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 and Imke Sievers

Firstly, we would like to thank you very much for the constructive comments and suggestions for the manuscript “Enhancing sea ice knowledge through assimilation of sea ice thickness from ENVISAT and CS2SMOS”. Your insights are very useful in enhancing the quality of our work. Based on the comments and suggestions, we have revised the manuscript.

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

1. Reviewer: Imke Sievers

RC: ***Currently the article is missing a clear discussion of the differences in skilfully predicting the sea ice state between assimilating ENVISAT and CS2SMOS. The title, summery and aim in the introduction (line 60) give the impression that the article mainly addresses new insight from assimilating ENVISAT in comparison to only assimilating CS2SMOS, however the article only discusses the difference between the reduction of bias and bias free root mean square error for both satellites, not the difference in forecasting skill. Keeping the large SIT bias of the model in mind, the bias correction is to be expected. Either additional analysis should be added, or this should be made clear in the title, introduction and summery and the choice to not analysing the difference in skill between assimilating only CS2SMOS and assimilating both SIT products should be motivated. For example does the summery state that the article focuses on the skill of seasonal prediction. From reading this I would expect that the article analysis the differences in skill from assimilating ENVISAT vs. CS2SMOS, however this is not the case. This is unfortunate, since the assimilation of ENVISAT is the main novelty of the study.***

AR: While we agree that assimilation of ENVISAT is one of the novelties of the manuscript, we do not see it as the main novelty. The main novelty of this study is that we have been able to extend the reanalysis and hindcast sea ice prediction period over a sufficiently long period (21 years) to robustly assess the added value of SIT. We think that the title clearly highlights this objective, but we fully agree that the introduction was misleading. We have revised the following paragraph (L75-86):

> In this study, we will investigate how assimilation of SIT observations from ENVISAT and CS2SMOS can first benefit our sea ice reanalysis and Arctic sea ice predictions by using seasonal hindcasts (i.e., retrospective predictions) started from 2003 to 2023. As such, this study provides for the first time an analysis of the added value of SIT initialisation for a sufficiently long period (21 years) to assess robustly its impact. Furthermore, to our knowledge, ENVISAT SIT observations have not been assimilated before in a GCM, so this study will investigate their use and feasibility of inclusion for assimilation in GCMs for the first time. We investigate not only SIE/SIT predictions but also the prediction of the sea ice edge location using the integrated ice edge error (IIEE).

Still, we have tried to compare the two observation products. However, this analysis is limited due to the shortness of the time series. For example, we have compared the assimilation influence (DFS) and assimilation diagnostics during both observation periods (Figures 1 and 2 in the revised manuscript). As expected (in view of the observation uncertainty), C2SMOS provides increased impact on the assimilation as shown by the increase in DFS (Figure 2c-d in the revised manuscript).

RC: ***2) It is clear that a lot of work and testing has gone into the assimilation set up, which is very well done. However the method section is currently a bit confusing and lacks some important information for the study to be reproducible: 1) how is the SIC updated by the SIT assimilation, in one categories, in several categories, etc? 2) How does Full filed assimilation differ from anomaly field assimilation? What effects on the results are expected of mixing them? 3) Is there a reason why you choose to not assimilate both SIT observations during their overlap? 4) Please add version numbers to the model components where applicable. 5) Which variables are in the state vector. For the Ocean this is clear, but how about the sea ice?***

AR: 2.1) The details of the assimilation have been described in (Kimmritz et al., 2018, 2019) extensively, and we build on that. However, we acknowledge that it was too succinct (as also highlighted by the other reviewer). We now clearly indicate the sea ice state vector(i.e., the multicategory sea ice fraction aicen) as well as diagnosing the multicategory sea ice volume so that the multicategory sea ice thickness is not changed by assimilation. Please refer to the main text (L126-145):

> Assimilation of ocean temperature and salinity profiles, sea surface temperature (SST), and SIC observations is performed as described in Kimmritz et al. (2019). We employ anomaly-field assimilation, using a monthly reference climatology calculated from 1982 to 2016. We update both the ocean and sea-ice components based on the observations from both components, so called strongly coupled ocean-sea ice DA (Laloyaux et al., 2016; Kimmritz et al., 2018). Strongly coupled ocean-sea ice DA in NorCPM was shown to be more effective than weakly coupled DA in which sea ice observations are used to only update the sea ice variables (Kimmritz et al., 2018). We update the full ocean physics state vector in isopycnal coordinates (i.e., 3D temperature, salinity, velocities and layer thickness) and update the multicategory SIC in the sea ice state vector (i.e., the multicategory aicen within the 5 categories, see DEPTH HI_PRESERVE in Kimmritz et al. (2018)). The sea ice volume in each thickness category is changed proportionally so that the thickness of each thickness category remains identical to that of the prior (i.e., the multicategory hicen before assimilation). This prevents the need to reshuffle ice to a different thickness category in the post-analysis, which proved to be optimal in an idealised twin experiment (Kimmritz et al., 2018). The post-processing step ensures that sea ice state variables remain within physical ranges and recompute the energy budget of each of the multicategory sea ice quantities (Appendix 1 in Kimmritz et al. (2018) for further details).

> When assimilating SIT observations, we only update the individual category sea ice fraction, which can change the sum of the ice fraction. In the post-processing of the assimilation, the sea ice volume in each thickness category is changed proportionally so that the thickness of each thickness category remains identical to that of the prior. We do not update the ocean component, as the covariances between SIT and the ocean are very small, and may cause more harm than benefit because of sampling error.

2.2) The problem of full-field versus anomaly assimilation has also been raised by the other reviewer, and we have made several modifications to explain why we have chosen this approach. Anomaly assimilation neglects the climatological difference between model and observation and only aims to update the anomaly.

NorCPM used anomaly assimilation for the ocean because a full field introduces large prediction drift (reemergence of the bias) that degrades prediction performance, in particular in places where there are no observations (e.g, intermediate to deep ocean) (Garcia-Oliva et al., 2024; Counillon et al., 2016). Because the ocean has a much larger heat capacity than sea ice, we also perform assimilation of sea ice concentration in the anomaly field so that the ice mask is in equilibrium. For the assimilation of thickness observations, we use full-field assimilation. Please refer to the text in the manuscript (L144-147):

> NorESM has a large SIT bias (Bentsen et al., 2012), and while assimilation of ocean observation reduces it partially, some of the bias remains. Bethke et al. (2021), compared two versions of NorCPM assimilating ocean observations, one that updates only the ocean component and one that updates the ocean and sea ice components. The latter yields a strong reduction of the bias of SIT and provides enhanced predictions. Note also that it takes about ten years for the model to rebuild the SIT bias once assimilation is stopped (their Figure S15). We, therefore, use full-field assimilation to correct the SIT bias that can influence the variability. In the first attempt, we used anomaly-field assimilation. However, the assimilation impact of SIT anomalies was inconclusive, with no added skill for predictions (not shown).

2.3) In theory, the reviewer is fully correct that both C2SMOS and ENVISAT can be assimilated jointly if they were independent, and it could have been an interesting experiment. However, we do not think it is straightforward and it may not lead to a significant improvement, for the following reasons: i) the retrieval algorithm from the altimeter may introduce some correlation in the final products, and it is hard to quantify it exactly. The largest discrepancies between the two products revolve around much higher biases in ENVISAT due to instrument differences. ii) The C2SMOS observation product is much more accurate, so that the ENVISAT SIT becomes nearly ineffective if both products are assimilated.

2.4) We have updated to show the versions of each model (L93-106)as follows:

> The NorESM version used here is NorESM1-ME (Bentsen et al., 2013). It is based on the Community Earth System Model (CESM1.0.4, Hurrell et al., 2013). However, the ocean component is replaced with an isopycnal coordinate ocean general circulation model (BLOM, Bentsen et al., 2012), and the Community Atmosphere Model version 4 (CAM4, Neale et al., 2010) with the original prescribed aerosol formulation is replaced by the atmospheric model CAM4-OSLO with a prognostic aerosol life cycle formulation using emissions and new aerosol-cloud interaction schemes (Kirkevåg et al., 2013).
>
> As in CESM1.0.4, NorESM1-ME uses the Los Alamos Sea Ice Model version 4 (CICE, Hunke et al., 2015) and the Community Land Model (CLM) version 4 (Lawrence et al., 2011). These are coupled using version 7 of the coupler designed for the CESM (Craig et al., 2012).

2.5) See our answer to 2.1)

1.1. Minor comments

RC: ***line 25-27: please add reference***

AR: Added reference to Nghiem et al. (2007) and Sumata et al. (2023) on changes in the sea ice cover thickness, thanks.

RC: ***line 234: first occurrence of acronym RHS***

AR: Corrected, thanks.

RC: ***line 280-281: add citation***

AR: Added reference to Sumata et al. (2015), thanks.

RC: ***line 315 which visual agreement is referred to?***

AR: This is referring to Figure 5d, which we now clarify in the text (L349-351):

> All systems capture the decreasing trend in SIV well. Interannual variability is stronger in CTRL than in FREE and even more pronounced in +SIT (Figure 6d).

RC: ***table 2: it would increase readability to use the same exponent within one column (not the case for SIV of +SIT)***

AR: Agreed, thanks for the suggestion, we have changed all the exponents in the SIV column to match, thanks.

RC: ***line 319: +SIT has a strong discontinuity only in SIV, the SIE is actually in line with observations, or? (figure 5)***

AR: Yes, we were referring to the SIV only, we clarify this in the manuscript now (L354-355):

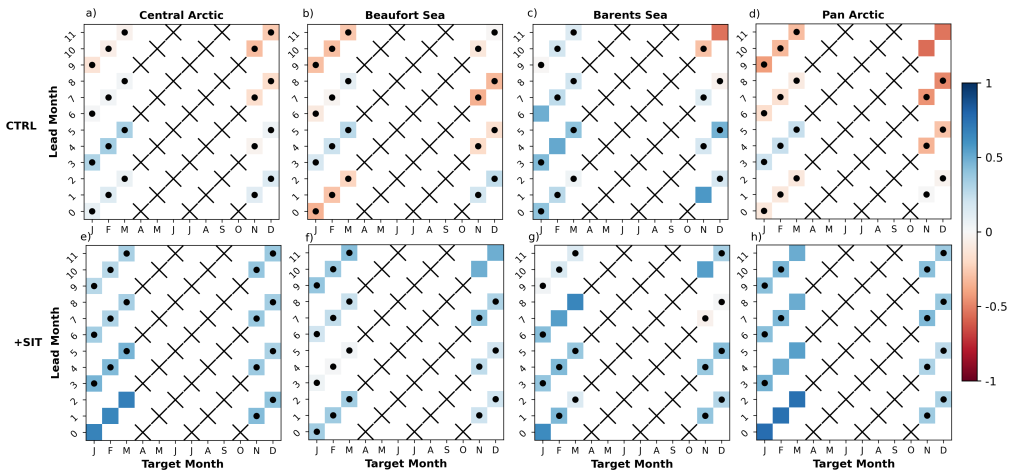

Figure R1: Detrended ACCs of our seasonal hindcasts for SIT from CTRL and +SIT with observations of SIT from CS2SMOS. Crosses are shown when comparison with observations is not possible due to lack of observations. The dots represent the ACC values that are not statistically significant.

> +SIT has a strong discontinuity in 2010 for SIV during the transition between ENVISAT and C2SMOS.

RC: ***1) line 320-325 which table figures are you referring to?***

We have clarified this section to clearly refer to the different tables and figures we are discussing (L356-360):

> In September, all systems have high positive SIE biases as a direct consequence of anomaly assimilation, as seen in Figure 5. Table 2 shows that CTRL and +SIT show higher ACC values than FREE. The agreement is better in +SIT, with ACC increasing from 0.7 to 0.8, and slightly reduced bfRMSE. In Figure 6, the ensemble mean of FREE shows, again, nearly no interannual variability. In the same figure, we see that +SIT better captures the amplitude of the peaks and, in particular, the minimum in 2007 and 2012.

RC: ***3) figure 3: what is the criteria for not enough point to calculate a yearly average?***

AR: The criteria is that if there are more than 30 continuous days of missing data in one year, we would compute the yearly average for this specific year. For example, ULS C was not used after early 2008. So there is no yearly average in the plot after 2007. We have modified the caption for Figure 4 to clarify this as follows:

> If there are more than 30 continuous days of observations missing from a ULS mooring, we do not compute a yearly average and these years are masked.

RC: ***2) figure 7: please add a accessible colour bar varying between two colours.***

AR: We have added the Red-Blue colour bar similar to what we have used in other plots for this plot, the new plot is shown in Figure R1.

RC: ***Line 408-409: Which section is this based on? From figure 5 it looks as if the sea ice extent is only improved in September, not in March during the ENVISAT period.***

AR: This section is meant to refer to two things: 1) the improved performance in September for +SIT is due to the reduction of SIT bias by the ENVISAT assimilation, and 2) the hindcasts, where ice thickness and ice edge estimates are improved between August and October. We have modified the sentence (L451-455) to clarify this:

> We evaluated the assimilation of ENVISAT and CS2SMOS SIT data into NorCPM. While ENVISAT has higher uncertainties than CS2SMOS, it extended the reanalysis period and improved SIT and ice edge hindcast estimates in the central Arctic, particularly during the melt season through the SIT bias reduction in winter.

RC: ***Line 410: CS2SMOS is only available from 2010, so it can not improve anything before.***

AR: Agreed, this sentence was meant to be a comparison of ENVISAT to CS2SMOS observation assimilation. We have clarified the meaning of this sentence to say (L454-456):

> CS2SMOS provided more accurate data and greater reductions in biases in comparison to ENVISAT.

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