Review of « The Ice Sheet State and Parameter Estimator (ICESEE) Library (v1.0.0): Ensemble Kalman Filtering for Ice Sheet Models » submitted to GMB by Kyanjo et al.

In this paper, the authors describe a library that implements the Ensemble Kalman Filter (EnKF) from Evensen (2003) as well as several other deterministic variants. The library is coupled to several models including two state-of-the-art ice flow models, ISSM and icepack.
Inverse methods are relatively widely used to initialise ice flow models ; However transient data assimilations methods are not so common. Compared to 4DVAR, ensemble methods are attractive as they require less developments in the direct models. Recently, several synthetic studies have shown their potential for ice flow simulations. The development of an open-source library should encourage such applications.

The paper is divided in 3 main sections. The first section describe the equations, the second the implementation and the third shows two applications one with icepack and one with ISSM.

Generally speaking, I find that certain sections in the description of the equations lack sufficient details, particularly the implementation of non-linear observation operators, the ensemble initialization and modelling of the model error. The descriptions of the test cases are also very brief and missing important details/discussions on the exact choices of the model and assimilations set-up, so that it is difficult to understand if the experiments show good results for good or wrong reasons.

There are several points in particular that I'm concerned about for the applications:

- Choice of the state variables:
  - for both applications the velocity components (u and v) are presented as state variables, however the momentum equations are time independent so that the velocity is a diagnostic variable. As such, they are not part of the state vector in Gillet-Chaulet (2020) and Choi et al. (2025), so that the momentum equations act as a non-linear observation operator for the ice thickness (state variable) and the boundary conditions (bed elevation and friction parameters).
  - For the application with ISSM, both h, s and b are estimated. However, I assume that the application with ISSM solves the shallow-shelf equations with the floatation condition, so that the 3 variable are not independent; i.e. s=b+h for the grounded part and s and h are related by the floatation condition for ice-shelfs.
- Estimation of b and c under floating ice: by definition, surface observations are not sensitive to the bed conditions where the ice is floating. In in Gillet-Chaulet (2020) and Choi et al. (2025), the basal conditions are not estimated where ice is floating, so I would expect the basal conditions below the ice-shelf to remain the same with or without assimilation on Fig. 7.
- Use of model error: From Sec. 2.3, I understand that what the authors call "Noise modelling" is the modelling of model errors. Usually model errors represent errors due to the model assumptions (simplified physics, resolution, etc…). Here the applications are twin experiments where the synthetic observations have been generated with the model, so we are considering the case of a perfect model experiment, in this case the use of model errors is not justified?
- Initial ensembles: the description of how the initial states are constructed is sometimes a little imprecise, but I also wonder about the decision to use biased initial ensemble states, e.g. for the smb in the icepack experiment. EnKF as most of the other DA algorithms rely on the assumptions of unbiased observations and models. Although it might actually work, as it seems to be the case, I'm wondering about this choice for synthetical applications used to illustrate the library performances.

Detailed remarks:

- **Acronyms:**
  - EnKF is defined multiple times and used to refer to ensemble Kalman Filters in general and the version proposed by Evensen (2003). Use different acronyms.
  - The Ensemble Transform KF is usually referred to as ETKF not EnTKF
- **Notations:** In the equations for the KF, use upper case for matrices and lower case for vectors to avoid confusion.
- **Introduction:** Introduce and cite other existing open source libraries that implement ensemble KF; e.g. PDAF used by Gillet-Chaulet (2020) and DART used by Choi et al. (2025).
- **Abstract *"while physics-based inverse … » :*** I don't think that the inverse methods used here are more *» physics-based »* than the ensemble DA. Basically the inverses methods can be interpreted in terms of Bayesian estimation where the regularisation acts as a prior. Here assuming that the friction coefficient has smooth variations does not include more physics than an informed prior initial state.
- Sec 2 in general: Explain how you deal with non-linear observation operators H in the different KF equations.
- **Eq. 4 :** Re=1/N-1 DD^T in Evensen 2003 (Eq. 51)
- **Section 2.3 :**
  - make two different sections to describe initialisation procedures and model error.
  - Give more details on the random field generations and explain the differences between the possible choice so that the user could take informed decision on the initialisation procedures.
  - I understand that noise modelling referrers to « model error » ; see my main comment ; why using model error in perfect model twin experiments. Improve the description of the methos. I don't understand where the decorrelation length appears.
  - Discussion on the innovation : why this discussion here in a section about ensemble initialisation and model error ? The innovation should be the difference between the observations and their model equivalent. "di » is defined in eq. 3 as the perturbed observation vectors ; not the innovation which would be « di-H(x_i^f) » ?
- **Section 2.4 :**
  - Better explain what inflation and localisation are, for non-specialist users.
  - Improve the description of the available implemented choices for localisation
  - There is not too much discussion on the inflation methods ; which are more introduced in section 2.5
  - *« For the serial implementation of the stochastic EnKF in ICESEE » :* I understood that the stochastic EnKF from Evensen was parallel and that the deterministic filters were serial ?
- **Section 2.5**
  - *"ICESEE adopts the dynamical model for parameters introduced …»* : Explain what it is.
  - *« ICESEE applies a complementary approach by deliberately inflating the parameter subspace more than the state subspace »* : The inflation procedure has not been described ; How the ratio of inflation between state and parameters is chosen ? Is it a user-free parameter ? I don't see much description of this in the experiments.
  - discussion on the *« noise modelling »* : See above, I don't understand what the noise modelling represent ?
- **Section 3.2.6*: "*ℹ**"** *and loading observations and transforming them to the model grid »* : How is this done ? Requires interpolation/extrapolation ? Is the library restricted to assimilate observations located on the model grid ?
- **Section 3.4.2: *"*** *During the initialization phase, the observation operator H »* : This is for a linear observation operator. What kind of operator are implemented if the observations needs to be projected on the model grid ? How to deal with non-linear observation operators ?

- **Section 4.1***: "to estimate key ice sheet state variables, including ice velocity, ice thickness, and surface mass balance (SMB). »* See my main comment, the velocity is not a state variable. Is the smb solution of an equation or constant in time ? In this case it is a parameter and not a state variable ?
- **Section 4.1.:**
  - The description of the experiment is not sufficient. We don't know what the reference solution represent. It seems that there is a small transient in the reference during the first 40 years but we don't have information about the boundary conditions, basal friction ?, bed elevation ? is there a floating part? the "true" smb, is it constant? Uniform?
  - Why 425 degrees of freedom for each variable? Is the grid regular?
  - Are the observations at every grid point?
  - There is several methods presented in section 2.3 for the initial ensembles and I don't know what is used, pseudo random can mean many things. Again I don't see the link between the initialisation and the "noise" modelling with a decorrelation length scale.
  - I'm surprised by the standard deviation values given for the initial states. The spread of the initial ensemble should reflect the uncertainty in the initial state. Here as shown in Fig. 5 the initial spread is very small, one order of magnitude small that the initial difference between the mean state and "truth".
  - I don't know what a "smooth linear bump" is.
  - *« The ensemble spread around the mean remains nearly constant throughout the simulation, indicating stable uncertainty representation and limited ensemble collapse »* : The objective of DA is not only to improve the mean but also reduce the initial spread. See above, here the initial spread is very low and does not include the truth. Looking at the thickness in Fig. 5 it seems that the spread is increasing, I assume due to inflation and the « noise » modelling. So I think it is for wrong reasons.
  - Fig 5. From the individual members (grey lines EnKF) it seems that there is short term variability (annual ? or following the time step ?) I don't understand where it comes from.
  - *« true value, showing that ICESEE can recover slowly evolving or weakly constrained parameters that are not directly observed. »* According to 4.1.1 smb is observed.
- **Section 4.2**
  - See main comments. The velocity is not a state variable , h, s and b are not independent. Please explain.
  - Description of the initial ensemble is somehow unprecise and contradictory :
    - *« glacier in 3D »* : Choi et al. (2025) use a vertically integrated model ; so the setup is 2D.
    - I don't understand the base and surface parametrisations : In Choi et al., the bed is defined and the model is spin-up by evolving the ice thickness so that the base and surface elevation are defined by the floatation condition and not « parameterized »
    - What is « exponential » noise ? Noise with a spatial correlation defined by an exponential variogram ?
    - If an offset is added to the bed elevation why not directly proving the correct equations for the bed elevation ?
    - What are a *« Gaussian random field »* and an *« exponential kriging field »* ? Same as above ?
    - Why adapting the variogram for the initial friction field? This should reflect the uncertainty on the initial friction field; as it is independent of the bed elevation in Choi et al., why the variogram should better reflect the adjusted bed topography?

- What is *“nudging the mean friction field”?* You just mentioned that you generated an initial ensemble using random fields.
- Initial conditions for the bed, base and surface: clarify, the base is equal to the bed elevation where grounded, while it is defined by the by the floatation condition and the ice thickness on the floating part. Would be better to define the initial ensemble for the ice thickness which is the state variable.
- *“observations are assumed to be available everywhere”*: does that mean at every mesh node?
- *“bed topography is observed once”:* Maybe this deserves discussion are the observations have been used to generate the initial bed ensemble; they are used twice if they are assimilated. As a general principle the initial ensemble should be independent of the assimilated observations.
- Inversion of the friction coefficient: I think this could deserve discussion and at least it would be interesting to compare the performance of the experiment using the inversion and an experiment where the friction is updated by the EnKF. More or less both methods try to achieve the same results, but the EnKF use the prior information defined by the ensemble why the inversion in fact introduce another “prior” from the regularisation term. I assume that the inversions are performed using the perturbed observations as for the EnKF? So that the results reflects the uncertainty on the surface observations?
- *“Effective pressure”:* is the friction law dependent on the effective pressure?
- I don’t understand the *“adaptive under relaxation strategy”* : explain when it is applied and why is it used as Choi et al. (2025) show good results without this “strategy”.