of the ice field sampled within the region. The differences between both approaches therefore highlight that sea-ice motion cannot be neglected when analyzing the daily evolution of sea-ice thickness and snow depth within a fixed area. It also means that the uncertainties are not, with this method, explaining the difference between the conventional and drift-aware gridding.

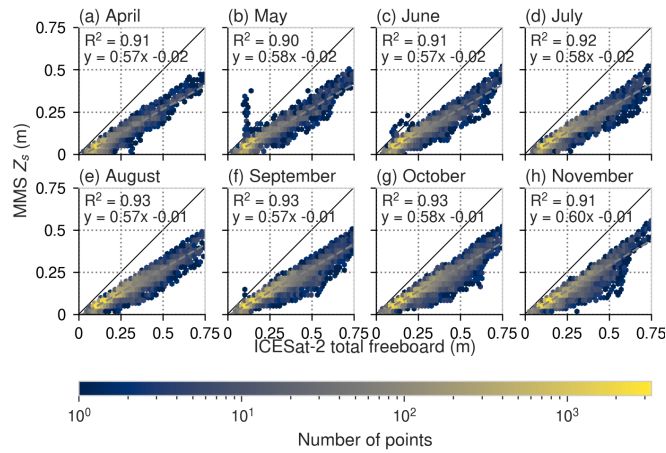


Figure 10. Relationship between snow depth and total freeboard for each month. Same as for Figure 6 of the manuscript

170 *This section has been improved to clarify both the aim of the analysis and the main outcomes illustrated by the figure, see comment above.*

175 **Code and Data Availability:** Do the authors plan to make the derived MMS SIT and SD products publicly available? Given the pan-Antarctic coverage and the 2018–2025 time series, public access to these products would potentially be valuable to the broader sea-ice community.

We thank the reviewer for this comment. We confirm that both the sea-ice thickness (SIT) and snow-depth (SD) products will be made publicly available for the final version of the manuscript and hopefully before. They are currently being revised by the data publisher.

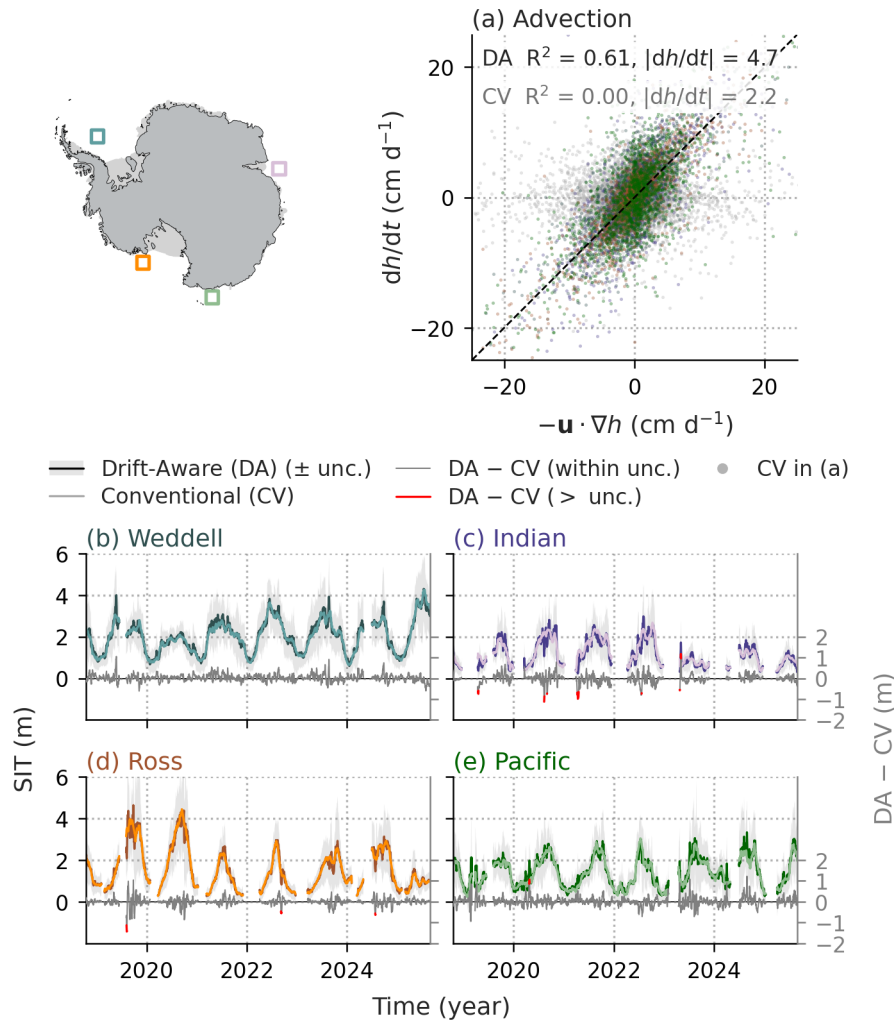


Figure 11. Revised Figure 10. (a) Daily thickness change versus the thickness change expected from advection by the ice drift ($-\mathbf{u} \cdot \nabla h$, OSI SAF drift), for the drift-aware (DA, coloured by region) and conventional (CV, grey) products; the dashed line is the 1:1 line. (b–e) Box-averaged SIT time series for DA ($\pm$ uncertainty) and CV; the DA–CV difference is shown on the right axis, in red where it exceeds the uncertainty.

180 References

- Lavergne, T. and Down, E.: A Climate Data Record of Year-Round Global Sea Ice Drift from the EUMETSAT OSI SAF, Tech. rep., ESSD – Ice/Snow and Sea Ice, <https://doi.org/10.5194/essd-2023-40>, 2023.
- OSI SAF and EUMETSAT SAF On Ocean And Sea Ice: GBL SIDR CDR 1OSI-455Global Sea Ice Drift Climate Data Record Release v1.0 - Multimission, https://doi.org/10.15770/EUM_SAF_OSI_0012, 2022.
- 185 Ricker, R., Lavergne, T., Hendricks, S., Paul, S., Down, E., Killie, M. A., and Bocquet, M.: Drift-aware sea ice thickness maps from satellite remote sensing, <https://doi.org/10.5194/egusphere-2025-359>, 2025.