Review: Sea Ice Albedo Bounded Data Assimilation and Its Impact on Modeling: A Regional Approach

The paper presents a perfect model experiment comparing the prediction improvement caused by assimilating albedo in comparison to sea ice concentration and sea ice thickness in one dimensional Icepack simulations, for four regions in the Arctic. The study finds that depending on the error of the assimilated albedo and the region, that albedo assimilation outperforms SIC and SIT assimilation, except for one region. The work is relevant to the scope of The Cryosphere. Overall the paper is well structured and the experiments well designed and I would recommend minor revisions.

Thank you for sharing your overall favorable assessment.

Main comments:

1) The results emphasize the importance of the observation uncertainties. It is reasoned well why the SIC uncertainty varies with SIC, but should the same consideration not also be applied to SIT uncertainty and albedo uncertainty? I am unfamiliar with error dependencies in satellite albedo retrievals, but SIT errors are typically greater for thinner ice/thicker ice, depending on the product used. Since the errors are such a central part of the outcome of this study I would expect a higher focus on this.

Thank you for your insightful comment. Reviewer #2 raised a similar question regarding the uncertainty distributions and their influence on our results. Our choice of uncertainty configurations was guided by prior studies (e.g., Karellson et al., 2024 for SIAL; Wieringa et al., 2024 for SIC and SIT) and by discussions with Dr. Walt Meier at the National Snow and Ice Data Center (NSIDC). These reflect the distinct observational retrieval methods underlying each variable and their associated uncertainties. Specifically, SIAL retrievals are based on radiative transfer and depend on reflected shortwave radiative fluxes at the top of the atmosphere, whereas SIC retrievals rely on passive microwave measurements that exploit emissivity contrasts between open ocean and sea ice. SIT retrievals rely on a combination of both passive and active satellites, and its uncertainty is difficult to quantify. Because these retrieval techniques differ fundamentally, their uncertainty structures are also expected to differ.

To our knowledge, there are no widely accepted uncertainty constraints for any sea ice variable used in data assimilation—whether SIAL, SIC, or SIT. SIC is certainly the most developed and well-studied, given its widespread use in assimilation systems. For SIC, we used a negative parabolic uncertainty distribution with a maximum error centered at 12.5%. To test the sensitivity of this choice, we performed an additional experiment where the maximum SIC uncertainty was reduced to 5%, consistent with the "low" SIAL uncertainty configuration. The results, shown in Figure A, indicate that—except for the Barents Sea—this modification had little impact on the outcomes. We anticipated this limited sensitivity due to the bounded nature of sea ice data assimilation: during transitional seasons (melt and freeze-up), SIC evolves rapidly toward its bounds, making the exact shape of its uncertainty distribution relatively inconsequential in comparison to avoiding filter divergence during transitional seasons.

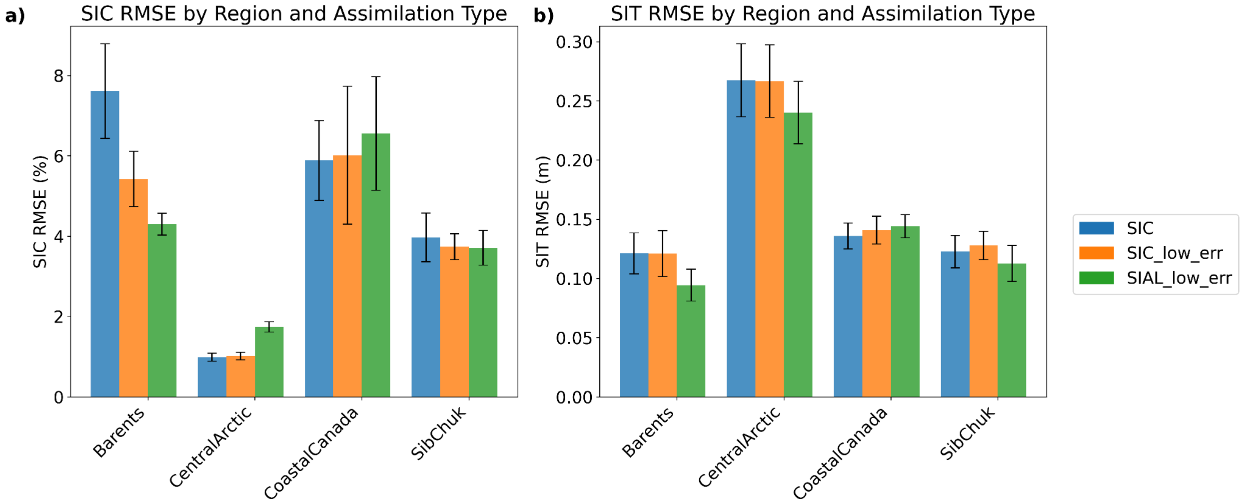


Figure A: Demonstration showing that varying the maximum SIC uncertainty (12.5% vs. 5%) has minimal influence on assimilation outcomes (using the level melt pond scheme).

For SIAL, the seasonal evolution of albedo allows for more gradual transitions—from higher SIAL values to lower ones—driven by snow melt, persistent bare ice, and melt pond development. Thus, constraining SIAL uncertainty has a more noticeable effect on the results. The linear form of SIAL uncertainty reflects the dependence of retrieval error on viewing angle and the bidirectional reflectance distribution function (BRDF), which makes it harder to accurately observe bright surfaces such as snow and ice. Consequently, higher SIAL values tend to have greater absolute uncertainty, although the precise magnitude remains uncertain—this is an important topic for future research. Conversely, lower SIAL values (associated with open ocean or melt ponds) generally exhibit smaller retrieval errors. Although this was not stated explicitly in the manuscript, SIAL uncertainty from satellite retrievals is likely around 5–10% of SIAL. The largest uncertainty sources are cloud-masking errors and the effects of temporal averaging to mitigate BRDF impacts. Until these uncertainties are better constrained, comparing SIAL assimilation under different assumed uncertainty distributions (low, medium, high) remains necessary. Given the long satellite record of SIAL, our study emphasizes the value of systematically testing these uncertainty structures.

For SIT, we acknowledge that retrieval errors are typically larger for both very thin and very thick ice, though the exact magnitude depends strongly on the product used. Additionally, for Arctic SIT products, observations are typically only available in areas that are more than ~50% ice covered (depending on the product, e.g. CryoSat-2 vs. ICESat-2. This tends to screen out large regions of very thin ice in pan-Arctic sea ice thickness products. Quantifying SIT uncertainty is therefore challenging—both because of the limited observational coverage and because each retrieval approach (e.g., radar altimetry, lidar) has different sensitivities. For this reason, we intentionally adopted a conservative approach by assigning SIT the lowest possible uncertainty distribution, comparable to the low-uncertainty configuration used for SIC. In this context we use the term ‘conservative’ to test our null hypothesis: that SIAL assimilation improves mean ice state prediction by assigning SIAL higher uncertainties and constraining SIC and SIT to low uncertainties. This enables a “best-case” comparison among SIC, SIT, and SIAL assimilation. Moreover, our use of a pan-Arctic daily assimilation window is highly idealized relative to the temporal resolution of the most accurate SIT products (e.g., ICESat-2), which provide only ~6 years of data and are difficult to validate given the scarcity of in-situ measurements. Because no universally accepted SIT uncertainty distribution currently exists, we chose this best-case configuration to avoid biasing our comparison in favor of SIAL assimilation.

Given the above information, we allude that the purpose of this study is to examine the additive effects of assimilating SIAL, and thus testing other uncertainty structures for SIC or SIT largely remains outside the scope of this study. It is of interest to the authors as potential future work.

2) One major issue in the paper is that the perfect model experiment is conducted in regions in which dynamics do play a non neglectable role in the ice grows. All experiment locations are located in regions which would probably yield different results, if conducted in a 3-D set up. This is not possible to fully address, but it would add to the significance of the study to include a site located in a region which is typically covered by land fast ice. If this would be the case it will be easier to relate future studies conducted in a 3-d set up to the findings in this study.

We thank the reviewer for this thoughtful suggestion. In response, we have added a fifth assimilation location in the Beaufort Sea to represent landfast ice. We selected this location because it has been the focus of extensive landfast ice research, owing to its proximity to Alaska’s North Slope. The exact grid point used is shown in Figure B. To ensure that this location reflects landfast ice conditions, we turned off all dynamic processes by setting deformation forcing to zero (i.e., eliminating rafting and ridging parameterizations). This creates a point that is, in principle, analogous to a location in a three-dimensional model where dynamics are negligible.

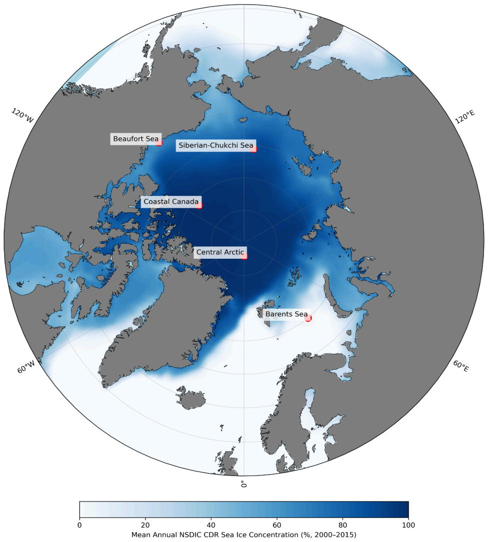


Figure B: Locations of the discrete point-based regions used to spin up *Icepack* and to provide distinct ice conditions for evaluating the influence of different variable-assimilation configurations.

However, SIAL assimilation at this site resulted in degraded performance relative to SIC and/or SIT assimilation, and sometimes even the free run. We attribute this to the nature of landfast ice: it typically exhibits an abrupt transition from 100% SIC to 0% at a discrete boundary. Landfast ice is difficult for large-scale sea ice models to represent because of its small horizontal scale and largely thermodynamic behavior (Gu et al., 2022; Plante et al., 2024). Landfast ice is also difficult to resolve in observations at the satellite pixel scale similarly due to its small horizontal scale (Fraser et al., 2020).

In regions with active dynamics, SIAL assimilation tends to improve SIC and SIT RMSE because processes such as rafting and ridging introduce variability in surface properties that SIAL captures in correlation to SIC. In contrast, surface conditions in the Beaufort landfast region (based on this model configuration) are governed entirely by thermodynamics, which is much less correlated to SIC. To illustrate this, we include a correlation heatmap in Figure C during the melt season. The figure reveals that SIAL and SIC are not well correlated during the melt season within the Beaufort region, compared to the other seasonal ice locations. This suggests that SIAL is not an effective assimilation variable for SIC in this region—a result consistent with our findings in the Central Arctic, where SIC remains near 100% year-round and most assimilation configurations (outside of SIC-only assimilation itself) are similarly ineffective.

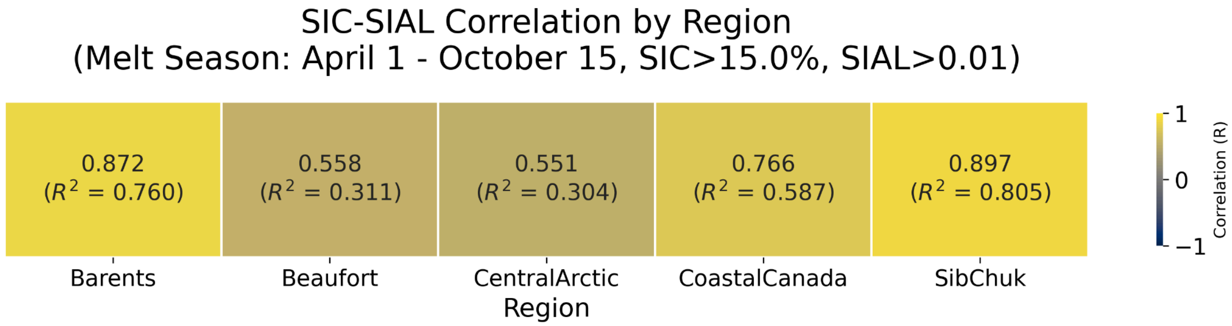


Figure C: Pearson correlation between SIAL and SIC in different *Icepack* modelled regions during the peak melt season (April 1 - October 15; SIC > 15% and SIAL > 0.01).

A key question is therefore why SIAL and SIC are only loosely correlated in our Beaufort experiments. Although we disabled lateral dynamic forcing to isolate purely thermodynamic evolution, the *Icepack* column still uses a slab-ocean formulation that permits basal heat exchange and melt, which is inconsistent with the mechanically constrained conditions required for grounded landfast ice. Therefore, we chose a location in the Beaufort Sea that is likely not bottomfast but instead part of the "stabilized fast ice" regime—floating ice that is only weakly anchored, if at all. The literature shows that the extent of Beaufort fast ice varies substantially year to year, and in some winters the region contains little or no fast ice at all. Thus, it is possible that our selected point lies outside the climatological landfast zone entirely, meaning the slab-ocean setup may actually be more representative of free ice at this location than a more landfast behavior would be. These factors together likely contribute to the lower SIC–SIAL correlations in the model relative to observations. As shown in Figure D, observed correlations from 2011–2015 using NSIDC SIC and CLARA-A3 albedo are higher than those simulated, suggesting that either (1) Icepack's thermodynamic-only framework cannot reproduce Beaufort landfast behavior, (2) the selected site is not representative of persistent fast ice despite prior classifications (e.g., Jewell et al., 2025; Lange et al., 2025), or (3) SIAL assimilation provides limited benefit in regions where mechanical processes or interannual variability in fast-ice presence dominate seasonal evolution.

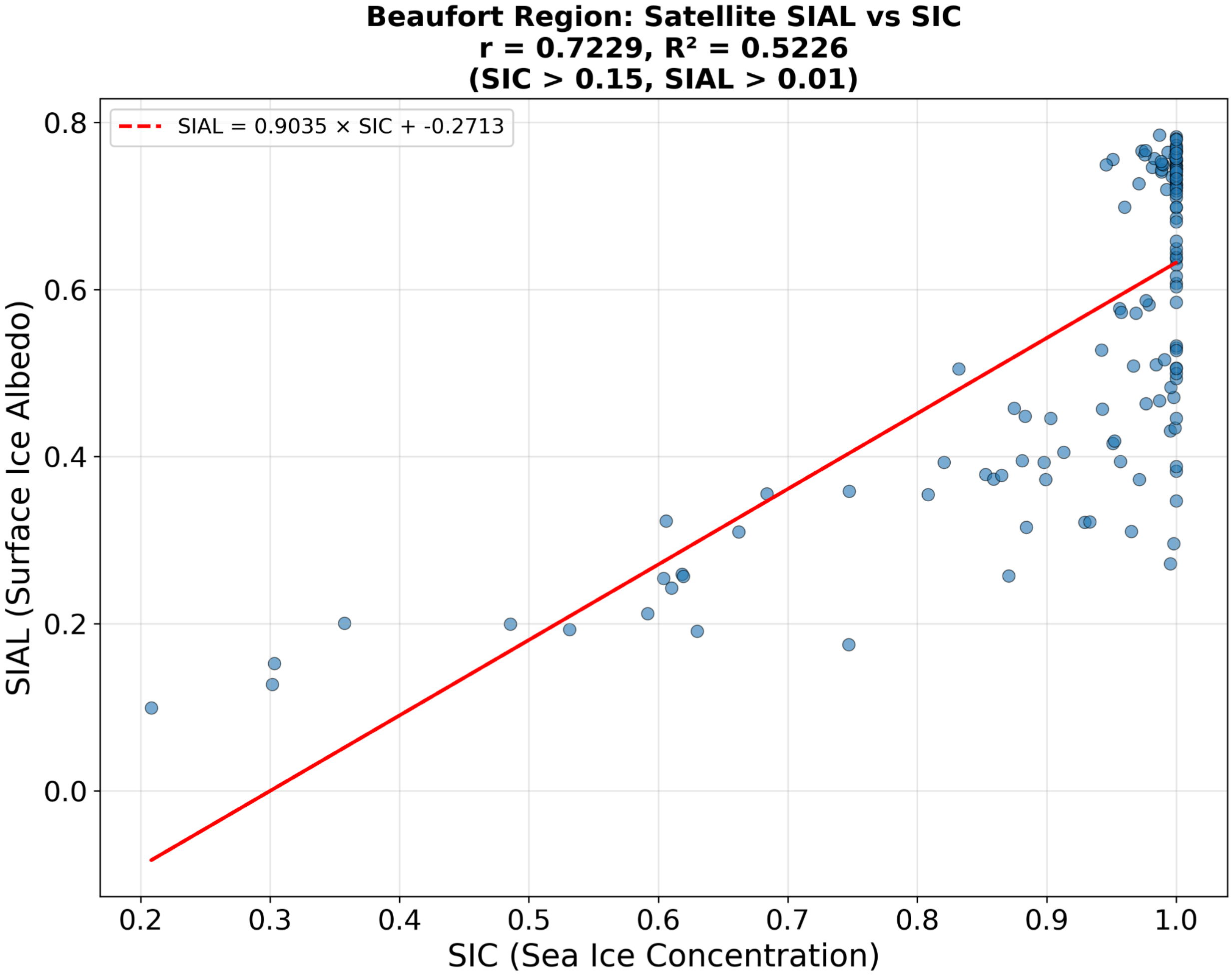


Figure D: Correlation between SIAL and SIC in satellite observations at the Beaufort Sea location (lat=75.54°, lon=174.45°; SIC > 15% and SIAL > 0.01) .

We therefore conclude that accurately representing Beaufort Sea landfast ice within our current *Icepack* configuration is challenging. The fine spatial scale of landfast ice, combined with JRA-55 atmospheric forcing and the absence of any dynamics, likely prevents *Icepack* from reproducing realistic spatial and temporal behavior. For these reasons, we do not pursue further landfast ice experiments. Nonetheless, we include the Beaufort site and its results in the manuscript, noting the important caveat that this location may not be directly comparable to real landfast ice conditions, but that SIAL assimilation leads to degraded performance in the Beaufort Sea.

3) Currently the temporal set up is unclear. It reads as if the spin up is run for 11 years, the reference run for 5 and the assimilation for 7 months? A common description of which runs are run for how long would be nice for readability.

Thank you for this helpful comment. We agree that the temporal setup required clarification. In our experiments, the model was first spun up for 11 years to ensure equilibrium. The reference (free-running) simulation was then integrated forward for 5 years, after which data assimilation was applied over a 7-month window (April–October 2011). We also performed assimilation experiments for subsequent years (2012, 2013, etc.) and found that although the absolute RMSE values varied somewhat by year, the relative performance of the different assimilation configurations (SIC, SIT, and SIAL) remained consistent. For clarity and brevity, we present results from the first year only in the manuscript. We will add this clarification around Line 90 to make the temporal setup more explicit.

4) The albedo is typically a parameter over which sea ice models are tuned. To ensure that the results are useful for future studies it would be desirable to attach the relevant namelist parameters. How would the authors expect the results to change if different values for, for example, snow grain size would be used?

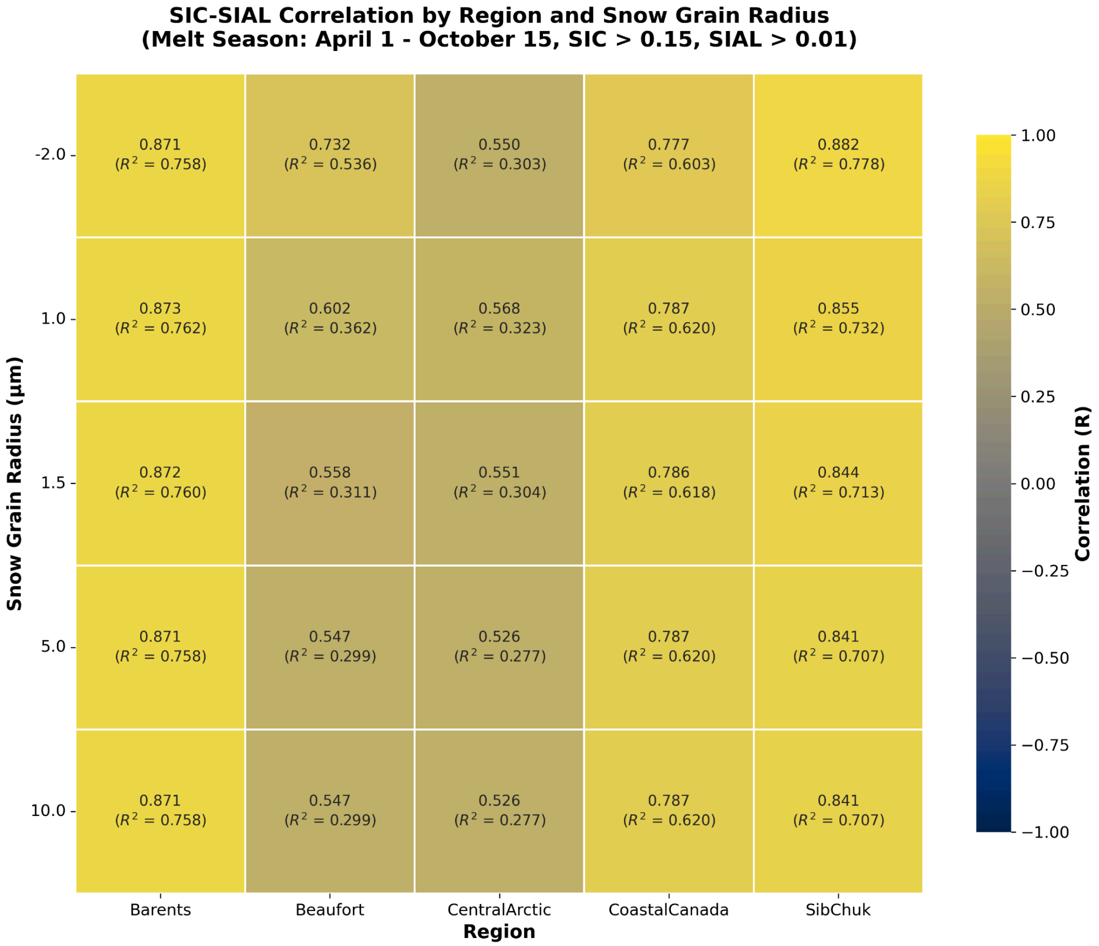
Thank you for this helpful comment. We will include all albedo- and snow-related namelist parameters in the supplementary material as two tables for clarity and reproducibility, and have provided the relevant values below for your review.

Regarding the sensitivity of our results to albedo-related parameters: although parameters such as the snow grain effective radius are commonly tuned in sea ice models, we do not expect that varying them within physically reasonable ranges would meaningfully alter our conclusions. All albedo- and snow-related namelist parameters in our experiments use the **standard defaults recommended by the CICE consortium for CESM–CAM4 on the gx1 grid**, including the default snow grain radius parameter **R_snw = 1.5 μm**. This value lies squarely within the recommended range used across CESM and CICE configurations and is widely adopted in the broader community.

While some configurations adjust R_snw (e.g., toward smaller values or negative offsets) to fine-tune melt onset for particular atmosphere–ice couplings, such modifications primarily shift the **absolute magnitude** of simulated albedo rather than the underlying **covariance structure** among SIAL, SIC, and SIT. In our perfect-model assimilation framework, the relative performance of assimilating SIC, SIT, or SIAL is determined primarily by these covariance relationships.

To evaluate this directly, we conducted sensitivity tests varying the snow grain radius across a wide range (-2–10 µm) in all five regions (Figs. E & F). These experiments led to only **minimal changes** in the simulated SIAL–SIC or SIAL–SIT correlations. Because these correlations are the dominant factor controlling assimilation outcomes, we expect that alternative but physically reasonable parameter choices would not change the relative behavior of the SIC-, SIT-, and SIAL-based assimilation experiments—only the overall magnitude of albedo, applied uniformly across experiments.

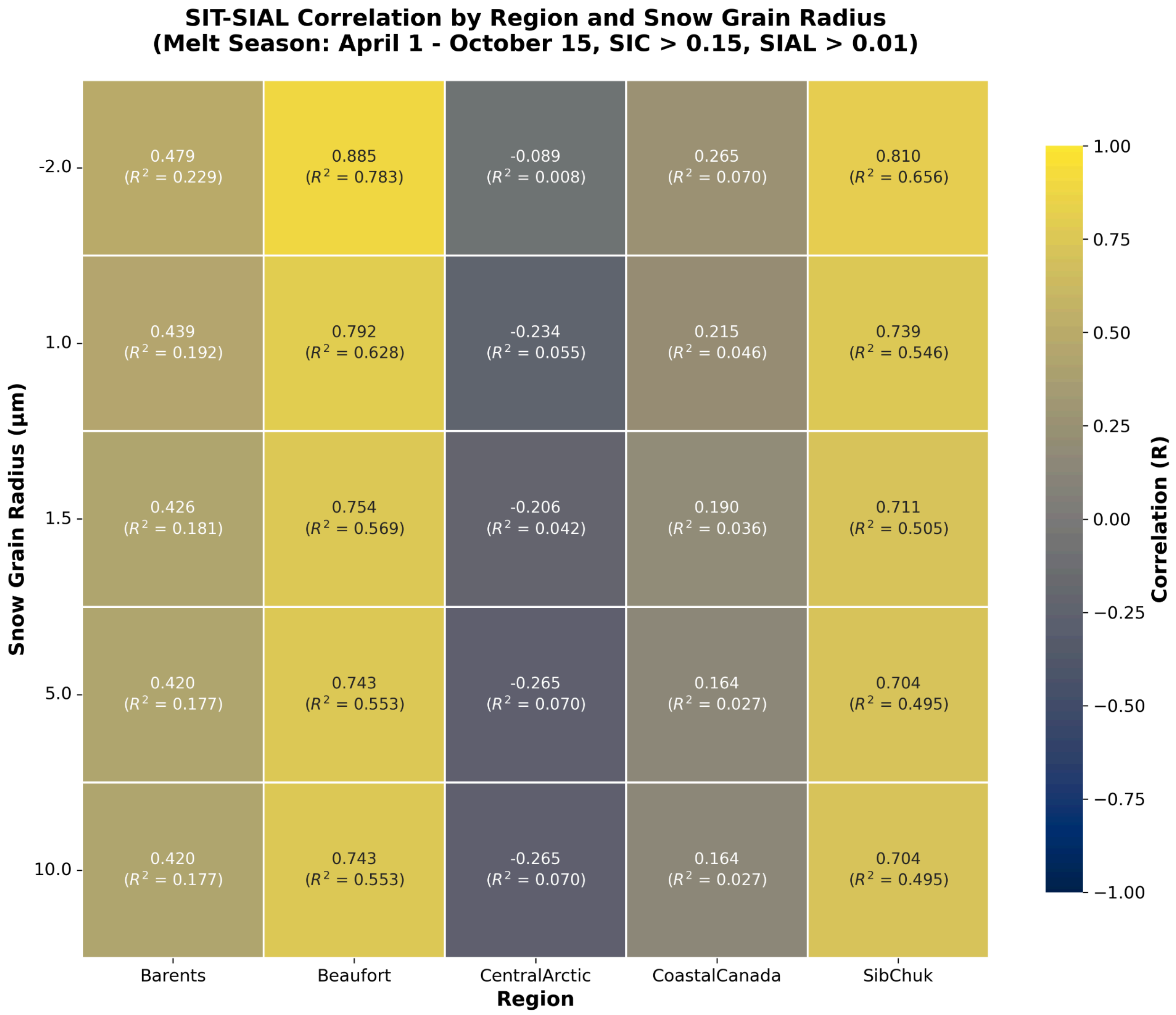
Accordingly, we are confident that our main results and conclusions are robust to typical parameter-tuning choices, including variations in snow grain radius and related albedo parameters.



SIC-SIAL Correlation by Region and Snow Grain Radius
(Melt Season: April 1 - October 15, SIC > 0.15, SIAL > 0.01)

Snow Grain Radius (µm)	Barents	Beaufort	CentralArctic	CoastalCanada	SibChuk
-2.0	0.871 (R^2 = 0.758)	0.732 (R^2 = 0.536)	0.550 (R^2 = 0.303)	0.777 (R^2 = 0.603)	0.882 (R^2 = 0.778)
1.0	0.873 (R^2 = 0.762)	0.602 (R^2 = 0.362)	0.568 (R^2 = 0.323)	0.787 (R^2 = 0.620)	0.855 (R^2 = 0.732)
1.5	0.872 (R^2 = 0.760)	0.558 (R^2 = 0.311)	0.551 (R^2 = 0.304)	0.786 (R^2 = 0.618)	0.844 (R^2 = 0.713)
5.0	0.871 (R^2 = 0.758)	0.547 (R^2 = 0.299)	0.526 (R^2 = 0.277)	0.787 (R^2 = 0.620)	0.841 (R^2 = 0.707)
10.0	0.871 (R^2 = 0.758)	0.547 (R^2 = 0.299)	0.526 (R^2 = 0.277)	0.787 (R^2 = 0.620)	0.841 (R^2 = 0.707)

Figure E: Impact of varying the snow grain radius on the SIC–SIAL correlation in *Icepack*. Changes in the correlation are minimal across the tested parameter range, except in the Beaufort Sea where correlation is relatively dependent on snow grain radius.



	Barents	Beaufort	CentralArctic	CoastalCanada	SibChuk
-2.0	0.479 (R^2 = 0.229)	0.885 (R^2 = 0.783)	-0.089 (R^2 = 0.008)	0.265 (R^2 = 0.070)	0.810 (R^2 = 0.656)
1.0	0.439 (R^2 = 0.192)	0.792 (R^2 = 0.628)	-0.234 (R^2 = 0.055)	0.215 (R^2 = 0.046)	0.739 (R^2 = 0.546)
1.5	0.426 (R^2 = 0.181)	0.754 (R^2 = 0.569)	-0.206 (R^2 = 0.042)	0.190 (R^2 = 0.036)	0.711 (R^2 = 0.505)
5.0	0.420 (R^2 = 0.177)	0.743 (R^2 = 0.553)	-0.265 (R^2 = 0.070)	0.164 (R^2 = 0.027)	0.704 (R^2 = 0.495)
10.0	0.420 (R^2 = 0.177)	0.743 (R^2 = 0.553)	-0.265 (R^2 = 0.070)	0.164 (R^2 = 0.027)	0.704 (R^2 = 0.495)

Figure F: Impact of varying the snow grain radius on the SIT–SIAL correlation in *Icepack*. As in Figure E, the resulting correlation differences are negligible, except in the Beaufort Sea where correlation is relatively dependent on snow grain radius.

Icepack Model Configuration Parameter Tables

Parameter	***Icepack* Variable Name**	**Default Value**	**Units**	**Description**
Snow grain radius	`r_snw`	1.5	unitless	Snow grain radius tuning parameter
Ice surface scattering layer	`hi_ssl`	0.05	m	Ice surface scattering layer thickness
Snow surface scattering layer	`hs_ssl`	0.04	m	Snow surface scattering layer thickness
Snow melt grain radius	`rsnw_mlt`	1500.0	kg/m²/s	Melting snow grain radius
Melt pond drainage timescale	`dt_mlt`	1.0	days	Drainage timescale for melt ponds

Table 1: Albedo-Related Parameters that we specified in *Icepack* for our spinup, free run, and assimilation experiments.

Parameter	***Icepack* Variable Name**	**Default Value**	**Units**	**Description**
Snow thermal conductivity	`ksno`	0.3	W/m/K	Thermal conductivity of snow
Ice density	`rhoi`	917.0	kg/m³	Density of sea ice
Snow density	`rhos`	330.0	kg/m³	Density of snow
Ridging work parameter	`Cf`	17	unitless	Ratio of ridging work to potential energy change
Ice-ocean drag coefficient	`dragio`	0.00536	unitless	Drag coefficient at ice-ocean interface

Table 2: Other sea ice tuning parameters relevant to our model setup in *Icepack*.

5) Overall the methods are well structured, including both the description of the experiment set up and the evaluation methods. It would further improve the structure of the paper to move the description of the category wise DA to the method section (4.3 to to example 2.5).

Thank you for this suggestion. We have moved the bulk of the category-wise DA description to the Methods section by adding a new subsection (Section 2.5), titled *"Category-wise Data Assimilation."* Specifically, we relocated lines 319–347 and made minor revisions to the wording to ensure the section fits naturally within its new position in the Methods.

Minor comments:

row 15: AA is only used once. No acronym needed.

Thank you for this comment. We have removed the acronym from our manuscript.

Line 27-31: missing reference

Thank you for your comment. We have added the appropriate references to cite that SIC and SIAL covary, especially during the melt season (Agarwal et al., 2011), and support of bare ice and open ocean albedo (Becker et al., 2023), as well as melt pond albedo (Grenfell and Perovich, 2004).

Some statements seem unnecessary for example line 41-46 and line 59-60. If the statements are not relevant to the study, why mention them. If the authors want to anyways include them, maybe these could be summarized to a motivation to study Arctic albedo processes.

Thank you for this helpful comment. We originally included these statements to emphasize the broader motivation for studying Arctic albedo processes. One of the main takeaways from this work is that uncertainty in sea ice albedo (SIAL) should be better quantified, and so the authors mention that understanding secondary processes—such as cloud and ocean feedbacks—is key to improving our representation of Arctic albedo evolution through reductions in observational uncertainty.

That said, we agree that the current wording is somewhat redundant and can be streamlined for clarity and focus. In the revised manuscript, these sentences have been condensed into a single motivating statement that better links the broader context to the objectives of this study. The revised text (centered around the original lines 41–46) now reads:

"Secondary processes such as changes in cloud cover and ocean temperature interact with sea ice melt to influence surface albedo and Arctic energy balance. Improving how these interconnected processes are represented in coupled sea ice simulations is essential for advancing our understanding of Arctic albedo evolution and reducing uncertainty in its role within the global climate system. The authors leave this as an open area of study for future research based on improved representation of Arctic sea ice."

Line 260: how the TRUTH was constructed should be in the methods

Thank you for this helpful comment. The construction of the TRUTH dataset is already described in the Methods section (lines 92–97). We have reviewed this portion to ensure the explanation is clear and sufficiently detailed, and for now are keeping the original text as shown below:

"For each assimilation experiment–defined as the set of simulations conducted for one of the five Arctic locations–a randomly selected ensemble member was designated as the reference TRUTH state, from which synthetic observations were derived for assimilation. To account for sensitivity to the choice of TRUTH, we repeated the assimilation experiments using ten different ensemble members as TRUTH states (ensemble members 3, 5, 10, 12, 14, 16, 19, 21, 25, and 28). Synthetic observations of SIAL, SIC, and SIT were generated from each of these TRUTH realizations for assimilation into the remaining ensemble members.”