Regime-dependence when constraining a sea ice model with observations: lessons from a single-column perspective

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The authors would like to thank the editor and both referees for the time and effort that have been dedicated to providing feedback on this manuscript. Please find below, in blue, our responses to referee comments, questions, and concerns. All page and line numbers refer to the revised manuscript.

Responses to Referee 1

This paper aims to quantify the influence that assimilating different observations of sea ice can have under different sea ice conditions. The authors use a single column sea ice model and use an ensemble data assimilation to test the assimilation of synthetic observations of sea ice concentration, sea ice thickness, radar and lidar freeboard in an idealized experiment. The authors investigate the effects of the assimilation on both the aggregate sea ice concentration, sea ice volume and snow volume, as well as the thickness categories. It was found that the assimilation of sea ice thickness provides the largest, positive impact. Laser freeboard was found to be the second most impactful observation to assimilate, and unlike radar freeboard, it did not degrade the snow volume. For the different regime conditions of sea ice, the study showcases a need to carefully treat the categorized state variables when assimilating observations. The paper is well written and the methods are well described. The figures are well thought out and interpreted thoroughly for the results section.

Novelty

The main novelty from the paper is in the assessment of ice thickness and freeboard (both radar freeboard and laser freeboard) and how the assimilation affects different regimes of the sea ice. The novel approach finds a potential best-case scenario for assimilation of different types of sea ice observation. The study will provide a lot of insight for those interested in sea ice data assimilation, and particularly for the assimilation of thickness and freeboard, which is an emerging field of study in sea ice. A key result showed that summer and early autumn assimilation of SIT shows strong skill in reproducing the true sea ice state, summer SIT observations were only first produced a few years ago, and their benefit in data assimilation and sea ice studies has not yet been fully explored. The study also provides insight into comparison of freeboard and thickness assimilation and interestingly shows that freeboard assimilation may be less effective than SIT assimilation. The insight into the effects of the assimilation of different observations on the sub-grid scale categories of the state variables is interesting for those interested in implementing sea ice data assimilation themselves, particularly in the implementation of sub-grid scale thickness assimilation

We thank the reviewer for highlighting the novelty and timeliness of this work, and for their kind words regarding the manuscript's structure and writing.

General Comments

Were any specific criteria chosen to determine locations of the pack, seasonal and first year sea ice i.e. in terms of sea ice concentration or sea ice age (e.g. 0.8 commonly being used to separate pack ice from seasonal ice). Alongside this, a map clearly showing the locations of the three defined types of sea ice (pack, seasonal, first year), which are described in the first paragraphs of the results section, would be beneficial.

We determined the selected locations based on the annual cycle of sea ice concentration. For PACK ICE, we required that the ensemble mean SIC remained above 0.8 throughout the year. For SEASONAL ICE, the criteria were an ensemble that experienced ensemble mean SIC greater than 0.8 *and* less than 0.15 during the annual cycle, and for FIRST-YEAR ICE, we required a location where all ensemble members melted completely for at least some portion of the year. As this comment is aligned with a similar comment from the second reviewer, we have added these selection criteria to the methods (*Prior Ensembles*, L159-164). The requested map figure has also been introduced as Figure 1 (*referenced at* L169-170).

Could the authors provide details of how the nonphysical modeled values in the state vector are post-processed after the assimilation, when they occur?

We have added a description of the postprocessing approach to the methods section (*DART,* L125-141). If the reviewer is interested in the more specific details of the postprocessing algorithm, it is also available on Github as a part of the official DART release (https://github.com/NCAR/DART/blob/main/models/cice/ice_postprocessing_mod.f90).

The discussion (or conclusion) could be further enhanced if the paper outcomes were compared to real world available observations. For example, the authors find that summer and late autumn observations are key, and that SIT observations have the most impact. However, they do not then reference to Landy et al., 2023 (although it is listed in the references, I could not find it referenced in the paper itself). This could be done for other observations also, which would increase the papers usefulness and insightfulness for others in the field.
We assume that this comment refers to a need to provide more real-world context as to the availability of different types of observations in ice conditions and times of year in which our results indicate they would be most useful. We agree that this would strengthen the manuscript and have added text to the discussion section of the paper that expands upon this point. L376-392 in *Discussions and Implications* now reads:

> "Across the three sea ice regimes, assimilating observations during the summer and early autumn freeze-up period demonstrated the greatest ability to reconstruct the true sea ice state. Of the observation types tested, SIT observations had the broadest, and often the largest, positive impact. Not only is MAE for modeled SIT reduced in all regimes, but assimilating SIT also reduces modeled SIC error in seasonally ice-covered regimes. This result arrives at a promising time, as advances in observation processing increasingly enable year-round estimates of SIT from remote sensing observations (Landy et al., 2022). While real, basin-wide SIT observations are still relatively limited during the summer months, these findings should reinforce efforts to improve SIT observing systems during the summer, particularly preceding the transition to freezing conditions.
>
> A novel finding of this study is the comparative impact of FBR and FBL observations, which differ in their impact on modeled snow depth in thick ice environments. While these two types of freeboard observations both appear to constrain thin ice environments very well, it must be noted that for present-day observing systems, both FBR and FBL observations

are only available in regions that exceed a relatively high sea ice coverage threshold (Petty et al., 2023; Kurtz, Galin & Studinger, 2014). Thus, FBL observations are likely to have a more positive overall impact compared to FBR observations, as FBL may also improve SIC and avoid degrading SND in thick ice regimes. Additionally, while freeboard observations of either type display very limited impact in seasonal ice, SIC observations perform comparably to SIT observations in this regime. Given their year-round availability and relatively low observational uncertainty compared to current SIT observational estimates, assimilating a year-round combination of FBL and SIC observations is likely to produce the most accurate sea ice state estimate in current three-dimensional applications."

We assume that the reviewer refers to Landy et al. (2022): *A year-round satellite sea-ice thickness record from Cryosat-2*, which was published in *Nature*. We have included this reference explicitly (above) and made sure it is listed properly in the references section.

Figures

For figure 2, the ticks for the top 2 rows of figure and the bottom rows are different, and the labels are only shown on the bottom row, the authors could make the x-axis ticks consistent between all the figures, so that the figure is easier to read.

Thanks to the reviewer for catching this mistake! It has been corrected in the figure, which is now Figure 3 in the updated manuscript.

The authors should add panel labels to the figures and each subfigure, which would allow easier reference to them in the text. On line 211 they refer to figure 4 panel labels but the labels do not exist in the figure.

We appreciate this suggestion and have added figure labels to multi-panel figures that are referenced in the text (Figures 2-6, Figure 14 in the updated manuscript).

Minor Comments

Line 9: DA is not defined yet.

Thanks for catching this! We have addressed this issue by defining data assimilation (DA) in line 2.

Line 34-35 add references to SIC assimilation papers

We have added references to Lisaeter et al. (2003), Schweiger et al. (2011), and Posey et al. (2015) as examples for SIC assimilation efforts at L35.

Line 77 add references to mushy-layer and delta-Eddington scheme

The relevant references (Turner, Hunke, & Bitz, 2013; Briegleb & Light, 2007; Holland et al., 2012) have been added to the manuscript at L77-78.

Line 141-142 confusing wording/sentence – seems like a list is introduced but then not continued.

This was a missing component of the reference to Table 1. It has been corrected at L157 in the revised manuscript.

Line 167 missing word "table"

Thanks for catching this omission, as well! We have corrected it (L189 in the revised manuscript).

There are a number of references which appear in the references list which do not seem to be cited in the paper e.g.: Brennan and Hakim, 2022, Chen et al., 2024, Holland & Kwok, 2012, Landy et al., 2023

We would like to express our appreciation for the reviewer's attention to detail in the reference section—we would likely have missed these errors without this comment! These citations have been removed from the references section, which has also been thoroughly checked for any other inconsistencies.