

**Response to comments on “Adjoint-Based Simultaneous State and Parameter Estimation in an Arctic Sea Ice-Ocean Model using MITgcm (c63m)” by François Massonnet (UCLouvain)**

Lyu et al.

Review of “*Adjoint-Based Simultaneous State and Parameter Estimation in an Arctic Sea Ice-Ocean Model using MITgcm (c63m)* »

by François Massonnet (UCLouvain). I did not look at the other reviewer’s comment before submitting mine.

In this study, Lyu and colleagues employ the MITgcm and an adjoint method to jointly estimate the state and parameters of the ocean-sea ice model. They assimilate satellite and in-situ observations and compare the results of the CTRL run (no assimilation), adjoint-SE (state estimation only) and adjoint-SPE (state and parameter estimation) to independent observations. Most of the improvements come from the state estimation but further improvements are noted with the parameter estimation.

The study is interesting and the attempt to estimate parameters and state together has some future, I believe, especially in the context of prediction where model drift can be an issue.

My main remark on the paper is that the authors do the analysis on one year, and in fact on a very particular year : 2012. **Why this choice ? Is there a risk that the outcome of the paper could be drastically different for other years?** I am asking because 2012 is such a special year, with a strong cyclone (not something that is model-dependent) that may bias the results. Related to that, **I am not sure what is the overall implication of this work.** Are the authors willing to recommend new parameter values for the MITGcm community? If so, I would like that they test whether the state is improved on a year without assimilation (e.g., running 2017 from the normal initial conditions but using parameters obtained for the 2012 estimation) and show the improvement.

Response:

We thank François Massonnet for his valuable comments on our manuscript and for insightful discussions on results.

The second reviewer also raised concerns about the one-year assimilation window and the robustness of conclusion if applied to another year or period. As addressed in our response to the first reviewer, we selected the year 2012 as our test year with two reasons. First, **the seasonal evolution of SIC errors in 2012 represent the general SIC errors pattern in the other years and the other Arctic ocean and sea ice reanalysis datasets**. As shown in Figure R1 and Figure 4 (in the manuscript), the SIC errors increase to a peak in June, decrease slowly through September, and then rise sharply in October. A one-year assimilation window is sufficient to test whether joint optimization of parameters and state can reduce such seasonal SIC errors. Second, the 2012 sea ice retreat has been extensively investigated, providing a well-characterized reference to validate our assimilation results.

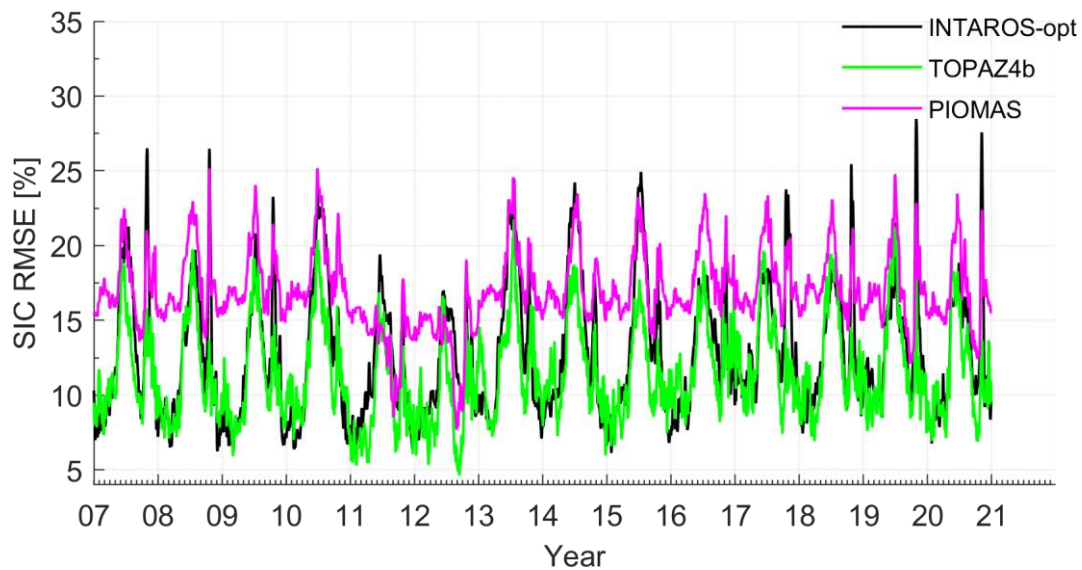


Figure R1. Root mean square errors of sea ice concentration between satellite observations and INTAROS-opt (black line, Lyu et al.,2021), TOPAZ4b (green line), and PIOMAS (magenta line).

In theory, when applying the data assimilation system to another year, data assimilation will adjust the control variables to bring the model simulations close to the observations for that specific year. The performance of such an application would depend largely on the quantity and quality of available observations of the target year.

Regarding the boarder implication, our work is not intended to propose new parameter values, as is common in parameter studies. Instead, **we intend to developed an improved Arctic ocean-sea ice assimilation and reanalysis system and produce a new Arctic ocean and sea ice reanalysis dataset** of higher accuracy. As demonstrated in our previous work (Lyu et al., 2021b, see the manuscript), our results are already comparable to the TOPAZ4 results and the others. With the simultaneous state and parameter estimation scheme presented in this study, we anticipate further improvements in the Arctic ocean-sea ice reanalysis dataset. We also suggest the other Arctic ocean-sea ice reanalysis system to try optimizing the model parameters, given that most existing Arctic ocean-sea ice reanalysis datasets exhibit similar SIC error patterns to those in our dataset.

The English could be improved at places, as suggested below.

We thank François Massonnet for his patience of correcting the English, we response the minor corrections one by one.

[1] Line 18 : tunned→tuned (many other instances in the text)

Response: Agree, we have revised these typos throughout the text.

[2] Line 19 : of AN Arctic

Response: Agree, we have added “an” in front of Arctic.

[3] Line 27 : applied to perform/produce (not reproduce) ?

Response: Agree, we have changed “reproduce” to ‘produce’.

[4] Line 33 : not sure that the processes themselves undergo changes : processes remain (e.g. heat conduction, ice melting), but it is the state of the system (affected by these processes) that changes

Response: we thank the reviewer’s comment, we revised “key processes” to “the ocean and sea ice state undergoes rapid changes”

[5] Line 34 : To me, parameters stemming from parameterizations cannot be measured by construction. Nature ignores what a parameterization is.

Response: That’s true that nature ignores what a parameterization is. Likely, parameterizations are created by scientists. And therefore, we stated here, most of the parameters cannot be measured. However, as far as I know, there are parameters which we can measure, such as ice and ocean albedo. Am I right?

[6] Line 35 : is assumed, not are assumed

Response: agree, and we have revised it.

[7] Line 42 : I would use the past tense as in the previous sentence. In general, please keep consistency of the tenses.

Response: agree, we have revised it.

[7] Line 44 : budgetS

Response: Agree, we have changed “budget” to “budgets”.

[8] Line 48 : sensitive

Response: Agree, and has been corrected in Line 51.

[9] Line 60 : likely TO improve

Response: Agree, and we have corrected it.

[10] Line 112 : The authors justify that assuming  $B^{-2}$  to be diagonal is a consequence of the fact that they rely on the adjoint model to project the model-data misfits on the control variables. First, I do not understand what the two sentences have to do with each other. Second, I am surprised to read that B is assumed to be diagonal. In general, one can assume the observation error R to be diagonal (i.e., uncorrelated observational errors) but for the background model state, this seems to be a very strong assumption! Indeed model background errors are certainly correlated. Can the authors provide justification for the diagonal nature of B?

Response:

There is no consequence between using a diagonal B and adjoint model, we deleted the word “therefore” in Line 123.

Definitely, the model background errors are correlated. In EnKF and 3DVar with assimilation window of days, we rely on these background correlations to achieve a multivariate adjustments on the initial conditions. The background correlations are mostly statistical covariance or simplified model dynamic equations. In our system, both adjoint model and the background correlation can project the model-data misfit to the control variable, realizing multivariate adjustments. We use a one-year assimilation window in this study, which is long enough for the adjoint model to propagate the model-data misfits to all the model state and along the circulation pattern, and we prefer propagating these signal with model dynamics, rather than the statistical covariance in the background terms. Also, impacts of the initial conditions can hardly last for more than couple of months. Therefore, we choose to use a diagonal B, rather than a statistical covariance matrix or a diffusion model.

[11] Line 119 : uncertainties are set to 20% ; please be more specific : I assume this is the standard deviation of the error distribution (assumed Gaussian) ?

Response: That’s true, we assume Gaussian error distribution with standard deviations of 20% of the corresponding parameter values. We revised it in lines 130-131.

[12] Table 1 : could the authors justify where the ranges of parameters come from ?

Response: some of the parameters ranges are from literatures (e.g., Sumata et al., 2019), such as albedo. I guess, they likely get the parameters ranges from modelling experts.

[13] Line 141 : please specify what « uncertainty » means here.

Response: we thank the reviewer for pointing out this problem. we mean observational errors here, rather than uncertainty.

[14] Line 156-158 : why multiplying here ?

Response: the SIC dataset doesn’t provide observational error estimate, we have to provide observational error by ourselves. The basic criteria is that: Considering the dependence of SIC product error on absolute value of SIC (Chen et al., 2023) and larger SIC errors off the coast due to the poor accuracy in the SIC product and the poor representation of landfast ice in the model.

We choose this step function depending on SIC and multiplying these factors on the background errors. There are also other ways of defining the SIC errors.

[15] Line 161 : this is not very clear, especially when it is said that SIT is  $SIT \times SIC$ . I would use another symbol, maybe  $SIT_{floe}$  for the in-situ and SIT for the effective. Also, I assume that the “gridded SIT” means the model SIT?

Response: we appreciated the reviewer’s advice here. in our manuscript, SIT represent sea ice thickness averaged over the ice-covered region. Effective SIT (we changed it to grid-mean SIT) is the mean SIT over the model grid. Multiplying the grid area, we get the ice volume. We have change effective SIT to grid-mean SIT in Line 186.

[16] Line 202: *“Firstly, the parameter changes within the range of uncertainties have considerable impacts on the model simulation.”* is presented as «a prerequisite » but it is not. Did the authors mean « a hypothesis » maybe ? But then I am confused by the sentence after that. Maybe they meant « requirement » ?

Response: That’s a good comment. Definitely this is not a hypothesis. The word “requirement” is better. if the two situations are met, the assimilation system is able to optimize the parameters. we have changed the word “prerequisites” to “requirements” in Line 202.

[17] Line 207 « perturb by 10% » could mean many things : is that the range, the standard deviation, with perturbation statistical model ?

Response: not that complex, we change the 13 model parameters (see Table 1) one by one by adding 10% of their default values. Overall, we run the forward model 13 times.

[18] Line 291 : this ocean heat

Response: Agree, we have corrected it.

[19] Line 295 : a much

Response: agree, we have corrected it.

[20] Line 296. Starting a sentence with « While, « is strange

Response: Agree, we have changed While to “And”.

[21] Fig. 8 the colormap is not adapted for colorblind people, can you please choose a colorblind-friendly one?

Response: we thank the reviewer’s advice. We have selected a colorblind-friendly colormap to show trajectory of the IMBs.