M. Bocquet (Referee)

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I am an expert neither in glaciology nor climate modelling. I will comment on the data assimilation aspect and the related methodology which represent a significant part of this study.

I enjoyed reading the manuscript which has a clear and straightforward structure. To my superficial knowledge on glaciology, this study is state-of-the art and quite demanding since the authors used a 25-member EnKF on a wind-forced global coupled sea-ice 3D model, for over 2 years of simulation. This seems to represent a very significant work.

I have several comments and criticisms on the methodological part, which I believe could significantly be improved. I see there four main problems:

(1) The description of Eq.(1) is just wrong. This equation applies to the forecast and analysis state, not each member of the ensemble. There is no such equation for the Ensemble Transform Kalman filter that you claim you use. There is a similar update equation for the stochastic EnKF but the observations in d are independently perturbed for each member.

P. Mathiot and co-authors: Equation 1 is actually correct (cf Evensen et al. 2003, eq 20). However, the description of the method and the notation was somewhat confusing. Consequently, the notation has been changed and the description has been modified : « The analysis step for the EnKF consists of the following updates performed on each of the ensemble members:

$$\mathbf{x_j}^{\mathbf{a}} = \mathbf{x_j}^{\mathbf{f}} + \mathbf{K}\,(\mathbf{d_j} - \mathbf{H}\mathbf{x_j}^{\mathbf{f}}).$$

The control vector $\mathbf{x_j} \in \Re^{n\times 1}$ contains all the relevant variables (i.e., all two-dimensional and three-dimensional oceanic variables and all sea ice variables except sea ice temperature and heat content) on all grid points of the model for the jth members of the ensemble. The sea ice heat content and temperature are largely non-linear (L distribution, Lisaeter et al. 2003). An update of their fields by EnKF leads to non-physical behaviour (large melting/formation rate) during the first step of the forecast. Therefore, we decided to exclude these variables from the control vector. n is the dimension of the control vector for each ensemble member. $\mathbf{x_j}^{\mathbf{a}}$ is the analyzed state and $\mathbf{x_j}^{\mathbf{f}}$ is the forecast state, while $\mathbf{d_j} \in \Re^{p\times 1}$ is a vector containing the p available observations at that time for the jth members of the ensemble. The observations used for the jth member are perturbed according to the uncertainties in the measurements: $\mathbf{d_j} = \mathbf{d} + \boldsymbol{\varepsilon}_\mathbf{j}$, where $\mathbf{d}$ is the unperturbed observation vector and $\boldsymbol{\varepsilon}_\mathbf{j}$ the perturbation for the jth ensemble member. The operator $\mathbf{H} \in \Re^{p\times n}$ projects the model state into the observational space. This projection ranges from a simple interpolation onto the observational grid to complex transformations of the model variables to some observed quantities. **K** is called the ``Kalman gain matrix'':

$$\mathbf{K} = \mathbf{P_e}^{\mathbf{f}}\mathbf{H}^{\mathrm{T}}(\mathbf{H}\mathbf{P_e}^{\mathbf{f}}\mathbf{H}^{\mathrm{T}} + \mathbf{R_e})^{-1},$$

$\mathbf{R_e} \in \Re^{p\times p}$ is an approximation of the observation error covariance matrix. $\mathbf{P_e}^{\mathbf{f}} \in \Re^{n\times n}$ is an approximation of the model forecast error covariance matrix. The covariance matrix is approximated because the full error covariance matrix for observations is poorly known and, for the model, the matrix is too large to be computed explicitly in oceanographic applications. The EnKF approximates it by …»

(2) **Some essential parameters (of indirect physical relevance) are missing in the data assimilation setup. What are the localisation lengths used here? What are the error priors chosen for each variable type? Do you resort to inflation?**

P. Mathiot and co-authors: All the missing details have been added to the new version of the manuscript. The localisation radius is 800 km and no inflation is used in this study. More informations about the observation errors, such as details about the magnitude, are now given for both data types. The following sentences have been added in Sections 3 and 4 : " … . We use the localized analysis presented in Sakov et al. (2010) to address the limitations due to the relative short size of our ensemble size (25 members) compared to the size of the state space. The localization radius applied in this study is 800 km. … . It is worth mentioning that no inflation is applied to enlarge the spread of the ensemble. … . The uncertainties in the synthetic observations are identical to the ones of the real observations. … . The uncertainties in sea ice concentration vary in time and in space. During summer, the error is estimated up to 20%, while during winter the deviation between ice concentration measurements and ice charts are around 10%. Close to the ice edge or in areas with very compact sea ice (sea ice concentration of about 100%), the uncertainties are lower, about 7%. … . As for sea ice concentration data, ice freeboard data are interpolated on the model grid each day. Uncertainties in ice freeboard data are assumed equal to the standard deviation of all data available in each model grid cell, i.e. 15 cm in average over all the data points and over all the periods."

(3) **To run a consistent synthetic experiment, you should perturb the observations, which you do not seem to implement.**

P. Mathiot and co-authors: The observations are perturbed in agreement with the specified error for each observation points. This detail has been added in the description of the Ensemble Kalman Filter. See response to the first comment.

(4) **By only describing the analysis experiments, your experiments just prove that your data assimilation system is consistent. In general, on average, the data assimilation run should be closer to the observation. But this is not enough to prove that it is useful. To truly validate a data assimilation system, there are several approaches. In your case, since sea-ice forecasting is of major geophysical, societal and industrial interest, I would suggest that you perform forecast experiments. For instance, each month of the 2-year experiment, perform a one-month (or longer) forecast and compare with the observation. Compare the performance of the free and data assimilation forecast run. Assuming I correctly understood the authors' methodology, my main criticism is on point (4) which may require additional work.**

P. Mathiot and co-authors: This study shows that the Ensemble Kalman Filter manages to assimilate successfully sea ice concentration and freeboard data in a global model over several years. We also have shown that assimilating ice concentration improves the representation of thickness and that assimilating freeboard during a part of the year has a positive impact on the model results all year long. As you and the second reviewer mention, it is an important step for climatic or operational forecast applications. However, the goal of this study is not to make a forecast exercise but to explain the method and open perspectives about the applications. Regarding your suggestion, we think it is out of scope and would correspond to a dedicated study and not an additional section to this paper. Seasonal and decadal predictions are a « young science » that requires a specific experimental design and which open specific questions as for example how to deal with trends during the first seasons or years after the initialisation of the forecast ? Consequently in the new version of the manuscript, we insist on the importance of this kind of method for sea ice reanalysis (Massonnet et al., submitted) and for operational and climate forecasting applications (COMBINE project, http://www.combine-project.eu/Science.763.0.html).

Massonnet, F., Mathiot, P., Fichefet, T., Goosse, H., Koenig Beatty, C., Vancoppenolle, M,, Lavergne, T.: A model reconstruction of the Antarctic sea ice thickness and volume changes over 1980-2008 using data assimilation, Ocean modelling, submitted.

Minor remarks or related to the main points:

(5) **p.1628, l.6 : Change "sea ice" to "sea-ice", for the sake of consistency.**
DONE

(6) **p.1628, l.9 : Change "through the use of satellite data" to "though the use of real satellite data". Otherwise the non-opposition to "synthetic" in the same sentence creates a confusion.**
DONE

(7) **p.1628, l.25 : Please define "Ice concentration". That is obvious to most of us but could help a broader readership.**
DONE

(8) **p.1632, l.20-21: What is "qualitatively close"?**
P. Mathiot and co-authors: The sentence has been changed into « **…** Our results are similar to those from simulations performed with an earlier version of the model (Timmermann et al. 2005) in both hemisphere as detailed below. …”

(9) **p.1634, l.16: "The EnKF is a sequential data assimilation technique that approximates model error statistics by using an ensemble of model runs". No: although it is clear you understand the point, the statement is misleading. Prefer "The EnKF is a sequential data assimilation technique that approximates state estimation error statistics by using an ensemble of model runs"**
DONE

(10) **p.1635, l.3-15: Please, clearly state that you are using an ensemble transform ensemble kalman filter.**
DONE

(11) **p.1635, l.16: See comment (1)**
P. Mathiot and co-authors: See response to the first comment. The section has been largely modified to take into account the comments.

(12) p.1635, l.25: "Therefore, we decided to exclude these variables from the state vector.": do you mean "from the control vector"?
Yes, DONE

(13) p.1635, l.25-26: contradicts line 16.
P. Mathiot and co-authors: You are right, n corresponds to the size of the control vector (i.e., all two-dimensional and three-dimensional oceanic variables and all sea ice variables except sea ice temperature and heat content) and not the dimension of the model state.

(14) p.1637, l.21. Eq.(5) isolated in between two sentences.
DONE

(15) p.1638: I believe that Section 4 could be split and merged into Section 5 and Section 6.
P. Mathiot and co-authors: This was a discussion we had between authors during the preparation of the manuscript. We finally think it is easier for the reader to find information about the data (generation, sources, error …) if all the information is merged in a single section instead of being split in two different sections.

(16) p. 1640, l.16: "the data are compatible with the model physics": when the data are perturbed as they should be, they are not per se compatible with the model physics. But the EnKF handles them by projecting the innovation onto the ensemble space. I suggest rephrasing: "the unperturbed synthetic observations are consistent with the model physics".
DONE

(17) p.1640-1641, Section 5.1: Please detail the chosen error magnitude such as the prior errors. What are the localisation lengths? (There must be one length together with a support radius to report.)
See response to comment 2.

(18) p.1642, Section 6.1: Please, detail the chosen error magnitude such as the prior errors. What are the localisation lengths?
See response to comment 2.

(19) p.1644-1646: Validate with a forecast (for instance). See main point (4).
See response to comment 4

(20) Throughout the text, there should not be any capital E in the "ensemble Kalman filter", only in the acronym.
DONE

(21) Throughout the manuscript: punctuation marks in the equations are missing.
DONE