

1 Estimation of the state and parameters in ice sheet model
2 using an ensemble Kalman filter and Observing System
3 Simulation Experiments
4 – Authors’ response (RC1) –

5 Youngmin CHOI et al.

6 September 23, 2025

7 *The revised version of the manuscript greatly improved the presentation of the methodology and*
8 *experimental design. It has a more logical flow, and, with the exception of some minor issues*
9 *outlined in the specific comments below, the key aspects of the results are now adequately addressed*
10 *and discussed. The additional experiments presented in the Appendix provide further value.*

11 We thank the reviewer for their constructive comments, which have helped improve the manuscript.
12 We address the minor issues below.

13 *[Now, we use consistent terminology (model state) throughout the manuscript.]*

14 *There are still instances in which you do not use model state (e.g., L12).*

15 We have corrected all remaining inconsistencies and now use model state throughout the manuscript.

16 *L26-27: I suggest adding a sentence that better links the two paragraphs by describing how DA*
17 *methods can reduce the uncertainty in key model parameters and model initialisation.*

18 We have added the following sentence at the beginning of the second paragraph to improve the
19 flow:

20 *“Data assimilation (DA) is a method of combining information from models with observations to*
21 *improve the accuracy of the model state variables and/or specific model parameters.”*

22 *L52-54: As new observations are incorporated within the assimilation period, the ensemble mean*
23 *presents an increasingly more accurate estimate of the model state.*

24 *This seems to contradict your statement in L14-15: additional observations do not improve and*
25 *may even degrade long-term estimates of model parameters and state.*

26 This sentence (L52-L54) is meant to describe the general expected behavior of ensemble data
27 assimilation methods. However, our results show that DA performance can degrade under certain
28 condition. We have revised the sentence to:

29 *“As new observations are incorporated within the assimilation period, the ensemble mean is gen-*
30 *erally expected to provide an increasingly more accurate estimate of the model state under ideal*
31 *conditions.”*

32 *We revised it to “true values”.*

33 *I suggest adding “synthetic twin experiment” in L95.*

34 Done.

35 *We used an adaptive mesh based on ice velocity and included a new figure (Fig. 1(d)) in the revised*
36 *manuscript.*

37 *Add a reference to Fig. 1d to the end of L127. Is the mesh adjusted as the grounding line retreats?*
38 *Note that the rainbow colour scheme in panel d is not in line with the journal guidelines.*

39 The mesh is temporally static. We have clarified this in the manuscript and added a reference to
40 Fig. 2d. Additionally, we have updated the color scheme in Fig. 2d.

41 *$z_{b,deep}$ = Depth of the bedrock topography in Table 1*

42 *This is confusing, as your bedrock topography in Fig. 2 varies spatially. Consider: Maximum*
43 *depth of the initial bedrock topography.*

44 Done.

45 *L156: “these surface and basal forcings”*

46 *Since the lines directly above are discussing the melt rate, consider re-stating what these forcings*
47 *are or refer to them as “perturbed surface and basal forcings.”*

48 We have revised to *“perturbed surface and basal forcings”*.

49 *L169: “we choose the EAKF due to its reduced sensitivity to ensemble size”*

50 *This is somewhat confusing, as in L179, you state a common challenge with [...] EAKFs [...] arises*
51 *when the size of the ensemble is significantly smaller than the independently observed degrees of*
52 *freedom.*

53 We have added “*compared to stochastic EnKFs*” for clarity.

54 *L282: EnKF*

55 *Should this be EAKF?*

56 We have revised it to “EAKF”.

57 *L297: “continues to decrease steadily”*

58 *It does not continue to decrease steadily.*

59 We have removed this.

60 *L301-302: “the benefits saturate as the ensemble size increases from 50 to 100”*

61 *Be more precise here. For bed elevation and ice thickness, an ensemble size of 100 has a larger*
62 *RMSE at $t = 30$ a than for a size of 50.*

63 We have revised this sentence.

64 *“While increasing the ensemble size from 30 to 50 shows clear improvements in DA performance,*
65 *further increasing the size to 100 does not consistently reduce RMSEs and, in some cases, even*
66 *results in slightly higher errors..”*

67 *L302: “illustrative purposes”*

68 *What do you mean by that?*

69 We chose this configuration as a representative setup to demonstrate performance.

70 *“For the remaining twin experiments, we proceed with an ensemble size of 50, a localization radius*
71 *of 4 km, and an inflation value of 1.12 as a representative setup to demonstrate performance.”*

72 *Fig. 7: What causes the sharp grounding line extent towards higher x values at $y = 10$ km in the*
73 *no assimilation panel?*

74 *You did not provide an answer to this question.*

75 We revised the description of the model domain's initial condition to address this point:

76 *"A sharp grounding line advance is observed near $y = 10$ km, likely caused by low surface elevation*
77 *and high spatial variability in the underlying bed topography in this area."*

78 *We chose to show the difference in ice thickness in Fig. 8 because changes in thickness are difficult*
79 *to detect visually from the similar figure as Fig. 6 and 7.*

80 *Yes, but wouldn't it also be easier to detect the changes if you plotted the differences in Figs. 6 and*
81 *7?*

82 We appreciate the reviewer's suggestion. While agree that plotting the difference in Figs. 6 and 7
83 could further aid interpretation, we chose to keep the original figure to preserve the spatial context
84 of the results and allow direct comparison of the physical variables between experiments. Our
85 intention in showing only the difference in ice thickness in Fig. 8 was to highlight subtle variations
86 that may be difficult to detect visually in plots such as Figs. 6 and 7.

87 *L362: "although RMSE values continue to decrease until the end of the assimilation window"*

88 *At 15 km across-track spacing, not all RMSE values continue to decrease.*

89 We have removed this.

90 *We added the reference to Fig. 13 and described the increase in RMSE for the 20 km grid data.*

91 *Fig. is missing for some of these references.*

92 We have revised those references.

93 *L437: "observations years"*

94 *Change to "observation years."*

95 Done.

1 Estimation of the state and parameters in ice sheet model
2 using an ensemble Kalman filter and Observing System
3 Simulation Experiments
4 – Authors’ response (RC2) –

5 Youngmin CHOI et al.

6 September 23, 2025

7 *I am satisfied with the substantial changes made by the authors throughout the manuscript in*
8 *response to my first review. I am happy for the manuscript to proceed to publication if the authors*
9 *are able to revisit one point.*

10 *In my original review, I suggested that if the authors were to claim that EAKF with DART is*
11 *more computationally tractable than adjoint-based variational DA methods, then this needed to*
12 *be backed up with computational benchmarking. The authors have since softened this claim and*
13 *indicate that a direct computational comparison is beyond the scope of this study. I find this to*
14 *be an acceptable response. However, it is still the case that if this study is meant to provide a*
15 *proof-of-concept for the utility of using DART and ensemble-based methods more broadly, having*
16 *some information about the computational resources required for such methods would seem nec-*
17 *essary so that readers who might think of using such an approach would know ahead of time what*
18 *computational resources are required. Specifically, it would be useful if the authors could provide*
19 *some information about the computational overhead associated with running DART for some of*
20 *these simulations. In principle, the assembly and computation of the analysis in Kalman-based DA*
21 *methods can be done with relatively little computational expense compared to the forecast. How-*
22 *ever, in practice this requires gathering output from difference processes (if the ensemble members*
23 *are run in parallel, which is what makes ensemble-based methods so promising from a computa-*
24 *tional perspective) and then calculating information on potentially large arrays. This can prove*
25 *to be a challenge from an I/O and memory perspective as problems scale in size. I’m not asking*
26 *for the authors to add a whole new section on this, but simple to use their existing ensemble sim-*
27 *ulations to estimate the marginal computational cost associated with the analysis step. Even just*
28 *comparing the total walltime of two cases with the same number of ensemble members run on the*
29 *same number of processes, but with more assimilation cycles would help to estimate the added*

30 *computational cost of each analysis cycle. This can be described in a few sentences added in the*
31 *results or discussion section and shouldn't require running any new simulations assuming that the*
32 *existing run logs already include information about total run time.*

33 We thank the reviewer for this helpful suggestion. Based on our run logs, we compared simulations
34 with identical ensemble sizes and model configuration but with different number of assimilation
35 cycles. We have added a short description of these results to the discussion section.

36 *“To provide a sense of computational resources for ensemble DA, we compared runs with identical*
37 *ensemble sizes but different numbers of assimilation cycles over the same 30-year assimilation*
38 *window: 30 annual cycles versus 60 semiannual cycles. For an ensemble size of 50 on a Broadwell*
39 *node with 28 cores, the 30-cycle run required approximately 2.9 hours of walltime, while the 60-*
40 *cycle run required approximately 5.2 hours. Because both runs cover the same forecast period, the*
41 *additional cost in the 60-cycle case reflects the more frequent execution of the DART analysis step*
42 *and associated I/O (e.g., conversion between ISSM and DART). A direct comparison of per-cycle*
43 *times is not strictly meaningful, since the forecast interval in each cycle is shorter in the semiannual*
44 *case, but the nearly doubled walltime for the 60-cycle case suggests that the analysis step and*
45 *associated I/O represent a significant fraction of the total computational time. As a result, scaling*
46 *to larger ensembles or higher-frequency updates will likely increase computational demands due*
47 *to the analysis step and its I/O requirements.”*