Authors' Response to Reviews of

Enhancing sea ice knowledge through assimilation of sea ice thickness from ENVISAT and CS2SMOS

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The Cryosphere,

RC: ***Reviewers' Comment***, AR: Authors' Response, ☐ Manuscript Text

Dear Editor, Mitchell Bushuk and Anonymous Reviewers

Firstly, we would like to thank you all very much for the constructive comments and suggestions for the manuscript "Enhanced Predictability of Antarctic Sea Ice through Sea Ice Thickness Assimilation". Your insights are very useful in enhancing the quality of our work. Based on the comments and suggestions, we will revise the manuscript accordingly.

Please find our detailed point-by-point responses to the reviewers' comments in the following sections. Below, we list each comment (Reviewer Comment, **RC**) and insert our response (Authors' Response, **AR**) along with the corresponding revisions of the manuscript (inside the **black box**).

Sincerely,

Nicholas Williams
On behalf of all the authors

Reviewer: Mitchell Bushuk

RC: ***This manuscript presents a novel Antarctic sea ice data assimilation experiment, which assimilates the newly-available LEGOS sea ice thickness (SIT) observational product into the NorCPM model. The authors evaluate the reanalysis and seasonal prediction skill impacts of adding these new SIT observations. They find that seasonal predictions of regional Antarctic sea ice extent (SIE) and SIT are both improved by adding SIT assimilation, relative to the control experiment.***

This manuscript addresses a critical topic for the Antarctic sea ice prediction community, which is the effective use of SIT observations for seasonal sea ice predictions. I appreciate the careful methodology employed in this study, including a sufficiently long hindcast period to derive statistically robust results. However, I do have some concerns about the manuscript in present form which I think should be addressed before the manuscript is published. My recommendation is Major Revisions.

AR: We thank the reviewer for their appreciation, insightful comments, constructive feedback and proposals to further improve the paper.

0.1. Major Comments:

RC: ***1) Observational sea ice thickness uncertainty***

This study is based on the assimilation of LEGOS SIT observations, and shows improvements in SIE and SIT prediction skill associated with this SIT assimilation. A key question that remains unclear is the degree of observational uncertainty in the LEGOS SIT product, and the role that this uncertainty might play in the results presented. In particular, Figure 4 shows very large RMS differences between LEGOS SIT and IceSat-2 SIT and SMOS SIT. These RMSE values are even larger than the difference between the data assimilation experiments and SMOS/IceSat-2 SIT. The differences with SMOS are somewhat unsurprising given its known biases for thick ice, however, the differences relative to IceSat-2 are quite surprising. These differences are also notably larger than the uncertainty values provided in Bocquet et al. (2024). This raises the question: to what degree can LEGOS SIT be considered an observational "truth"? Some discussion on this point should be added throughout the manuscript, especially in sections 2.3, 4.1, and 5.

To better address this point, I suggest adding LEGOS SIV and also SIV based on IceSat-2 SIT to Figures 2 and 9. This would give a better sense of the observational uncertainty, and it would be helpful to see how the assimilation runs compare to these observational values.

Even if the LEGOS SIT product has systematic errors, I believe that seasonal prediction skill evaluation can serve as a useful and quasi-independent assessment of the value of this observational dataset. In particular, LEGOS SIT improves predictions of observed SIE, which suggests that there is certainly some meaningful information on SIV interannual variability that is being assimilated. I invite the authors to make this point somewhere in the Introduction or Discussion and Conclusions section.

AR: We thank the reviewer for this insightful comment on the uncertainty in the LEGOS SIT and their suggestions to clarify the role it plays in this study. We would like to emphasise that we never considered LEGOS SIT as the truth, on the contrary. We started the validation with LEGOS SIT for a sanity check (that the data assimilation does what it should) and because it has the longest period of observations. We agree with the reviewer that even if the LEGOS SIT product has systematic errors, it provides meaningful information from the interannual variability that is being assimilated. Furthermore because of the inclusion of our K-factor in the assimilation (Sakov et al., 2012), the observation error can be inflated at certain times or locations if the EnKF is not able to find a dynamical solution within the model ensemble. We add additional sentences in sections 2.3 and 5, and we have revised Figures 2 and 9 to include a LEGOS-OSTIA SIV derived using LEGOS SIT and OSTIA SIC:

In the datasets for assimilation section, we revise:

> The observation uncertainty is estimated in Bocquet et al. (2024) using an ensemble method. The main sources of uncertainty in deriving SIT are identified (snow depth, snow density, ice density, etc.) and multiple sources of in-situ, satellite or modelling estimates of these are used to estimate each of these and produce an ensemble.

In the discussions and conclusions section, we add:

> Despite these uncertainties, the improvement in seasonal prediction skill following the assimilation of LEGOS SIT provides an important, quasi-independent validation of its utility. In particular, improved prediction of sea ice extent suggests that LEGOS SIT captures meaningful large-scale variability in sea ice volume, even if absolute thickness values differ from other products.

Following the reviewer's suggestion, we have used LEGOS SIT and OSTIA SIC to produce a combined LEGOSxOSTIA SIV, and added these to figures 2 and 9 in section 4.1. For ICESat-2 it is not possible to add it to these figures due to the much shorter time period of availability (only 2018-2023). The updated figures are shown in Figures R1 and R2. The text discussing these figures in section 4.1 is also briefly revised as follows:

> The differences in the seasonal cycle of SIE between the two reanalyses are negligible. As we use anomaly assimilation for ocean and SIC, they both show a large bias compared to observations. On the contrary, the seasonal cycle of SIV is strongly different between EXP-OC and EXP-OCT (Figure 2b). Antarctic SIV is increased in EXP-OCT in austral winter, and decreased during the rest of the year in comparison with EXP-OC and NorESM, which brings closer agreement of EXP-OCT with the derived LEGOS-OSTIA SIV. The timing of the peak volume season also differs in EXP-OCT, as ice volume almost reaches its peak already in August.

RC: ***2) Comparison to reference forecasts It is encouraging to see the level of seasonal prediction skill for regional SIE and SIT. It would be useful to place these skill values in context by comparing the skill to an anomaly persistence or damped anomaly persistence forecast. I suggest adding this information into Figures 11 and 12. One way to do this would be to use upward facing triangles for ACC values that are statistically significant and exceed persistence skill, and downward facing triangles for values that are significant but have lower skill than persistence.***

AR: We thank the reviewer for this useful suggestion. We agree that comparing the prediction skill to an anomaly persistence forecast will improve the study further. We have changed the figure using triangles for ACC values, which are statistically significant and exceed persistence, while only using dots for significant values which do not exceed persistence (we use dots over downward-facing triangles as this enhances readability). The updated figures are shown in Figures R3 and R4. The text describing and discussing these figures is also revised. We can still find that our system has a lot of skill that beats persistence.

We also add a paragraph to the results section:

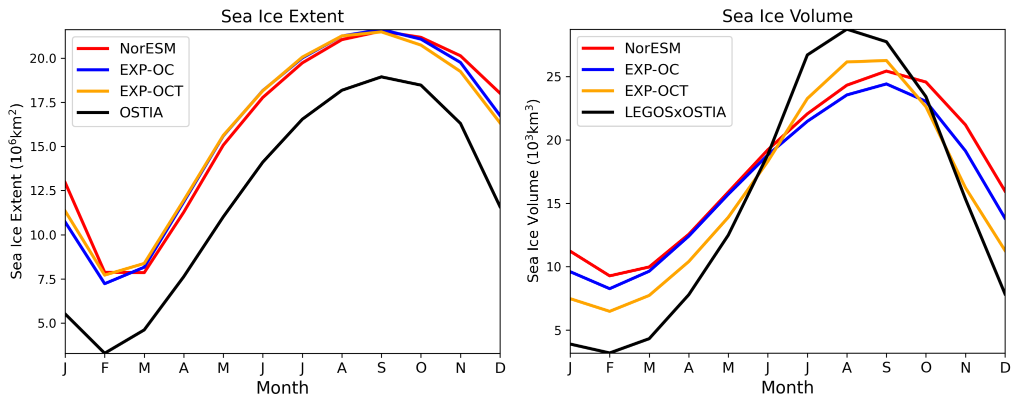

Figure R1: Monthly climatologies of the Antarctic sea ice extent (a) and Antarctic SIV (b) in NorESM, EXP-OC, EXP-OCT and the OSTIA observations (only in panel a) and LEGOS SIV (produced using OSTIA SIC-only in panel b) over the 1994-2023 reanalysis period.

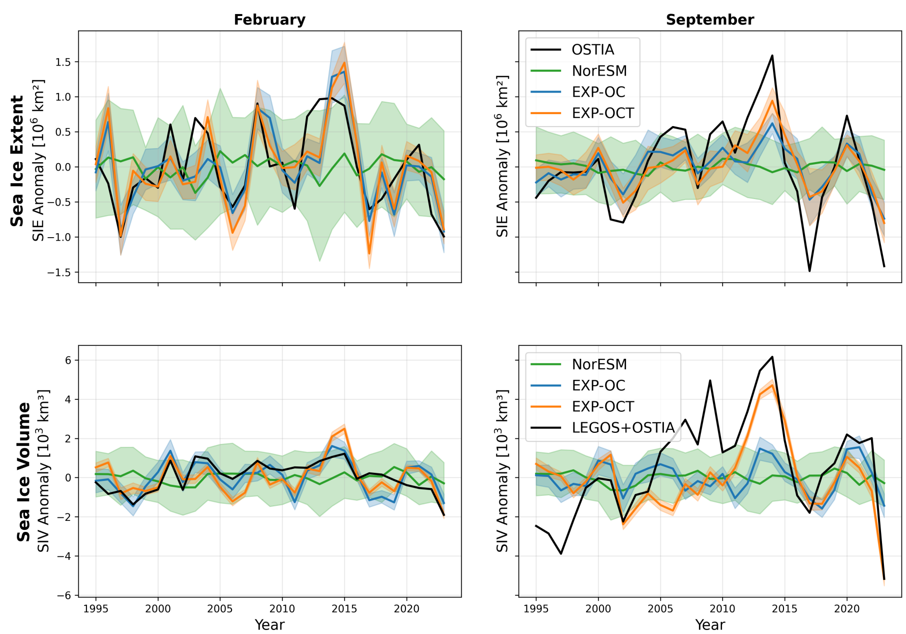

Figure R2: Time series of February and September detrended monthly anomalies in pan-Antarctic SIE (a, b) and SIV (c, d) between 1995 and 2023 for OSTIA, LEGOS SIV (produced using LEGOS SIT and OSTIA SIC) NorESM, EXP-OC and EXP-OCT. Shading shows ensemble spread for NorESM, EXP-OC and EXP-OCT defined as plus/minus one standard deviation.

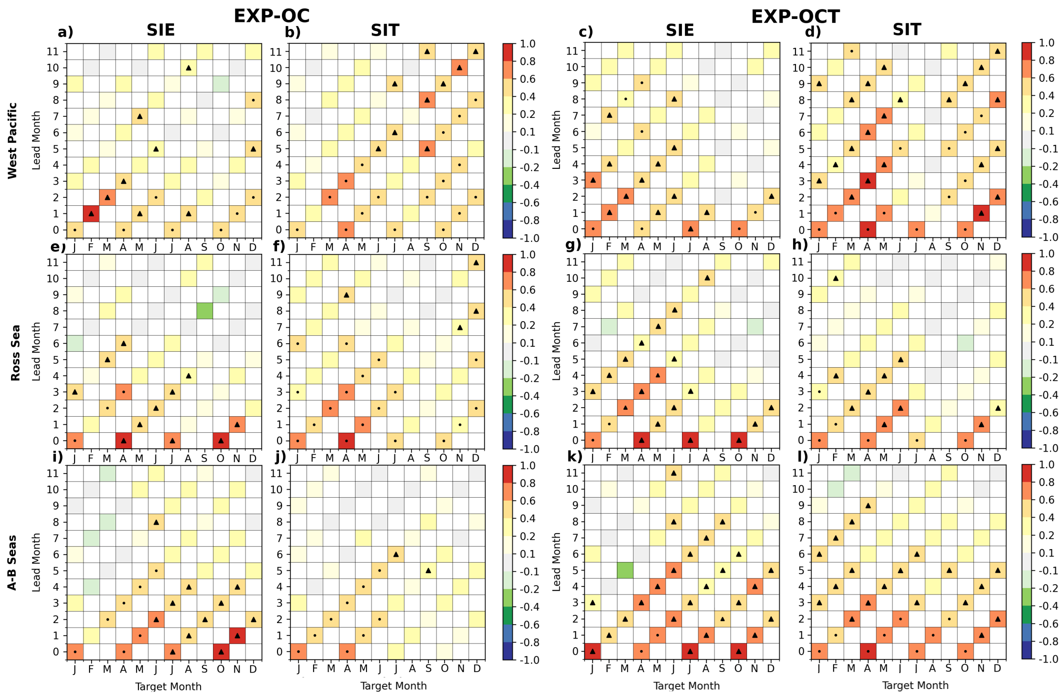

Figure R3: ACC for the West Pacific, Ross Sea and Amundsen-Bellingshausen Seas SIE and SIT for our seasonal hindcast datasets for EXP-OC and EXP-OCT in comparison with OSTIA SIC and LEGOS SIT. Target months are shown on the x-axis, with lead months shown on the y-axis. Triangle markers represent statistically significant ACC values and which exceed persistence, while dot markers only represent significant values which do not exceed persistence.

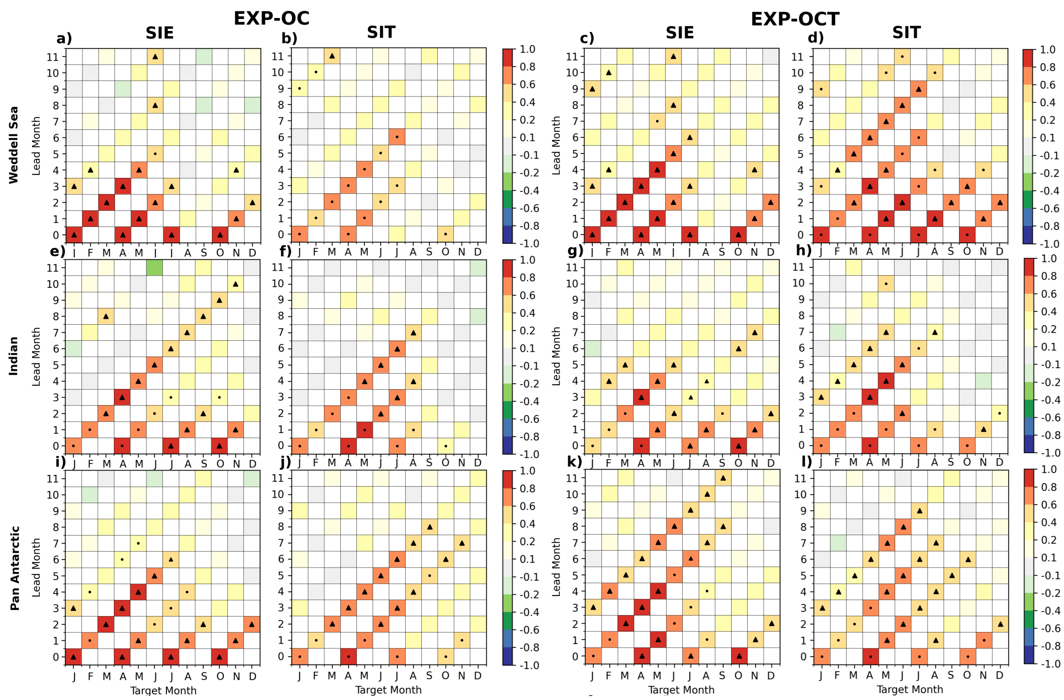

Figure R4: ACC for the Weddell Sea, Indian Sector and pan-Antarctic SIE and SIT in EXP-OC and EXP-OCT in our seasonal hindcast datasets for EXP-OC and EXP-OCT in comparison with OSTIA SIC and LEGOS SIT. Target months are shown on the x-axis, with lead months shown on the y-axis. Triangle markers represent statistically significant ACC values and which exceed persistence, while dot markers only represent significant values which do not exceed persistence.

In both EXP-OC and EXP-OCT, a substantial fraction of statistically significant ACC at the shortest lead times (0-2 months) does not exceed persistence, indicating that forecast skill can be largely attributed to the inherent memory of the sea ice system. However at longer lead times EXP-OCT shows more regionally and temporally localised improvements in SIE and SIT prediction skill, which are significant and exceed persistence. This demonstrates that the assimilation of SIT enhances NorCPM's sea ice prediction skill beyond persistence at longer lead times.

0.2. Minor Comments:

RC: ***Title: "Predictability" is an inherent property of a dynamical system, and therefore assimilating SIT does not enhance the predictability. Rather, assimilating SIE enhances the prediction skill. Therefore, I suggest changing the title to "Enhanced Prediction Skill of Antarctic Sea Ice through Sea Ice Thickness Assimilation."***

AR: As other reviewers also mentioned, the title can be improved to be more accurate and specific. We agree and propose changing the title to "Enhanced Prediction Skill of Antarctic Sea Ice through Sea Ice Thickness Assimilation".

RC: ***Line 31: I would argue that at least three primary mechanisms on the seasonal time scale have been demonstrated in the literature: 1) OHC persistence, advection, and reemergence, 2) SIT persistence and advection, and 3) SIE persistence. I suggest rephrasing this sentence to make it more clear that multiple mechanisms exist. Also, I suggest adding a sentence or two on previous findings related to SIT as a source of predictability.***

AR: We agree with the reviewer and clarify the first sentence in this paragraph to clearly state these three mechanisms:

On seasonal timescales, there are three primary mechanisms underpinning Antarctic SIE predictability. Ocean heat content (OHC) anomaly persistence, advection and re-emergence (Holland et al., 2013; Guemas et al., 2016), SIT persistence and advection (Morioka et al., 2021; Bushuk et al., 2021), and SIE persistence (Morioka et al., 2019; Bushuk et al., 2021; Xiu et al., 2025). OHC anomalies during the growth season...

RC: ***L111-112: Is there a reason why the CMIP5 forcings are still being used? It seems like a missed opportunity to not use the additional 9 years of historical forcing data (up to 2014) available from CMIP6.***

AR: A version of NorCPM was developed and contributed to CMIP6 DCPP (Bethke et al., 2021), but there was strong evidence of error in the forcing implementation that led to degraded performance (Passos et al., 2023). The land surface types and transient land-use [used in the new version] caused an unrealistic land-cryosphere cooling trend over the historical period. We have therefore decided to keep the CMIP5 version until the new CMIP7 is ready and fully tested (ongoing).

RC: ***L132-137: Figure 2 shows that NorESM is biased high in terms of sea ice extent in all months of the year. Does this bias affect the anomaly assimilation methodology? In other words, the observed anomalies may occur at a different spatial location than the model's sea ice edge. If the model is biased high, this might lead to unrealistic amounts of SIC variability within the ice pack. Is there any indication of this type of behavior occurring in these experiments? I suggest adding a few lines discussing this issue.***

AR: It is correct that NorESM has a bias for nearly all months. We have tested extensively the anomaly assimilation of SIC with NorESM (Kimmritz et al., 2019; Williams et al., 2025), and we have not noticed high variability in the ice pack. Also see figures (3,6,7). We think this is because with an EnKF, the model uncertainty is quantified from the ensemble spread. As such, if all member have 100% ice, the model uncertainty is 0 and there cannot be any change (Same is there is no ice, the spread is 0). In other words, change can only happen in the transition zone, and will happen gradually through iterative assimilation.

We have added the following sentence:

> Please note that the rationale for assimilating anomaly in NorESM has been described and verified in previous papers (Kimmritz et al., 2019; Bethke et al., 2021; Williams et al., 2025). We do not see that the assimilation causes artefact or instability, which we relate to the stabilizing properties of the Ensemble Kalman Filter.

RC: ***L196: It would be helpful to quote some typical uncertainty values here, including any spatial and seasonal variations that exist.***

AR: Thank you for your helpful suggestion. We add a few typical values for the ice edge and ice pack during February and September respectively.

RC: ***L210: Please add the forcing used (I believe it is CMIP5 Historical+RCP8.5).***

AR: Yes, it is CMIP5 Historical+RCP8.5, we specify this in section 2.1, thank you.

RC: ***L212: There is no atmospheric observational constraint in these experiments, correct? Suggest mentioning this explicitly here, or in the paragraph above.***

AR: Yes, there is no atmospheric observational constraint; we will clarify this by adding the following at line 205 (in the paragraph above):

> In this study, we do not assimilate data in the atmospheric component of NorCPM.

RC: ***Figure 1: What motivated this definition of the Weddell Sea? The region is small compared to the typical definition considered (e.g. Holland et al., 2013). In particular, the location of the Weddell polynya near Maud rise lies well outside this domain.***

AR: This is a definition we have used in previous NorCPM papers looking at regional Antarctic prediction (Xiu et al., 2025), so we wanted to continue using the same definition for consistency. The original reasons for this choice were geography and incorporating the NorCPM skill in simulating SIC variability.

RC: ***Line 248: I assume that this should be 95%?***

AR: For the statistical significance of the t-test, I believe this can be expressed as either 5% significance ($p < 0.05$) or a 95% (1-0.05) confidence level. We change this in the manuscript to clarify both:

> We test the statistical significance of the ACC using a Student's t-test at a 5% significance level (95% confidence level).

RC: ***Figure 2: It appears that the values for extent and volume are both off by a factor of 10 here.***

AR: Apologies, we found the values were scaled incorrectly and should be increased by a factor 10, we have corrected this in the updated figure shown in response to the previous comment above.

RC: ***Figure 4: What spatial domain are the RMSE values computed over?***

AR: Thank you for pointing out this uncertainty in the study. These values are computed over the spatial domain with which the relevant observations are available for the pan-Antarctic. We have added the following to the manuscript to clarify this:

> When comparing and validating against the ICESat-2, SMOS, and LEGOS datasets, we restrict the analysis to grid cells and time periods where both the model output and observational data exist. Monthly values are therefore computed only when a sufficient number of daily observations are available to form a representative monthly mean, ensuring that all metrics are evaluated over consistent spatiotemporal subsets of the data.

RC: ***Lines 286-288: I agree that EXP-OCT provides a clear improvement over EXP-OC. However, these errors are still very large. The errors are roughly 2 times the observed values from SMOS, even over the thickness ranges where SMOS is considered reliable. Some comments should be added on this, making clear that this product is not really doing a very good job at capturing the SMOS thickness values.***

AR: We thank the reviewer for highlighting this point. We agree that although EXP-OCT shows clear improvements relative to EXP-OC, the absolute errors remain relatively large when compared to the SMOS thickness estimates, even within the thickness ranges where SMOS is considered more reliable. This is also a motivation to assimilate SMOS, but it would be too short to demonstrate the added value for seasonal predictions. In the revised manuscript, we clarify this limitation in the discussion of Figure 5. We change the paragraph as follows:

> Therefore, we further examined model skill by SIT ranges (Figure 5). EXP-OCT shows improved performance across all thickness bins, with the largest reductions in RMSE for ice between 0.2 and 0.8 m. Improvements are therefore not limited to the ranges where SMOS uncertainty is greatest, indicating that the assimilation enhances SIT representation even within the more reliable SMOS measurements below 0.5 m. However, it should be noted that the remaining RMSE values are still relatively large compared with the observed SMOS thickness, indicating that the system continues to exhibit substantial errors in representing thin sea ice. The main improvement shown here is a relative reduction in error compared with EXP-OC, rather than a strong agreement with the observed thickness values.

RC: ***Figure 5: Are these RMSE values for the climatological thickness, or RMSE for the time-varying thickness (which includes interannual variability)?***

AR: These RMSE values are computed using time-varying thicknesses. We clarify this in the figure caption as follows:

> RMSE of modelled time-varying sea ice thickness from EXP-OC and EXP-OCT simulations compared to SMOS satellite observations, binned by SMOS sea ice thickness (0–1.0 m) taken across April–October for 2010–2022. Each bar represents the mean RMSE within the corresponding SMOS thickness interval.

RC: ***Lines 326-335: It would be helpful to place these IIEE values in context by including reference values from the IIEE of the observed SIC climatology in Figure 10.***

AR: Thank you for this comment which will improve the understanding from the figure. We have updated the figure with reference observation climatology values as shown in Figure R5.

RC: ***Typos: L88: "observational datasets" L185: Remove "and" at the start of this sentence.***

AR: Thank you, we have corrected these typos.

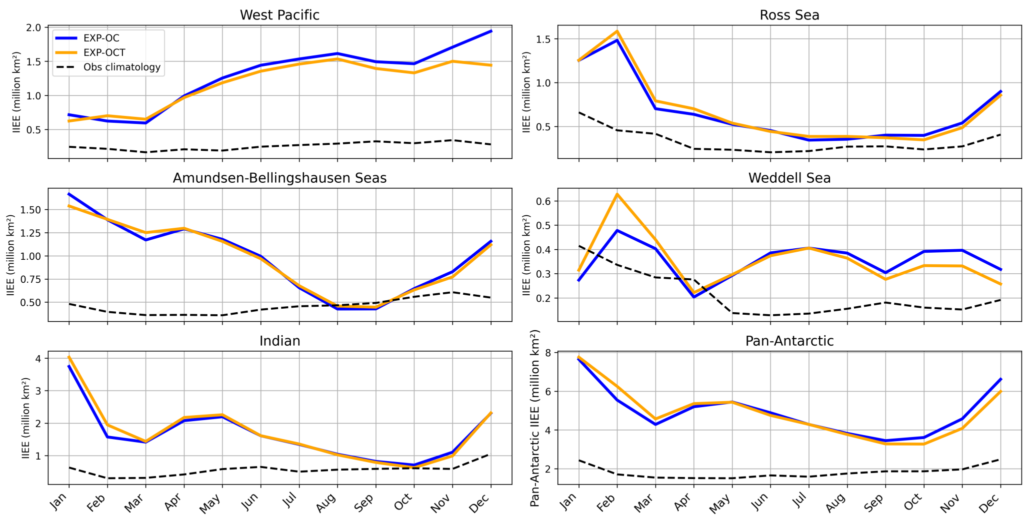

Figure R5: Monthly climatologies of the Antarctic IIEE in each of our defined regions, and for the pan-Antarctic, for EXP-OC and EXP-OCT and an observation climatological benchmark (Obs-climatology) compared with OSTIA observations between 1995 and 2023. Note that the y-axis scale differs in each subplot in order to show differences in each region clearly.

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