The Cryosphere Discuss.,
https://doi.org/10.5194/tc-2019-54-RC2, 2019

The Cryosphere
Discussions
Open Access
EGU

Interactive comment on "Assimilation of surface observations in a transient marine ice sheetmodel using an ensemble Kalman filter" *by* Fabien Gillet-Chaulet

Anonymous Referee #2

Received and published: 16 July 2019

First of all, I would like to apologise to the author and the editor for providing my review so late. I consider this paper treats an important subject in an innovative manner and, as such, deserves a careful review. I hope you will find my review insightful.

OVERVIEW

The paper aims to adapt an Ensemble Kalman Filter (EnKF) to estimate jointly the surface elevation, the bedrock topography and the basal friction coefficient in the case of a flowline marine ice sheet. Time-dependant ensemble data assimilation (DA) ap-

proaches are relatively new for ice sheet initialisation. The paper focuses on the case of a grounding line retreat for unstable glaciers, which is a hot topic in ice sheet modelling and climate change. It also studies the influence of DA on forecasts of grounding line retreat.

GENERAL COMMENTS

The paper targets an important and timely question: how to initialise and estimate basal parameters to forecast the evolution of marine ice sheets and glaciers especially in the case of an unstable retreat? and proposes to use an EnKF (here an ESTKF) in this context. EnKFs have shown how efficient they can be in a wide range of applications (not exclusively meteorology and oceanography but also hydrology, crop modelling, oil extraction, pollutant dispersion, . . .), are a good alternative to adjoint-based methods and are the basis of hybrid methods that are now popular in DA (see e.g. Bannister, 2017). The paper shows clearly that EnKFs are a good toolbox for DA in glaciology. The experiment shows clearly how beneficial this approach could be with adequate figures and a very insightful analysis. Overall I am convinced that the paper in its final form will be a very good introduction of ensemble DA methods in ice sheet modelling.

Nevertheless, there are few points that prevent me to publish the paper as is. I list them below:

- I have some reservation about the experimental setup mainly on how the reference run is designed and on how the basal friction coefficient C is estimated.
  - About the reference run: The long-term objective of the study is to forecast accurately grounding line retreat for Antarctic hemispheric glaciers in the context of global change. However, in the reference run of the experiment, the grounding line retreat is triggered by the abrupt change of ice rigidity

B. I wonder if the simulated grounding line retreat is “realistic” compared to one triggered by climate change. Also I have the same question about the sinusoidal basal friction parameter C. How realistic is it compared to real cases? I know we are in flowline cases using SSA equations. But it would strengthen the paper if the author could reflect on that subject in the section 3.1. Part of my comment may be due to my lack of knowledge in glaciology, so please accept my apologies if my comment is irrelevant.

  - About the assimilation setup: The basal friction coefficient C must be positive. To ensure such thing, you use the following change of variable $C = \alpha^2$. But by doing so, you do not ensure the unicity of the estimation as α and $-\alpha$ would lead to the same C. Also I thought that the C parameter could be of different order of magnitude. To counteract those potential issues, Bonan et al. (2014) chose the following change of variable $C = 10^\alpha$ ensuring the positivity of C, the unicity of the change of variables and mimicking behaviours with different order of magnitude. Could you explain why the change of variable you used is more appropriate in your context?

- The paper is full of interesting results but sometimes they deserve a more thorough analysis.

  - The assimilation window is between 1 yr and 35 yr (you run forecasts from analysed states at $t = 20$ yr and $t = 35$ yr). But the grounding line is almost steady between $t = 13$ yr and $t = 32$ yr. We also see that after the first 10 years of assimilation, RMSD for C remains stable. I wonder if those two points are correlated meaning is it easier or more difficult to estimate C in the case of a retreating grounding line (hence a more dynamic ice sheet) or an almost steady state? As the behaviour of grounding line is different from one marine glacier to another, it would be beneficial to the community if you could push your study in that direction in the revised version of the

manuscript (for example continuing DA after $t = 35$ yr for the next ten years and study what happens).

  - Figure 5 shows interesting results about the performance of ESTKF with inflation and localisation and varying sizes of the ensemble. Bonan et al. (2014) has performed the same kind of studies for grounded ice sheet using an ETKF. Do you obtain similar optimal parameters for inflation and localisation in your experiment or are they different from Bonan et al. (2014)? It would be interesting to reflect on how the physics of the model influences such parameters.
  - You only show results after 300 km (nothing between 0 km and 300 km). Does it mean that what happens between 0 km and 300 km does not have an influence on the grounding line retreat? Does it mean DA is pointless in those areas (in that case, that would make DA more affordable as less grid points need to be treated)? If so, please state it more clearly and if not, provide more results for that area.
  - I am worried by some of the results shown for ESTKF for small ensembles ($N_e = 30$) as RMSD reduction is only 20% for the bedrock topography and 30% for the basal friction coefficient. For 2D real cases (either using Full-Stokes or SSA), we need an ensemble approach working for small ensembles due to the cost of the experiment and 30 members might be too expensive. Could you reassure me and provide the reader that the approach would be beneficial even in 2D real cases?
  - About the forecast experiments, Figure 1 shows clearly how beneficial an ensemble forecast can be compared to a deterministic forecast. It also shows that the distribution of the grounding line position is not Gaussian. Could you provide more information (maybe using histograms) on how grounding lines are distributed in the ensemble?

- While on average, the paper is perfectly readable. There are few parts that are hardly accessible to the reader. As I think the target audience of this paper is the ice sheet community and more generally the glaciology community, the paper would benefit from a careful editing. I detail those parts in the Specific comments section.

Overall I consider the paper as a highly valuable addition to data assimilation for ice sheets. But it deserves mostly some rewriting. Therefore I recommend a minor revision as almost all the science is already here!

SPECIFIC COMMENTS

Overall I think it would be nice for the reader to have two tables summarising the various variables used in this paper, one for the ice flow model and one for data assimilation.

About Ensemble Kalman Filters:

- I feel localisation and inflation should be better explained in the paper (either in the introduction and in the DA section). I agree they are both used to counteracts the effects of undersampling. But the reader would benefit from having more information. Undersampling causes underestimated variances (counteracted by inflation) and spurious correlations (counteracted by localisation in the case of long-range spatial spurious correlations). Could you add few lines on the subject. Also few references are missing. For inflation:

  Anderson, J. L. and Anderson, S. L.: A Monte Carlo implementation of the nonlinear filtering problem to produce ensemble assimilations and forecasts, Mon. Weather Rev., 127, 2741–2758, doi: 10.1175/1520-0493(1999)127<2741%3AAMCIOT>2.0.CO%3B2, 1999.

  For localisation, the first one is for local analysis (the one you use), the other two are for covariance localisation (the historical one)

  Ott, E., Hunt, B. R., Szunyogh, I., Zimin, A. V., Kostelich, E. J., Corazza, M., Kalnay, E., Patil, D. J., and Yorke, A.: A local ensemble Kalman filter for atmospheric data assimilation, Tellus A, 56, 415–428, doi: 10.1111/j.1600-0870.2004.00076.x, 2004.

  Hamill, T. M., Whitaker, J. S., and Snyder, C.: Distance-dependent filtering of background error covariance estimates in an ensemble Kalman filter, Mon. Weather Rev., 129, 2776–2790, doi: 10.1175/1520-0493(2001)129<2776%3ADDFOBE>2.0.CO%3B2, 2001.

  Houtekamer, P. L. and Mitchell, H. L.: A sequential ensemble Kalman filter for atmospheric data assimilation, Mon. Weather Rev., 129, 123–137, doi: 10.1175/1520-0493(2001)129<0123%3AASEKFF>2.0.CO%3B2, 2001.

- Also about inflation, the term “forgetting factor” introduced by Pham et al. (1996) is, unfortunately, very uncommon in the EnKF community. Could you state somewhere that this is just the inverse of the traditional inflation parameter known widely in the EnKF community?

- p. 6, l. 23: There is no unicity of the symmetric square root matrix $\mathbf{C}$. It is known that the choice of $\mathbf{C}$ can have a significant impact on results (see e.g. Livings et al., 2008). Could you detail how $\mathbf{C}$ is calculated in PDAF?

  Livings, D. M., Dance, S. L., and Nichols, N. K.: Unbiased ensemble square root filters, Physica D, 237, 1021–1028, doi: 10.1016/j.physd.2008.01.005, 2008.

- p. 7, first paragraph on how to use the ESTKF with a nonlinear observation operator. It is a very good point you raise especially in the case of assimilating surface ice velocities (highly nonlinear observation operator). However, I find it difficult to see where the nonlinearity of the observation operator intervenes.

Could you rewrite the whole section 2.2 and consider directly the case when the observation operator is nonlinear? That would avoid confusion for readers.

About the experiment:

- p. 8, l. 1-2: About the roughness signal b_r ,could you detail, in annex for example, how do you simulate the roughness (which equation?) because I do not know this approach.
- p. 9, l. 21-22: you mention the term "*variogram*" which is not well known for readers. Could you provide more details how do you generate the ensemble of initial bedrock topographies, in annex for example?
- p. 9, l. 30-31: same comment as previous.

About the discussion:

- p. 12, l. 25-29: you seem to oppose ensemble and variational methods, but more and more, the tendency is to develop hybrid methods as detailed in Bannister (2017) and Vetra-Carvalho et al. (2018). The main tendency is to use variational approaches in which the adjoint is replaced by ensembles making those adjoint-free approaches. Could you modify your paragraph to reflect this tendency?
- p. 13, l. 4-13: There is a now long range of DA literature on how to estimate model bias. One good reference is the following:

  Dee, D. P. Bias and data assimilation, Q. J. Roy. Meteor. Soc., 131, 3323–3343, doi: 10.1256/qj.05.137, 2005.

  Could you reflect on that possibility in your discussion?

- p. 13, l. 14-20: Same comment as before on estimating observation error covariances matrices. A good review paper:

  Tandeo, P., Ailliot, P., Bocquet, M., Carrassi, A., Miyoshi, T., Pulido, M. and Zhen, Y.: Joint Estimation of Model and Observation Error Covariance Matrices in Data Assimilation: a Review. Mon. Weather Rev., submitted, available at: https://arxiv.org/abs/1807.11221v2, 2018.

  Most approaches are based on Desroziers diagnostics, see:

  Desroziers, G., Berre, L., Chapnik, B. and Poli, P.: Diagnosis of observation, background and analysis-error statistics in observation space. Q. J. Roy. Meteor. Soc., 131, 3385–3396, doi: 10.1256/qj.05.108, 2005.

MINOR COMMENTS AND TYPOS

- p. 1, l. 5: "*starting FROM this initial state . . .*"
- p. 3, l. 15: "*the Kalman filter analysis is REWRITTEN and . . .*"
- p. 3, l. 16: The references you mention are all about deterministic versions of the EnKF (Pham et al., 1998, SEIK filter; Bishop et al., 2001, ETKF filter: Nerger et al., 2012, ESTKF filter). But not every EnKF has a deterministic analysis, the stochastic EnKF has also been an important part of EnKF history. Could you add the following references to make your point broader?

  Burgers, G., van Leeuwen, P. J., and Evensen, G. Analysis scheme in the ensemble Kalman filter, Mon. Weather Rev., 126, 1719–1724, doi: 10.1175/1520-0493(1998)126<1719:ASITEK>2.0.CO;2, 1998.

  Houtekamer, P. L., and Mitchell, H. L. Data assimilation using an ensemble Kalman filter technique, Mon. Weather Rev., 126, 796-811, doi: 10.1175/1520-0493(1998)126<0796%3ADAUAEK>2.0.CO%3B2, 1998.

- p. 3, l. 23: "*However the many applications in meteorology and oceanography show . . .*" While EnKFs have been primarily developed for those two applications, it has been successfully used in a wide range of applications, from hydrology, to crop modelling and oil extraction. Could you rephrase the sentence to show the broad range of applications for EnKF including some that may be closer to glaciology? Maybe add other references too?
- p. 6, Eq. (13): Could you define $\bar{\mathbf{X}}^f$?
- p. 9, l. 13: "*the transient ASSIMILATION ON model projections*"

Interactive comment on The Cryosphere Discuss., https://doi.org/10.5194/tc-2019-54, 2019.