Response comment Reviewer 2

Anonymous Referee #2 Received and published: 4 December 2018

General Comments

In this paper, the authors perform 5 experiments with a 20 km coupled ROMS-CICE model forced with ERA-Interim forcing for 3 full years for the period of 2011-2013. The five experiments are 1) assimilation of OSISAF sea ice concentration (SIC) only, 2) assimilation of OSISAF SIC and CryoSat-2 sea ice thickness (SIT), 3) assimilation of OSISAF SIC and SMOS SIT, 4) assimilation of OSISAF SIC and AMSR-E/2 snow depth observations, and 5) control run without any data assimilation. The Ensemble Kalman Filter (EnKF) is the data assimilation technique used in this study. Ocean boundary conditions are provided by the FOAM ocean model. Two sets of experiments are performed: 1) assimilation experiments with 20 ensemble members with a 7-day assimilation time step, 2) seasonal forecasts with 20 ensemble members for the fivemonth period beginning in April/May to examine the skill in predicting the September sea ice minimum extent.

The authors computed the annual RMSE of the ensemble mean SIC over the threeyear period and found that from January – August, the SIT experiments performed similarly and outperformed the SIC-only run during that period when using the weighted AMSR-E/2 data. From September – November, the SIC experiment had the lowest error. This could be related to no IT data during the summer months. The authors speculate the model has difficulty in transitioning from the melt to growing season. When comparing against the OSISAF ice concentration (which was assimilated into the model), the SIT experiment using SMOS showed the lowest RMSE from January – July. The snow depth experiment showed a lower RMSE than the SIC-only experiment for the period of January – June.

The authors examined “hit rates” to determine which experiment led to the most accurate number of grid cells classified as open water (concentration < 10%), low (<50%) or high concentration (>50%) and found that the experiments with the assimilation of ice thickness performed best. Total ice volume is examined for all 5 experiments and they find that except for the control run, the volume steadily decreases from year to year. The authors need to better address why this is happening, and propose future studies to investigate this further.

The decrease in sea-ice volume is not a model problem, but a response to the assimilation where the model, in general, has too much and too thick ice. An attempt at a discussion of this case was given on page 11. line 26-32 in the old manuscript. This section has now been modified to make this more clear, new text is added: « The control model is found to have too thick ice compared to the observations, while the experiments assimilating SIT are much closer to the observations, though largely biased. This can be used to explain the drastic decrease in sea-ice volume found in Fig.

\ref{fig:extent_volume}b. The model SIT is adjusting towards the observations by rapidly thinning the sea-ice.»

Comparisons are performed with the annual mean ice thickness and snow depth from all 5 experiments versus data from NASA Operation IceBridge. Since IceBridge data is only available for typically 10 transects for March/April each year; this is not a very compelling analysis. While Arctic snow depth data is difficult to obtain, it is recommended that the authors examine additional sources of ice thickness data, such as ice mass balance data (see comment below) which has much better temporal and spatial resolution.

Thank you for this valuable suggestion. We were not aware of these observations, and they are now included in the validation of the experiments.

Seasonal forecasts are evaluated by performing 5-month experiments for all five cases beginning in April of 2011, 2012 and 2013 to examine the SIC RMSE. When averaged for all three years, the SIT experiments perform best. Through mid-June, the snow depth experiment is very similar to the CryoSat-2 (SITI), but afterward the error increased significant and mirrors the control runs high error from August through September.

With the exception to the Lisæter (2007) reference, throughout the paper you should consistently refer to CryoSat as CryoSat-2.

This is corrected

Why aren't ice mass balance buoys used in your study? Look at available data at: http://imb-crrel-dartmouth.org/results/. During the period of your study, there is drifting buoy data available.

They are now included.

Are melt ponds used in your CICE simulations? If yes, state that in Section 4.3.

Yes, the model use melt pond parametrization. Information regarding this is now added to the description of the model in section 2: «The model has a thermodynamic component calculating the local growth rate of snow and ice, ice dynamics component calculating ice drift based on the material ice strength, a transport component, a melt pond parametrization and a ridging parametrization used to distribute ice in thickness categories \citep{Hunke_2015}.»

Why didn't you evaluate model ice drift errors using the International Arctic Buoy Programme buoy data? See http://iabp.apl.washington.edu/

We did not have in mind to include ice drift in the study, thus unfortunately, the model drift output was not saved.

This is a very well written paper with clear tables and complementary graphics. I recommend publication after my comments are addressed.

We thank the reviewer for the kind words and the careful and constructive feedback.

Specific Comments

Page 2 lines 15-25: Suggest you add the following reference to this section when discussing operational system assimilating SIC:

Posey, P. G., Metzger, E.J., Wallcraft, A.J., Hebert, D.A., Allard, R.A., Smedstad, O.M., Phelps, M.W, Fetterer, F., Stewart, J.S., Meier, W.N., Helfrich, S.R., 2015. Assimilating high horizontal resolution sea ice concentration data into the US Navy's ice forecast systems: Arctic Cap Nowcast/Forecast System (ACNFS) and the Global Ocean Forecast System (GOFS 3.1). The Cryosphere 9 2339-2365. doi: 10.5194/tcd-9-2339- 2015.

Thank you for the advice, this has now been added: «\cite{posey2015assimilating} assimilated high-resolution SIC observations (~4 km) into a coupled ocean sea-ice model, the Arctic Cap Nowcast/Forecast System (ACNFS) using the 3DVAR assimilation method. In this study, they showed that increased observation resolution has a significant impact on the ice-edge forecast.»

Page 3 first paragraph: Consider adding the following recent references when discussing the use of CryoSat-2 data:

Allard, R. A., Farrell, S. L., Hebert, D. H., Johnston, W. F., Li, L., Kurtz, N. T., Phelps, M. W., Posey, P. G., Tilling, R., Ridout, A., and Wallcraft, A. L.: Utilizing CryoSat-2 sea ice thickness to initialize a coupled ice-ocean modeling system, Advances in Space Research, 62, doi:10.1016/j.asr.2017.12.030, 2018.

Blockley, E. W. and K. A. Peterson: Improving Met Office seasonal predictions of Arctic sea ice using assimilation of CryoSat-2 thickness, Cryosphere, 12, 3419–3438, doi:10.5194/tc-12-3419-2018.

Xie, J., F. Countillon, and L. Bertino: Impact of assimilating a merged sea-ice thickness from CryoSat-2 and SMOS in the Arctic reanalysis, Cryosphere, 12, 3671-3691, doi:10.5194/tc-12-3671-2018.

Thank you, we were not aware of the recent papers. We have improved the text to include these studies: «In the last couple of years, there has also been an increase in the use of Cryosat-2 observations in various forms for assimilation. \cite{Chen_2017} assimilated both the SMOS thin SIT and the CryoSat-2 thick SIT into the National Centers for Environmental Prediction's (NCEP) Climate Forecast System version 2 \citep{Saha_2014} using the localized error subspace transform ensemble Kalman filter \citep{Nerger_2013}. This study showed improved sea-ice prediction with SIT assimilation, thus verifying the importance of SIT observations to achieve accurate sea-ice forecasts. \cite{xie2018impact} assimilated a blended SMOS CryoSat-2 product into TOPAZ. They showed that these observations provide the primary source of observational information in the central Arctic, and when assimilating this product the model SIT was improved. \cite{blockley2018improving} argued that by assimilating Cryosat-2 observations, the Arctic summer prediction of ice extent and location were significantly improved. \cite{allard2018utilizing} used CryoSat-2 observations for initialization in the coupled ocean sea-ice ACNFS model. The study showed improved model thickness with CryoSat-2 initialization when compared to independent ice thickness observations.»

Page 4 line 12: Please state the horizontal resolution of the ERA-Interim dataset

This is now added: «The coupled model is forced by atmospheric data from the ERA-Interim dataset from the European Centre for Medium Ranged Weather Forecast \citep[ECMWF;][]{Dee_2011}. The ERA-Interim dataset has a horizontal resolution of approximately 0.7°, corresponding to T255 spectral truncation.»

Page 4 lines 13-14: You use FOAM for prescribed ocean boundary conditions. What do you use for the CICE boundary conditions?

At the moment no boundary conditions are used for the sea-ice. For the most part of the year, this is not a problem because the sea-ice is surrounded by ocean. While during winter when the sea-ice extends beyond the Behring straight this might be a problem for this area, but this is not included here, and we do not believe this to be an issue regarding the results.

Page 6 last paragraph: What is the accuracy of the AMSR-E/2 snow depth data?

This has now been added: «For the snow depth product uncertainty estimates exist for every grid point. There are two main sources of uncertainties in this observation product: The first is that the number of IceBridge observations used to develop the empirical relationship between brightness temperatures and snow depths is small compared to the coverage of the product. The second uncertainty is in the input parameters (brightness temperature, ice concentration etc.). More on how the uncertainties are explicitly calculated can be found in \citep{Rostosky_2018}.»

Page 8: You state the coupled modeling system is run for 1 year as an initial state. Was it spun-up from rest? How was ice initialized? Uniform everywhere from a particular thickness?

This has now been clarified in the manuscript: «The initial ensemble is generated from ice states from January 1. based on 20 different years of a standalone ice model run without assimilation. The standalone model was initialised without ice in 1979. All initial ocean states are model output at initial date January 1. 2010. This output is taken from a model spin-up over1993-2010.»

Page 8 last paragraph: Why didn't you include another experiment which included a blended CryoSat-2/SMOS ice thickness?

The focus of this study was on the individual observation products. , we could have tested all sorts of combination between the products, but this would become quite messy. In addition, the blended product provided an alternative dataset for model verification.

Page 13 Figure 4b: Please explain your views on why the ice volume (except for control run) steadily decreases. I suggest in your conclusions section to include to some possible follow-on studies to better investigate this issue.

This is already mentioned on p.11 lines 26-32 in the previous version of the manuscript. The decrease is related to too much ice in the control model, and due to assimilation, the thickness is slowly going towards the observed values which are thinner. This section has been updated to further clarify this result, see comment above.. Thus no further studies of this effect should be necessary.

Page 14 lines 20-24: Please include figures and discussion on comparison for April 2012 and 2013?

Figure 7. is only meant as an illustration of the curves shown in figure 4b. Even though the figures could be added for 2012 and 2013 we do not think this would provide any additional information from figure 4b. Also, 8 more figures would take a lot of space in the manuscript and would be too messy as they are providing only little new information.

Page 14 last paragraph: Have you looked at Dartmouth (formerly CRREL) IMB data for an additional source of ice thickness data? These data sets have much more temporal coverage than just Mar/Apr from NASA IceBridge.

Yes, as mentioned previously a new section including verification of these data have been added: « Another independent dataset of SIT observations complementing the IceBridge observations by observations throughout the year is the IMB buoy dataset. The result of model validation with the IMB is shown in table \ref{tab:IMB_th}. For these observations, a slightly different method than that applied for IceBridge is performed. This is because IceBridge temporarily only covered March-April, while the IMB data span the entire year. The buoy observations are converted to daily averages on the model grid. From these values, the RMSE is calculated on the 7-day ensemble mean and averaged for each year. Since SIT is a relatively slow varying variable, for each 7-day output, observations from +/-3 days are used to increase the number of observations. The IMB observations do not include an uncertainty estimation, hence the RMSE is not normalised was the case for other other RMSE values in this work. The results show that over the three study years, the SMOS internal SIT assimilation system has the lowest RMSE values, followed by the CryoSat-2 internal SIT assimilation. The other three show similar results, indicating the positive impact of assimilating ice thickness in the model.» A table has also been added illustrating the yearly averaged results.

Page 16 last paragraph: Table 3 shows yearly averaged RMSE values of ensemble average of snow depth compared to NASA IceBridge. Explain how you can do this when NASA IceBridge is only available for Mar/Apr each year.

The yearly average is a Mar/Apr average. This has now been made clearer by adding it into the figure text: «The Mar/Apr-mean RMSE of the ensemble-mean snow depth averaged over all grid cells.» In addition, new text has been added: The same method as for the SIT in table \ref{tab:IceBridge} was used, where Mar/Apr model values are compared to the IceBridge observations and averaged.

Page 18 lines 15-16: You state five-month forecasts, but experiments are performed April – September What are the actual dates? Apr 30 – Sept 30 would be 5 months; April 1 – Sept 30 would be 6 months.

We mean it is an approximately 5-month forecast. The start date varied a bit because of the 7-day assimilation cycle. Information regarding this is now added to the text: «This is done by running each of the experiments from mid-April to mid-September each year without assimilation and validating against the OSISAF SIC observations. The actual start date varied slightly from year to year because of the 7-day assimilation cycle, but the start date was the same for all experiments.»

Technical Corrections:

Page 1 line 7: replace “asses” to “assess”

done

Page 1 line 12: should be CryoSat-2 (and throughout the paper)

done

Page 1 line 16: replace “lead” to “led”

done

Page 2 line 14: add comma after “later”

done

Page 8 line 30: reword “Five assimilation experiments” to “Five experiments”

done

Page 12: Fig 3 caption: first line should read “low concentration ice <50%” (not >50)

done

Page 13 line 8: replace “to much ice” to “too much ice”

done

Page 26 line 24: Provide more complete info for Sakov EnKF-C user guide (2015) reference

Added arXiv: «Sakov, P.: EnKF-C user guide. arXiv:1410.1233., 2015.