Anonymous Referee #1

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Please note that the comments from referee are given in black font “Times new roman”. Commnets from the authors are given in blue font “Calibri”. The changes in the manuscript are given in green font “Calibri”.

Summary

This paper describes the use of a basic OI/nudging method to assimilate ice concentration and SST observations into an uncoupled version of the CICE model with a mixed-layer ocean parametrisation.

Unfortunately, this work is not currently up to the standard required for publication. A detailed review is given below, but the main reasons are as follows:

(1) It is unclear what is novel about this work. The conclusion states that the authors’ use of a variable drag formulation is unique. However, Tsamados et al. (2014) previously incorporated a variable atmospheric and oceanic form drag into the CICE model. The paper has been cited by the authors, but they do not describe how their implementation of this method is related to any of their results. At the most basic level, the authors should show results with and without this formulation. The statement that other centres do not provide details of parameters other than ice concentration or thickness is inaccurate, particularly as many of those centres are also using the same CICE model as the authors, with the same available parameters. The main conclusion of the results seems to be that assimilating observations brings the model output closer to reference observations, which is not a new result. Perhaps the differences in results when using thin ice of < 60 cm compared to < 30 cm might be an
interesting angle, but this is not explored.

The authors would like to thank the reviewer for the comments and suggestions.

It is true Tsamados et al. (2014) has incorporated a variable atmospheric and oceanic form drag into the CICE model, but have not been used with a data assimilated model that produced parameters such as freeboard, sail, keel measurements.
The forecast centers are using CICE model a constant variable drag formulation. Moreover, the used models are coupled with ocean models.

(2) The statements throughout the paper, that the model fits the validation observations well, are not backed up by the results themselves. Although the assimilation improves results, there remain clear systematic differences between the model output and the reference observations.

The study estimates the bias observed over years and will use it for further tuning of the model.

3) There are many omissions in explanation of methods, several contradictions in the text, confusing wording, and the paper is missing references to current literature and relevant similar systems, e.g. TOPAZ, RIPS/RIOPS, ACNFS. Also missing is a description of how

the authors' system differs and improves on these, and indeed what the purpose of the new system is. A number of the citations given are conference papers or otherwise unpublished works, which are not peer-reviewed and should not form a significant basis of citations.

The assimilation and tuning of the model is still an ongoing work and will be compared with RIPS and other models in the future. Moreover, the cited conference papers include the developments of RIPS. The novelty of the manuscript is the regional implementation of the uncoupled model.

General comments

The relevance of how this work fits in with the published literature needs to be discussed, along with other regional modelling systems. How do the results compare to e.g. coupled ocean-ice systems?

The coupled ice-ocean systems are more complex and require additional tuning of ocean parameters. The purpose of the study was to go without an ocean model using a mixed layer parametrization and data assimilation to produce the best results. Coupling would require extensive work and is out of the scope of the current work.

What is the benefit of only using an SST parametrization? Is this system to be used for operational or research purposes? A large number of the references used in this paper are unpublished or non-peer-reviewed works including conference papers. A more complete discussion of the peer-reviewed literature Discussion paper is necessary.

Please note that the SST parametrization was discussed earlier in Parasad et al. (2015). Similar to RIPS 2016 the model used the same density parametrization but with a different criteria for forwarding the slab ocean model parametrization.

The paper needs more information on all the input and validation data sets, including descriptions and data access information. The authors also need to ensure that all the datasets used are properly cited.

All the input and validation data sets had been described and properly cited.

Why is the assimilation system set up to weight heavily in favour of the model rather than giving equal weight to the observations?

The assimilation followed work of Lindsay et al. Further tuning of the model physics and assimilation schemes have to be done to better understand the model behavior. The system is actually weighted heavily in marginal ice zones where significant bias can occur.

The paper repeatedly states that AVHRR data was assimilated. Actually, it looks like the authors are assimilating the AVHRR-only OISST analysis product, which although based on observations, is an analysis product. This needs to be made clear, along with information on the temporal resolution, timeliness etc of the product. Additionally, this product uses SSM/I and SSMIS information to create proxy SST observations for assimilation at high latitudes. This means the SST observations also include input from ice concentration data. Therefore, they are not independent from the SSM/I and SSMIS data being used for validation.

Yes, SST used an analysis product since model is assimilated over its domain including at ice edges where ice concentration has lower values. It was clarified in the paper that AVHRR-only OISST analysis product uses ice information to retrieve SST only for regions where ice concentration is greater than 0.5.
The following sentence has been included for clarity
“ The analysis product estimates SST from ice concentration only in regions where ice concentration is greater than 50%, otherwise uses satellite data to retrieve SST values.”

More detail and justification of which thickness ranges of SMOS and CryoSat-2 observations are being used is needed.
The justification has been provided in the paper “Also, it is strictly recommended not to use the SMOS data with an uncertainty greater than one meter (Tian-Kunze and Kaleschke, 2016) for practical applications.” This has been clearly stated in the user manual of the SMOS product.
For Cryostat-2 freeboard measures had been used for comparison. Since thickness estimates of CryoSat 2 is derived from freeboard estimates we think that it would be best to compare freeboad estimates with Cryosat-2 instead of thickness estimates.

What real benefit is the assimilation giving? Figures 5-7 show that it brings the model closer to the observations, but it still deviates and all modelled ice thickness is too high. It is not convincing to state that the M2 model has good correspondence with the observations due to being in the uncertainty range, as even the free-running model is also managing that most of the time. Assimilating SST in addition to sea ice concentration produces better results, but few if any operational centres will not already be assimilating ice concentration and not SST observations.

All modeling centres assimilate SST in Ocean model and passe the information to sea ice model. Here, we state that if we use analysis product of SST in the ice model itself it produces better results.
Moreover, operational centers give information on ice concentration but ice thickness significant biases are observed also, other information such as ridge height, keel depth, freeboard data are rarely discussed.

The authors acknowledge that the assimilation is not optimized. If changing the value of alpha or adjusting the nudging timescale is expected to improve results, why has this not been done? Similarly for the relationship between ridge and keel.

This is a parameter sensitivity study and is an ongoing work.

The authors need to also include RMS (or standard deviation) statistics, as well as mean difference when discussing how well models match validation observations. For figures 5,6,7 the modelled ice is too thick for all model runs after January. Although results for the M2 model are closer to observations than the M0 or M1 models, results are still not very good, which is not mentioned in the paper. In general throughout the paper, systematic biases or errors which are large in proportion to the model variable values are not addressed, or are dismissed as being within uncertainty levels. This shows a poor understanding of the validation results.

For results where the model thickness < 30 cm (figures 9,10,11), the models seem to be underestimating ice thickness rather than overestimating. This difference to the results seen in figures 5,6,7 needs to be addressed in the paper.

For figures 9,10,11 the modelled thin ice thickness remains roughly constant from December, and also the assimilation makes little difference. Reasons for this need to be addressed in the paper.

More information on methods is needed throughout. Instances of this are given under specific comments below.

The conclusions make a number of statements which are misleading. Details are given under specific comments below.

Many of the references are missing important information.

Specific Comments

Page 1
Line 6: Observations of ridge height and keel were not obtained from remote sensing data

The ridge height is not estimated from remote sensing data but keel depth is estimated using the Upward Looking Sonar Instrument.
The following text was edited in the Manuscript
"The modeled ice parameters including concentration, ice thickness, freeboard, and keel depth were compared with parameters estimated form remote sensing data."

Line 8: What is your maximum SMOS thickness data? Only thin ice thickness available from SMOS.
The maximum SMOS thickness is not mentioned. Instead we consider the thickness levels that are used for practical applications. Please note that for practical applications ice thicknesses with uncertainty greater than 1m is not used.

Line 9: CryoSat-2 freeboard observations should be mentioned.
Included the following text
"The model freeboard estimates were compared with the freeboard measurements derived from CryoSat2."

Line 15: Citations needed.
This is a general statement on importance of work.

Line 19: A 1992 reference seems a strange choice given the recent advances in ice thickness remote sensing.
The heterogeneous property of sea ice still poses a challenge for measuring several sea ice parameters.

Line 20: Need to specifically relate this to sea ice forecasting.
Please see the next sentence
"Data assimilation methods can provide more accurate initial conditions for forecasting systems"

Page 2
Line 5-10: The relevance of this and how your work fits into this needs to be discussed, along with other regional modelling systems.
In the sea ice data assimilation literature a detailed description of the parameters other than ice thickness is not provided. Even the discussions that already exists tend to omit the uncertainty of the ice thickness.

The following text was edited
"In addition to validation of the ice concentration we discuss the effect of the assimilation on ice thickness, freeboard, draft and ridge keel. Since freeboard, draft and keel are functions of ice concentration and ice volume it is reasonable to compare the model values with corresponded observations. The work suggests a methodology to extract the level ice draft and keel depth information from ULS measurements, which was then used to describe the relationship between ridge and keel."

Line 11: Do you mean assessment rather than analysis here? Can only produce an analysis of ice concentration and thickness by assimilating ice concentration and thickness, not by modelling thermodynamics and (assimilating?) ice motion.

Yes, we mean assessment. This is corrected in the manuscript.

Line 12: which satellite?
RADARSAT-1 and RADARSAT-2

Line 17: Before or after assimilation?
After assimilation
Following line was edited
"Ice concentration and extent was overestimated in the assimilated model, probably due to the bias in atmospheric forcing, underestimation of heat flux and over/under estimation of sea ice growth/melt processes."

Line 19: Reference Hunke et al. (2015) the first time CICE is mentioned.
Added.

Line 22: Confusing, as you have mentioned prescribing ocean conditions but then mention you will be assimilating SST, before you mention the ocean mixed layer parametrisation below.
The following sentence was edited for clarification.

"The optimal interpolation and nudging method is also used to assimilate SST estimated by a slab ocean parametrization in the sea ice model."

Line 31: "regional scale" - need to have a figure showing the domain.
Domain is shown in all modeling figures.

Line 31: "about 10 km" - Need to mention what grid you are using.
The following text was edited for clarification
"The sea ice model was implemented on a regional scale of about 10 km orthogonal curvilinear grid with a slab ocean mixed layer parameterization."

Line 32: Should say "Density-based criteria were used >following< Prasad et al. (2015)..." and elsewhere, where the method has already been published.
Included

Line 33: "analysis" should be "assessment" as the word analysis has a very specific meaning in the context of data assimilation.
Corrected

Page 3

Lines 3-6: Citations for the sources of all the forcing data are required.
Citations provided.

Line 5: Why use SST climatology data rather than the daily analysis fields? What sort of climatology? Daily? Monthly?
Monthly climatology. The sentence has been revised to clarify this.

"For SST, the climatology data derived from high-resolution NOAA were used as an input for the initial and boundary conditions"

Line 7: If assuming no ice at the start of the runs, important to state the spin-up time of the model (which should be mentioned anyway).
The model is spin-up for 4 months before assimilation. Please note that the experiments showed that 10 year spin up also produced similar result for free run.

Line 10: Assimilating AMSR2/AMSR-E data, not using for validation.
Revised

Line 16: Mentioned that AMSR-E shows best results above 65% concentration, but are validating against SMOS observations of thin ice, as found in the MIZ where concentrations are much lower than 65%. Need to discuss limitations of the AMSR-E/AMSR2 data for the ranges relevant to the paper.

We do not consider this in the present case since we use a long term standard deviation to assimilated AMSR-E data.

Line 18: AMSR-E data is interpolated to the model grid before assimilating (what about AMSR2?). The usual method would be to interpolate the model to the observation location. What is the benefit in interpolating the observations to the model grid?

Yes, the data assimilation methods do have an operator to observational space in our case it would be an interpolation and after assimilation it is interpolated back to the model grid. We currently neglect this forward operator. Interpolating it to model grid allows computational benefit, easiness of implementation. Moreover, since we introduce constant values for sigma, the observations are considered to have a constant uncertainty value and hence we assume the error would be less if the observation is interpolated to the model grid. Although it was also evident from the results it would be presented as a separate work later.

Line 22: How consistent are observations derived from the different AMSR-E and AMSR2 instruments? Information needs to be added to the paper. This was already stated in the section on "Remote Sensing Data for Assimilation and Validation"
"The same frequency (89 GHz) as in the AMSRE instrument was used to derive information from AMSR2. The spatial resolutions also remain the same for both AMSRE and AMSR2. The same algorithm was applied to derive ice concentrations from both AMSRE and AMSR2."

Table 1: Text says AMSR-E resolution is 6x4 km, but table says 5.4 km. Inconsistent. AMSR2 resolution is 5x3 km, so needs its own entry in the table. Additionally, not only SSMIS instruments in this time period - some were SSM/I (dates will depend on which OSI SAF product was used) so specifications for this instrument need to be included in the table as well

Please note that in the table mean spatial resolution was provided. The table has been updated. The product version 1.4 had been used and the documentation indicates SSMIS satellite data.

Line 23: Which OSI SAF product number and version?
Product OSI-401b and version 1.4

Line 24: Also uses SSM/I sensor.
Yes

Page 4
Line 2: How were erroneous data removed? Methods needed.
Erroneous data are indicated by flags so these data that carry the flags are removed before interpolating to model grid.

Lines 2-4: Make it clear using AVHRR analysis, not SST measurements directly.
Revised.

Line 5: CryoSat-2 altimeter is called SIRAL.

Added

Line 12: Clarify what you are using the CryoSat-2 data for: validation. Why is the focus mainly on the SMOS data, and why are the CryoSat-2 SIRAL specifications not included in Table 1?

Revised as

"Freeboard measurements from CryoSat-2 altimeter were used to compare the freeboard estimates by the model."

Line 14: Confusing that the SMOS thickness data resolution has a range. What is the resolution of the actual product used here? Also this is different to the range given in table 3.

Table 3 is corrected. The actual product resolution used here is 12.5km x 12.5km
The following text has been edited to clarify

"For ice thickness, data product derived from the SMOS Microwave Imaging Radiometer with Aperture Synthesis (MIRAS) instrument (1.4-GHz channel) (Kaleschke 2012) on a grid resolution of 12.5 x 12.5km is used."

Line 15-16, 19-20: Remove sentence "The ice thickness uncertainties are lower for thin ice and uncertainty increases as the ice thickness increases." as this is repeated below. Similarly for "Moreover, large errors occur during the melting period."

Removed.

Line 16: Needs a line or two explaining how the SMOS sensor obtains measurements of ice thickness.

The following sentence is included

"The ice thickness is retrieved from observation of the L-band microwave sensor of SMOS. Horizontal and vertical polarized brightness temperatures in the incidence range of < 40 degree are averaged. The ice thickness is then inferred from a three layer (ocean-ice-atmosphere) dielectric slab model. "

Line 20: What is the magnitude of the snow depth uncertainty?
Following text has been included for clarification
"The insufficient knowledge of the snow cover also introduces a large uncertainty in ice thickness estimates. Snow depth uncertainity can be 50-70% of mean value (zhou et al., 2018)."

Line 24: "...for our region of interest" - remove this, as not available in summertime for any Arctic region (and I don't think Antarctic SMOS ice thickness observations are available yet).
Removed

Line 24: Unclear what the Kerr and Barre citations are related to. Reword this.
Reworded

Table 2: Caption is same as for table 3, update this.
Caption is updated
“SMOS uncertainty”

Line 25: Show location of Makkovik Bank on map.
Shown as Figure 1.

Page 5
Table 3: Could this information be included in table 1? Are all these specifications directly relevant?
No this is information about sensor specification while table 1 shows the uncertainties of SMOS data.

Line 2: Confusing - state which distribution is shown in the figure, and what causes the variation in distributions.
The modes in the figure are clarified in the following sentence

“We assume that the first mode in the histogram corresponds to the level draft ice and the second mode corresponds to the keel depth measurement.”

The sea ice has level and deformed parts and moreover the ice is in constant motion. The deformation variations are captured in the second mode while the non deformed part is captured in the first mode.

Line 3: Why only include data for a single day?
This is only a sample. Including data for every day is not possible as data is available for 2005, 2007, 2009 form January till April/May. Moreover, we are performing ULS analysis for each day.

Line 4: What are these assumptions based on? Needs more explanation.
The modes in the figure are clarified in the following sentence

“We assume that the first mode in the histogram corresponds to the level draft ice and the second mode corresponds to the keel depth measurement.”

The sea ice has level and deformed parts and moreover the ice is in constant motion. The deformation variations are captured in the second mode while the non deformed part is captured in the first mode.

Line 6: What sort of quality control was undertaken for this data? Needs more explanation.
The data is available after the quality control and hence not discussed here.

Figure 1: Needs units on x-axis, and date of observations in figure caption.
Mentioned meters in X

Page 6

Line 7: For SST this is the AVHRR-only OISST analysis
This is updated thorough out the manuscript

Line 7: SST is not from model, it's a parametrization
The following sentence has been edited
" (for ice concentration and SST this is an estimate from SST parametrization)"

Line 11: "model estimate" should be "background model estimate" (as it's the background error in data assimilation terms)
Changed

Line 13: As sigma_o is different for sea ice concentration and SST and described below, remove from this line. Also "parameter may vary spatially" is confusing without additional explanation.

Line 15: If above 65% is 10%, this should be > 0.10 based on your stats given on page3, line 16.
The following sentence has been edited to clarify
"ice concentration error depends on various atmospheric factors for ice concentration values less than 65%."

Line 16: I think this is intending to say something like "ensure that the assimilation is heavily weighted to the model background when there is large variation between the model and the observation." Needs rewording as it's unclear. However, method will weight towards model background even if the observation error is similar to the background. Why?
The following text had been edited for the clarification
"ensure that the assimilation is heavily weighted towards the observation when there is large variation between the model and the observation."

Line 22-25: Needs rewording as it's unclear what this means, and how this mechanism might directly affect the results.
This is by intuition if there is a new ice area added to the cell that means some thickness exists in the cell otherwise what is the point in increasing ice area. If ice area is removed then the ice thickness has also to be removed from the cell.

Page 7
Lines 1-2: Reword this as implies model assimilates SST instead of ice in data gaps. Also gap between AMSR-E and AMSR2 should be mentioned here. Need to state that the model is free-running during periods where no data is available for assimilation.
The following statement had been included to clarify the data gaps

"The AMSR-E instrument stopped producing data since October 2011, and AMSRE2 data has been used for assimilation beginning August 2012."

"e.g. from 24 March 2005 to 31 March 2005 AMSR-E data are not available and, in that case, 'M2' assimilates SST instead of ice in data gaps. The AMSR-E instrument stopped producing data since October 2011, and AMSRE2 data has been used for assimilation beginning August 2012."

Line 4: "error" should be "mean difference", as the dataset being used as a reference is not necessarily "truth". This needs to be changed throughout the paper. Here, this should also say "absolute mean difference of ice concentration" for clarification. "OSI

SAF" should be "OSI SAF dataset" (or similar wording).

The corrections are made as follows

“column 1 shows the absolute mean difference of ice concentration between the non-assimilated model and the OSI SAF data, column 2 shows the absolute mean difference of ice concentration of the model assimilated only with ice concentration and OSI SAF data, and column 3 shows absolute mean difference of ice concentration of the model assimilated with both ice concentration and SST and OSI SAF data. Model M2 shows improvement in the ice concentration for January and March, but the results do not improve significantly“

Line 7: "the results do not improve much" Is this compared to Model M1? But in some locations the difference has reduced by about 20%, which is a good improvement. However, as you are assimilating the AVHRR-only OISST analysis, it is important to note that the product makes use of SSM/I and SSMIS ice concentration data to determine SST at high latitudes (though probably a different algorithm to the OSI SAF product). This means the SST observations you are assimilating are not truly independent from the SSM/I and SSMIS data you are using for validation. However, the AMSR-E/AMSR2 data is independent from the SSM/I and SSMIS data, and this should be stated.

As stated previously the assimilation is heavily weighted towards observations in the ice edges. Also, AVHRR SST is inferred from ice concentration only when ice concentration is greater than 0.5.

Page 8

Figure 3: Need to state that this is ice concentration and which product the models are being compared to in the figure caption. It also needs to be stated in the text somewhere what the spin-up period of the model is.

The following text has been included

“The absolute mean difference of ice concentration for models M0, M1 and M2 from January 2010 to September 2011 is shown in row 1 and from August 2012 to December 2015 is shown in row 2”

“The model was spin up for 3 months before assimilation, since no coupling with ocean model is done, the spinup time of 3 months is enough to estimate the ice conditions.”

Lines 2-3: Need to state which instruments the assimilated ice concentration and OSI SAF data use.

SSMIS. Added in text

Line 4: Why only giving the 2010 results? Also broken down into seasonal results would give a better picture.

This was provided as an example to the reader. We wanted to understand the model bias as this would enable with tuning the model further. Seasonal results would be averaged and the bias may be reduced further.

good

Line 8: This last sentence does not relate to anything shown in figure 4, remove this or improve discussion.

Removed the sentence.

Page 9

Line 2: Which model thickness category are you using for the comparison?

The following sentence clarifies the point

"For comparison and validation, ice thickness data from both the model and observation where the observed ice thickness has an uncertainty less than or equal to 100 cm are selected."

Line 2: observations from which instrument?

Clarified in the following statement

" The large unacceptable uncertainties in observation data derived from SMOS create difficulties for the analysis."

Lines 2-3: Unacceptable uncertainties in all observations? Confusingly worded.

Clarified in the following statement

" The large unacceptable uncertainties in observation data derived from SMOS create difficulties for the analysis."

Line 4: An uncertainty of 100 cm seems a lot for thin ice. What maximum ice thickness from SMOS are you using? From figures 5,6,7 it looks like 60 cm but this needs to be stated and explained. E.g. Xie et al. (2016; The Cryosphere, 10, 2745-2761) only use SMOS observations of < 40 cm, but others use up to 1 m thickness.

The following statement clarifies the point

"it is strictly recommended not to use the SMOS data with an uncertainty greater than one meter (Tian-Kunze and Kaleschke, 2016) for practical applications. For comparison and validation, ice thickness data from both the model and observation where the observed ice thickness has an uncertainty less than or equal to 100 cm are selected."

Line 5: How is model uncertainty determined?

Model uncertainty is not determined. The way the data was selected for comparison and model observations are stated in the following sentence

"For comparison and validation, ice thickness data from both the model and observation where the observed ice thickness has an uncertainty less than or equal to 100 cm are selected. The SMOS thickness has less uncertainty for thinner ice and higher uncertainty for thicker ice"

Selecting data this way gives a much better view of where the model data lies when compared with the uncertainty limits of observation.

Line 9: Add "As ice thickness increases through the season, so do the uncertainty

limits."

Added the sentence

Line 9: MO and M1 are too, except February 2013. What real benefit is the assimilation giving? Bringing closer to observations, but still deviates and are all still too high. Not convincing that it is only in the uncertainty range as even the free-running model is also managing that most of the time.

The assimilation bring model values close to the observation. It shows deviation during March and April. For example, if we consider January-February of 2013 the values are within the uncertainty limits with the assimilation.

Line 10: Add "from October" before "until the end of February".

The following sentence has been modified

"The values of Model M2 are within the uncertainty limits of SMOS ice thickness from October until the end of February (except for 2014) end."

Lines 10-11: Move discussion of uncertainties to previous paragraph.

Moved.

Line 12: Remove sentence beginning "Compared with the uncertainty values..." as this repeats information already stated.

Removed.

Lines 16-19: This is because the assimilation is strongly weighted to model background. Demonstrates this is not the optimum set-up. If changing the value of alpha is expected to improve matters, why has this not been done?

Not because assimilation is strongly weighted to model background. Assimilation is weighted heavily towards observation along the ice edge. We were looking whether improving ice edge would lead to improved results. Also, assimilating ice concentration includes the update of state variables related to variable drag parametrization. A sensitivity study/optimization work is going on and will be soon published in a separate work.

Figures 5,6,7: Combine these into one figure. The correspondence with the observations is poor after about January. All modelled ice is too thick, and although results for the M2 model are closer to observations than the M0 or M1 models, results are still not very good. However, for results where the model thickness < 30 cm (figures 9,10,11) the models seem to be underestimating ice thickness rather than overestimating. This difference needs to be addressed in the paper.

The figures have large data gaps and hence for clarity was presented as three figures.

Also, the model thickness < 30 cm will show an underestimation of ice thickness since the assumption of 100% ice concentration in the algorithm for estimation of ice thickness from SMOS.

Figure 7 caption: make clear that M1 is not assimilating ice concentration because

there is no AMSR data available.

Rephrased as

"The ice thickness from models M0, M1(not assimilating ice concentration as there were no AMSRE data available, but used the initial conditions from the model assimilated with ice concentration), M2 (assimilated only with SST and used model initial conditions derived from assimilating both ice concentration and SST) and observations (SMOS ice thickness) from October 2011 to April 2012. The uncertainty of observation (SMOS ice thickness) is shaded in gray."

Page 11

Lines 2-3: Why does figure 8 include regions where observed uncertainties are larger

than 1 m, when on page 9 you have stated that this data has been rejected? This makes the figure very difficult to interpret, as it implies the model is underestimating

ice thickness, but the comparisons in figures 5,6,7 indicate it is actually overestimating ice thickness for thin ice where the SMOS observations are more reliable - or underestimating for figure 9,10,11. Need to redo figure 8 showing only the relevant data, and also include panels with M2 differences to SMOS.

Please see that the explanation for the figure was provided in Page 11 as follows

"The Model M2 thickness, SMOS derived ice thickness, and the uncertainty of the SMOS derived measurement for 15 December 2010, 15 January 2011 and 15 March 2011 is shown in Figure 8, and includes regions where observed uncertainties are larger than one meter."

Page 12

Figure 8 caption: only showing for 3 individual dates, not 2010-2011 - update caption

to reflect this.

Caption has been updated as follows

"The model 'M2' estimated ice thickness, SMOS-MIRAS derived ice thickness, and the observation uncertainty for 15th December 2010, 15th January 2011 and 15th March 2011."

Page 13

Figures 9,10,11: Maximum model thickness looks like 20 cm rather than 30 cm. Model underestimates thickness from December as thickness remains roughly constant throughout the year after this date. Also the assimilation makes little difference. Reasons for these results need to be addressed in the paper. Also caption states only model M2 is shown, but all models are shown on plot, update caption.

Maximum model thickness looks like 20 cm since we considered only thin ice categories (< 30 cm) from the model. The results are averaged over the domain. Also, the observation has to be compared with the uncertainty of the thickness.

Page 14

Figure 11: What is the cause of the discontinuity in SMOS ice thickness and uncertainty between December and January? This needs to be addressed in the paper.

We think it was due to the process of product generation.

Figure 12: Needs to be larger, as it is difficult to see the shaded regions.

Made Figure 12 larger to fit the page width

Line 1: How is the "observation uncertainty" generated? Is this actually the AVHRR-only OISST analysis uncertainty? Add this to text. This is not independent data as it's being assimilated for model M2. Could choose a different dataset for validation.

Yes. This is AVHRR only OISST analysis uncertainty. We are validating with the same data since we do not have access to any other reliable SST products.

Line 2: Sentence beginning "The SST assimilation..." does not refer to figure 12. It is confusing to have this sentence here with no context

Rephrased as

"In general, the SST from AVHRR-only OISST assimilation improves the ice concentration and ice thickness results for the model M2."

Line 3: The model doesn't have "outliers", results show it has systematic biases in both summer and winter.

Rephrased as

The assimilated model M2 still has systematic bias during the summer and winter, which may be improved by decreasing choice of α (=6, presently) and by decreasing the nudging time scale (presently for SST nudging scale is 30 days)."

Lines 3-11: These lines give speculation on how the results could be improved, but this work needs to be done.

The work on optimization and sensitivity analysis is still an ongoing work and will be published soon. Several other factors that affects the update of state variables (e.g. ridged ice area, melt ponds and albedos) in the equations of Tsamados et al have to be examined,.

Page 15

Line 2: Need to describe the method here, as Prasad et al. (2016) is a non-peer reviewed conference paper.

Please note that the methodology is also described in "section 3. Remote Sensing Data for Assimilation and Validation"

The following sentence had been included for clarity

"The ULS measurements were separated into level ice draft and keel depth measurement as described in Prasad et al, 2016 and also in Section 3."

Line 6: Add that rho_w is the density of water.

The following sentence has been included to clarify

“ ρ_w = 1026 kg/m^3 is the density of sea water”

Line 7: "about 10 cm" - give specific value (variation with season? Different years?). Need to add RMS or standard deviation.

This is with respect to whole year also it is mentioned that this is absolute error.

Line 8: An error of 10 cm on a draft of 20 cm is proportionally very large, so can’t be described as good correspondence.

Changed:

“The error of 10cm on draft of 20 cm can be accepted considering large difference in spatial resolution between the ULS and Model.”

Line 8: Reiterate here for benefit of reader that only done analysis for 2005, 2007, 2009 as this was when data was available.

The following sentence was included for clarification

“ Also, the analysis was done only for 2005, 2007, 2009 as this was when data was available”

Line 10: "close to the location of the ULS" - are you interpolating the model result to

the observation location? If not what method is being used for the matchups and why?

The following sentence clarifies it. The point that is close to the location of the ULS is used for comparison. The model is also an averaged daily values.

“The discrepancy occurs due to the fact that ULS gives values at a particular location with high resolution (within the footprint of several meters), while the 10 model is of 10 km resolution gives an averaged result close to the location of the ULS.”

Page 16

Lines 1-2: "single melt pond" - even in winter? This method needs more description

Please note that this has been described in Tsamados et al, 2014 and a reference to the same has been provided.

Line 5: H_k is not used in equation (4), remove (given below for equation (5)).

Removed.

Line 6: m_r and m_k need more explanation - slopes given in degrees but what are 0.4 and 0.5?

Clarified in the following sentence

“m_r = tan(alpha_r) = 0.4, alpha_r = 21.8 is the slope of the sail and m_k = tan(alpha_k) = 0.5, alpha_k = 26.5 is the slope of the keel”

Lines 5-8: Where are these values obtained from? Not all the variables have been given values either.

These are values are from (Shokr and Sinha, 2015) given references and some are default values in CICE

Line 12: Citation required for this statement.

Citations are provided

(Peterson et al., 2013})

Line 13: Model and observation of keel depth or ridge height? Confusing.

Rephrased as

“Here the model and the observation of keel depth are used to estimate the parameter C.”

Line 16: Figure 14 only shows modelled and observed keel depth, not ridge height so can’t see this relationship. Also need to give statistics for difference between modelled and observed keel depth.

This part only does an estimation of parameter C form the keel depth of the model and the observation.

Lines 17-19: If further work may result in a different conclusion, you need to do this further work to be able to draw any conclusions.

This requires tuning of model and assimilation paramters and is an ongoing work.

Line 25: How did you calculate lead fraction? Or cite existing product if that is what you used.

Citation made

"The presence of leads was ensured by selecting the regions where lead fraction derived from CryoSat-2 (Ricker et al. 2014) was greater than zero."

Line 26: Need to clarify in the text that the uncertainty given is for CS2 freeboard measurements. Need more information on the CS2 (CryoSat-2) product, e.g. how often available, where data was accessed etc.

The information is provided. The product citation is provided and also mentioned in Section 3

"For the region, the uncertainty of the freeboard measurements is below 40 cm (Ricker et al. 2014) "

Equation (6): I can't find this equation in Tsamados et al. (2014) but it looks like it's

missing some brackets

This is only a shortened version of the equation (26) in Tsamados et al. 2014, the equation is represented in terms of draft. If the draft in the equation(6) is replaced by equation (3) and working out some math the same equation (26) in Tasamdos et al., 2014 can be derived.

Page 17

Line 1: "absolute difference" should be "absolute mean difference".

Changed

Line 2: "M2 freeboard measurements are close to the observed freeboard". This isn't true - figure 15 shows that the differences between the model runs and the observations are a large percentage of the actual values. There is also variation between the different months shown. It would be better to show differences rather than absolute differences on the spatial plot to be able to see where the biases are and in which direction. Other statistics such as RMS or standard deviation also need to be given

Our main intention was to see if the model and observation dereference is higher than the observed uncertainty which is 40cm for the region of interest. We will be doing further statistical analysis to quantify the model error. Moreover, the observation has large uncertainty which still leaves a doubt of computing RMSE would give much sense. Also, please see Figure 17.

Page 19

Figure 16: Caption should specify Jan, Feb, March 2011 and not just 2011. Also need to show the difference plot and give other statistics e.g. RMS.

Clarifications had been made to captions.

Line 4 (and line 6): The model values look systematically different to the observations in Figure 16. Figure 17 shows that the model is unable to replicate the seasonal changes in the freeboard observations, and just increases throughout the year.

Line 5: The data presumably still undergoes averaging if the points are observed multiple times within that month. Much more information on the dataset is needed.

Freeboard equations are dependent on the ice volume and ice concentration and hence the systematic errors observed in thickness and concentration will affect the freeboard too. Also, please note that the freeboard measurements are a monthly mosaic of the data collected (yes, some averaging will be going on) and also, has 40 cm of uncertainty. It is by comparing with the observation uncertainty we are saying the model values are within the range of observed values

Page 20

Lines 2-3: Needs references to back this up.

Added references

(Lemieux et al., 2016, Rae et al., 2015)

Line 6: Misleading, as have not validated the assimilation method itself, only assimilated different combinations of observations

Lines 6-7: This sentence implies the model is assimilating all these variables, which is incorrect. Reword

The sentence has been rephrased as

"The results from the updated model were compared with satellite derived measurements to validate the model estimates of ice concentration, ice thickness, freeboard. Moreover, the model results were used to estimate relationship between sail and keel depth."

Line 8: Disagree that it is a good correspondence.

This statement is made except for the maximum ice extent when the ice thickness goes beyond the uncertainty limits of the observed thickness.

Line 10: The RMSE should be mentioned previously with the rest of the results.

RMSE are mentioned in the text.

Line 11: Where have you split results into below 40 cm? Seems to be 60 cm for observations or 30 cm for model category (which looks more like 20 cm).

Sorry for the confusion. Here describing about the freeboard not ice thickness. Please see that the paragraph has been rearranged.

Lines 14-15: No remote-sensing ice thickness data is available in the summertime due to the presence of melt ponds. As summertime data has been excluded in this study the error contribution from melt ponds is likely to be small.

The meltpond evolution of the model will be a future part of the study.

Line 18: Agreement is not always close. This statement needs to be revised.

Revised

Lines 20-21: This needs to be done, rather than stating it as future work.

Modified

References:

Many of the references are missing important information, for example access URLs for technical reports, and format type e.g. book, report, dataset etc.

Technical corrections There are a number of instances of citations not being in brackets when they should be, and vice versa. The authors need to go through the manuscript carefully to correct these. The authors need to ensure that the paper is read by a native English speaker as there are a large number of minor but important grammatical errors. There are too many to list here. There are also several areas where information is repeated within the same paragraph. Some are listed above. Correcting these instances would improve the readability of the paper.

References were updated.

Anonymous Referee #2

Received and published: 30 July 2018

Please note that the comments from referee are given in black font "Times new roman". Commnets from the authors are given in blue font "Calibri". The changes in the manuscript are given in green font "Calibri".

General Comments

In this paper, the authors assimilate ice concentration and AVHRR-derived SST into a 10 km CICE model for Baffin Bay and the Labrador Sea for the period spanning from 2010-2015. A series of 3 experiments are performed to assess the model's performance against ice thickness from SMOS, ice draft and keel depth from a ULS, and freeboard estimates versus CryoSat-2. A control run does not have any data assimilation, while the other two assimilate SST and SST and ice concentration. A nudging and optimal interpolation technique based on Lindsay and Zhang (2006) is used. Model mean ice thickness is compared against the SMOS ice thickness for the periods of Oct – March for the years 2010-2015. Overall, the "M2" test case which assimilates SST and ice concentration performs best, and is generally within the uncertainty bounds of the SMOS data; however there is a significant positive bias shown for all years. An impressive comparison of the model's (M2) keel depth versus a ULS for 2005, 2007

and 2009 show very good agreement with data. However, model freeboard differences with CryoSat-2 data for Jan, Feb, and Mar 2011 show very little difference amongst the three test cases. Overall, while not "state-of-the-art", this paper shows some improvement with the assimilation of SST and ice concentration in a regional ice modeling system. I recommend publication with minor revisions.

We would like to acknowledge the reviewer for the comments and suggestions.

Specific Comments

How are ice boundary conditions addressed in the model? Same technique as discussed in Prasad et al. 2015 paper? If yes, state this in the paper.

The following text has been included for clarification

"The net heat flux from the atmosphere is the upper boundary condition for ice thermodynamics. The heat flux from the ocean to the ice is the lower boundary condition. Based on temperature profile and boundary conditions the melt and growth of ice is computed. The open boundaries are configured in the same way as in (Hunke et al., 2010, Prasad et al., 2015)"

You use a 35-50 km SMOS ice thickness product for your thickness comparisons. You state that the SMOS data should not be used for thickness greater than 1 m; Figure 8 (middle column) shows a significant area of ice thicker than 1 m by March 15, 2011. Why didn't you consider using a merged CryoSat-2/SMOS ice thickness product such as is available from AWI? Do you have plans to assimilate ice thickness or freeboard into your model?

Figure 8 has been described in the following sentence

"The Model M2 thickness, SMOS derived ice thickness, and the uncertainty of the SMOS derived measurement for 15 December 2010, 15 January 2011 and 15 March 2011 are shown in Figure 8, and include regions where observed uncertainties are larger than one meter"

During the time the merged product was not available. We will use the merged product in the future study. Yes, we do have plans to combine other products for assimilation.

Page 1 line 19: why limit discussion to "climate forecast researchers"? This is important for operational sea ice modeling as well.

The following text has been modified

"The climate forecast researchers and operational ice modeling communities depend on numerical modeling techniques implementing the physical process of atmosphere and ocean on large scale computational platforms along with data assimilation methods to retrieve the information on sea ice parameters."

Page 3 lines 7-8: Why does the assimilation begin in January 2005? If the model is started from a no-ice state in September 2004, why doesn't assimilation begin in October 2004, when you should have data?

Please note that the AMSRE ice concentration product was available from January 2005 and hence assimilation started from the same period. Also, the model was given a 4 months spin-up.

Page 3 line 11: Explain how you use AMSRE for validation of the model if you are

assimilating that same data?

This was corrected AMSRE was used for assimilation and the product was compared with OSI SAF data.

" Ice concentration derived from AMSRE of resolution 6 X 4 km (Spreen et al, 2008) were used for the assimilation of ice concentration."

Page 4 line 1: What do you mean by "erroneous data"?

The following text has been modified for clarification.

The erroneous data, were the ice concentration error was 100% or retrieval algorithm has failed were filtered out before the comparison.

Page 7 lines 1-2: Why does M2 only assimilate SST when there are gaps in AMSR-E (and I assume AMSR2)? Why not assimilate all the time?

M2 assimilated SST only when ice concentration is not available for assimilation, otherwise the model assimilated both SST and ice concentration.

Page 8: Why is there no discussion on error reduction for the period from Nov 2012 – Dec 2015? A table of error stats would be helpful here.

Only an example has been provided here. The rest of the results are shown as Figure 4.

Page 9: Have you tested different values of α?

Yes, different values of alpha were tested. A sensitivity of the parameter alpha has been shown in Lidsay et al. The value has to be further optimized considering the variable drag formulation variables for the model, which would be a future work.

Page 15: How is snow measured or estimated in the ULS data? I assume the model results shown in Fig. 13 are for M2? If yes, state in figure caption. How do M0 and M1 compare here?

Upward looking sonar measures the draft from below and the measurement of snow is not available. Since we were interested in the results of assimilated model only M2 results are given.

Page 17: I see little difference in Fig. 15 between column 2 and 3 in the plots. The paper states "M2 freeboard measurements are close to observed freeboard". I disagree. Perhaps the Jan 2011 looks best, but overall, the differences seem small for all 3 test cases.

Yes, these differences are very small. But M2 is found to be the best match with the observation.

Page 1 line 18: add "it" after "makes" and before "practically"

Included

Page 2 line 7: rephrase to "into CDOM using a 3D"

Rephrased

Page 2 line 9: replace with “Lindsay and Zhang (2016)”

Replaced

Page 2 line 16: “extent were overestimated”

Changed

Page 2 line 19: “of the CICE model”; which version of CICE is used? Specify in text

Rephrased as

“CICE version 5.1.2”

Page 2 line 20: “, and the combination”

Rephrased

Page 2 line 21: “(Lindsay and Zhang, 2006; Wang et al., 2013)”

Changed

Page 2 line 22: replace “cheap” with “inexpensive”

Replaced

Page 2 line 24: “Baffin Bay and the Labrador Sea”. resolution. . .” “This work uses a high-resolution...“

Changed

Page 2 line 33: replace with “Density-based criteria (Prasad et al., 2015) to compute. . .”

Rephrased as

“ Density-based criteria were used as in (Prasad et al., 2015) to compute the mixed-layer depth and thereby compute the SST and the potential to grow or melt sea ice.”

Estimation of sea ice parameters from sea ice model with assimilated ice concentration and SST

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Abstract. A multi-category numerical sea ice model CICE along with data assimilation was used to derive sea ice parameters in the region of Baffin Bay and Labrador Sea. The assimilation of ice concentration was performed using the data derived from Advanced Microwave Scanning Radiometer (AMSR-E & AMSR2). The model uses a mixed layer slab ocean parametrization to compute the Sea Surface Temperature (SST) and thereby to compute the potential to freezing/melting of ice. The data from Advanced Very High Resolution radiometer (AVHRRAVHRR-only OISST analysis) was used to assimilate SST. The modeled ice parameters including concentration, ice thickness, freeboard, ridge height, and keel and keel depth were compared with parameters estimated form remote sensing data. The ice thickness estimated from the model was compared with the measurements derived from Soil Moisture Ocean Salinity - Microwave Imaging Radiometer using Aperture Synthesis (SMOS-MIRAS). The model freeboard estimates were compared with the freeboard measurements derived from CryoSat2. The ice concentration, thickness and freeboard estimates from model assimilated with both ice concentration and SST were found to be within the uncertainty of the observation except during March. The model estimated draft was compared with the measurements from an upward looking sonar (ULS) deployed in the Labrador Sea (near Makkovik Bank). The difference between modeled draft and ULS measurements estimated from the model was found to be within 10 cm. The keel depth measurements from the ULS instruments were compared to the estimates from the model to retrieve a relationship between the ridge height and keel depth.

1 Introduction

Regional sea ice forecast is important for climate studies, operational activities including navigation, exploration of offshore mineral resources, and ecological applications, e.g. North Water polynya in Baffin Bay provides a warm environment for marine animals (Stirling, 1980).

Sea ice is a heterogeneous media and makes it practically difficult for remote sensing instruments to measure the ice thickness, freeboard, and ridge parameters (Carsey, 1992). The climate forecast researchers and operational ice modeling communities depend on numerical modeling techniques that implement implementing the physical process of atmosphere and ocean on large scale computational platforms along with data assimilation methods to retrieve the information on sea ice parameters. Data assimilation methods can provide more accurate initial conditions for forecasting systems (Caya et al., 2006, 2010). The estimation of sea ice parameters is a challenging problem in the region of Baffin Bay and the Labrador Sea due to the high interannual variability of sea ice in this area (Fenty and Heimbach, 2013).

Previous sea ice modeling and assimilation studies at the Canadian Ice Service (CIS) (Sayed et al., 1999) provided an overview of an operational ice model coupled with atmospheric and ocean modules. The research (Sayed et al., 2001) compared the evolution of ice thickness distributions followed by the development of an operational ice dynamics model for CIS (Sayed et al., 2002). These modeling works were also improved by the data assimilation methods (Caya et al., 2006, 2010). The Community Ice Ocean Model (CIOM) by Caya et al. (2006) used the Princeton Ocean Model for the simulation of ocean parameters and a multi-category ice model. The total ice fraction retrieved from the Special Sensor Microwave/Imager (SSM/I) was assimilated into ~~CIOM model~~ CDOM using 3D variational (3DVAR) technique (Caya et al., 2006) to estimate the ice concentration. The ice concentration estimates were further improved by assimilating information from both daily ice charts and RADARSAT (Caya et al., 2010). Assimilation studies by Lindsay (Lindsay and Zhang, 2006) showed significant improvement in assimilated ice concentration but with a large bias in the ice thickness pattern.

~~?~~ Karvonen et al. (2012) presented a method for ice concentration and thickness analysis by combining the modeling of sea ice thermodynamics and the detection of ice motion by space-borne Synthetic Aperture Radar (SAR) data from RADARSAT-1 and RADARSAT-2. The method showed promising results for sea ice concentration and ice thickness estimates. In another study, Ocean and Sea Ice Satellite Application Facility (OSI SAF) data were assimilated into Regional Ocean Modeling System (ROMS) for simulating sea ice concentration and produced better results than the simulation without assimilation (Wang et al., 2013). Ice concentration and extent ~~overestimated~~were overestimated in the assimilated model, probably due to the bias in atmospheric forcing, underestimation of heat flux and over/under estimation of sea ice growth/melt processes.

Sea ice models can be coupled to ocean and atmosphere models, but they can also be run in a standalone mode by prescribing the atmospheric and ocean conditions. The advantage of ~~CICE model~~the sea ice model, CICE version 5.1.2 (Hunke et al., 2015) is the standalone capability. Here we use a combination of modeling using the stand alone sea ice model, CICE~~(Hunke et al., 2015),~~ , and the combination of optimal interpolation and nudging methods (Lindsay and Zhang, 2006; Wang et al., 2013) to assimilate ice concentration. The optimal interpolation and nudging method is also used to assimilate SST estimated by a slab ocean parametrization in the sea ice model. The optimal interpolation method is computationally ~~cheap~~ inexpensive and was shown to provide better estimates than non-assimilated model (Wang et al., 2013). The simulated sea ice parameters are then validated with the observations in the region of the Baffin Bay and ~~Labrador~~the Labrador Sea. This work uses a high-resolution model configuration which was previously described in the work of ~~Prasad et al. (2015)~~ (Prasad et al., 2015). The changes in ice concentration were taken into account to estimate the changes in the ice volume and thereby thickness estimates. In addition to validation of the ice concentration we discuss the effect of the assimilation on ice thickness, freeboard, draft and keel depth. Since freeboard, draft and keel are functions of ice concentration and ice volume it is reasonable to compare the model values with corresponded observations. The work ~~also estimates a~~ suggests a methodology to extract the level ice draft and keel depth information from ULS measurements, which was then used to describe the relationship between ridge and keel~~using model values and ULS observation~~.

2 Model domain and forcing data

The sea ice model was implemented on a regional scale of about 10 km orthogonal curvilinear grids with a slab ocean mixed layer parameterization. Density-based criteria were used Prasad et al. (2015) as in (Prasad et al., 2015) to compute the mixed-layer depth and thereby compute the SST and the potential to grow or melt sea ice. The analysis assessment of the non-assimilated model fo of the sea ice concentration and its seasonal means showed that the error associated with the model mostly spread across the area of the North Water polynya and the Davis Strait where the interaction of cold and warm water is frequent. In the present study, a data assimilation module is also introduced.

The surface atmospheric forcing is from high-resolution NARR dataNorth American Regional Reanalysis (NARR) data (Mesinger et al., 2006). The ocean forcing is from various sources: currents from CFSRClimate Forecast System Reanalysis (CFSR), salinity from World Ocean Atlas, WOA-2013 and MLD (Levitus et al., 2013) and Mixed Layer Depth (MLD) computed from WOA-2013 Prasad et al. (2015)(Prasad et al., 2015). Atmospheric and ocean forcing were used as inputs to the model. For SST, the Sea Surface Temperature (SST), a monthly climatology data derived from high-resolution NOAA were used as an input for the initial conditions and open boundariesand boundary conditions. The net heat flux from the atmosphere is the upper boundary condition for ice thermodynamics. The heat flux from the ocean to the ice is the lower boundary condition. Based on temperature profile and boundary conditions the melt and growth of ice is computed. The open boundaries are configured in the same way as in (Hunke et al., 2015; Prasad et al., 2015). For the ice concentration and thickness, the initial condition is assumed as a no-ice state at the beginning of September . The 2004. The data assimilation starts from January 2005 and whenever remote sensing data are missing the model is not assimilatedcontinually assimilated whenever data was available.

3 Remote Sensing Data for Assimilation and Validation

Several remote sensing data were used for the validation of ice parameters estimated by the model. Ice concentration derived from AMSRE of resolution 6×4 km Spreen et al. (2008) (Spreen et al., 2008) were used for validation of model estimated the assimilation of ice concentration. AMSRE was developed by JAXA, and it is deployed on Aqua satellite. AMSRE and AMSR2 are passive sensors that look at the emitted or reflected radiation from the earth's surface with multiple frequency bands. The vertical (V) and horizontal (H) polarization channels near 89 GHz were used to compute the ice concentration from AMSRE Spreen et al. (2008)(Spreen et al., 2008). The Arctic Radiation and Turbulence Interaction STudy (ARTIST) sea ice algorithm used to determine ice concentration from AMSRE show excellent results above 65% ice concentration where the error does not exceed 10%. With low ice concentrations, substantial deviations can occur depending on atmospheric conditions. The original AMSRE data with 6×4 km resolution scale were interpolated to the model grid before assimilating. The parameters of the sensor are provided in Table 1. AMSRE ice concentration were available from January 2005 to September 2011, after which it stopped functioning. From August 2012 AMSR2 had been used for data collection. The same frequency (89 GHz) as that of the AMSRE instrument was used to derive information from AMSR2. The spatial resolutions also remain the same for both

AMSRE and AMSR2. The same algorithm was applied to derive ice concentrations from both AMSRE and AMSR2. The original AMSRE/AMSR2 data with 6×4 km resolution scale were interpolated to the model grid before assimilation.

Table 1. Specifications of microwave radiometers used to estimate ice concentration.

Specifications	AMSR-E ~~/~~	AMSR2	SSMIS	
Center Frequency, GHz	89	89	19	37
Mean Spatial resolution, km	~~5.4~~ 6×4	5×3	69×43	37×28
Polarization	HV	HV	V	HV
Incidence angle, deg	55	55	50	
Swath, km	1445	1450	1700	
Data availability, month/year	08/2002 − 10/2011	08/2012-Present	03/2005−Present	

The assimilated model results of ice concentration were compared with the OSI SAF data. The details of the sensors are given in Table 1. The OSI SAF product is derived from Special Sensor Microwave Imager Sounder (SSMIS) (Tonboe et al., 2016; Bell, 2006). The data is available on a 10 km polar stereographic grid and are derived from 19 V, 37 VH channels. The erroneous data, were the ice concentration error was 100% or retrieval algorithm has failed were filtered out before the comparison. ~~For SST assimilation of the measurements~~ Measurements derived from AVHRR-only OISST analysis ~~are used (Reynolds et al., 2007; Smith, 2016)~~ (Reynolds et al., 2007; Smith, 2016) were used for SST assimilation. SST data products are generated using a combination of satellite and in situ observations from buoy and ship observations and is available on a $0.25° \times 0.25°$ resolution. The analysis product estimates SST from ice concentration only in regions where ice concentration is greater than 50%, otherwise uses satellite data to retrieve SST values.

Freeboard measurements from CryoSat-2 altimeter were used to compare the freeboard estimates by the model. CryoSat-2 altimeter operating in the SAR mode, SIRAL has the accuracy of about 1 cm with the spatial sampling about 45 cm (Bouzinac, 2014). The pulse limited footprint width in the across track direction is about 1.65 km and beam limited footprint width in the along-track direction is about 305 m (Scagliola, 2013), that corresponds to an along-track resolution about 401 m (assuming flat-Earth approximation). Therefore, the pulse-Doppler-limited footprint for SAR mode is about 0.6 km^2. The CryoSat-2 freeboard and the ice-concentration products were generated at Alfred Wegener InstInstitute (AWI) (Ricker et al., 2014). The products are available in a spherical Lambert azimuthal equal-area projection of 25 km resolution cell. The uncertainty of freeboard measurements can arise from speckle noise, lack of leads which causes the estimation of sea surface height unreliable, and snow cover. The uncertainty up to 40 cm can be observed in the region of Baffin Bay and Labrador Sea (Ricker et al., 2014).

For ice thickness, data ~~of resolution 35 to 50 km~~ product derived from the SMOS Microwave Imaging Radiometer with Aperture Synthesis (MIRAS) instrument (1.4-GHz channel) ~~Kaleschke et al. (2012)~~ (Kaleschke et al., 2012) on a grid resolution of $12.5x12.5$km is used. The ice thickness ~~uncertainties are lower for thin ice and uncertainty increases as the thickness increases~~is retrieved from observation of the L-band microwave sensor of SMOS. Horizontal and vertical polarized brightness temperatures in the incidence range of $< 40°$ are averaged. The ice thickness is then inferred from a three layer (ocean-ice-atmosphere) dielectric slab model. SMOS data are available from 15 October 2010. The presence of snow accumulated over months also can increase the uncertainty. The uncertainty of SMOS ice thickness (~~observation)~~ observations) shown in Table 2 (Tian-Kunze et al., 2014; Ricker et al., 2016; Tietsche et al., 2017; Tietsche et al.) includes the error contributions, which are caused by the brightness temperature, ice temperature and ice salinity~~, see Table 2 Tian-Kunze et al. (2014); Ricker et al. (2016); Tietsche et~~ . The insufficient knowledge ~~on~~ of the snow cover also introduces a large uncertainty in ~~the thickness estimatesfrom SMOS. Moreover, large errors occur during the melting period~~ice thickness estimates. Snow depth uncertainity can be $50 - 70\%$ of mean value (Zhou et al., 2018). In general, the uncertainty of thickness observation increases with increasing ice thickness, increasing snow cover and the onset of melt ~~Kaleschke et al. (2013)~~(Kaleschke et al., 2013). The SMOS ice thickness retrieval produces large uncertainty during the melt season and hence retrieval is not conducted during the melt season. ~~Therefore, data from April to October are not available for our region of interest. Table 3 Kerr et al. (2001); Barré et al. (2008)~~ Table 3 shows the details on SMOS sensor (Kerr et al., 2001; Barré et al., 2008).

ice thickness (observations) shown in Table 2 include.

Table 2. ~~**SMOS sensor specifications.**~~**SMOS uncertainty**

Ice thickness	Uncertainty caused by a standard deviation of		
	0.5 K temperature brightness	1 K ice tempearture	1 g/Kg ice salinity
0 -10 cm	$<$ 1 cm	$<$ 1cm	$<$ 1cm
10-30 cm	$<$ 1 cm	1-5 cm	1- 13 cm
30-50 cm	1-4 cm	2-10 cm	2-22 cm
$>$ 50 cm	$>$ 4cm	$>$ 7cm	$\leq$ 40 cm

Table 3. SMOS sensor specifications.

Polarization	HV
Incidence angle	$0 - 55°$
Swath, km	900
Center Frequency (GHz)	1.4 (L-band)
Mean Spatial resolution (km)	~~$30 - 50$~~ $35 - 50$
Radiometric sensitivity over ocean, K	2.5 and 4.1

Ice draft measurements from ~~ULS instrument~~ an ULS instrument (Ross et al., 2014) located on the Makkovik Bank, see Figure1, at 58.0652° W and 55.412° N~~(Ross et al., 2014)~~, were used to analyze the ~~keel depth~~ ridge keel and the level ice draft in the region.

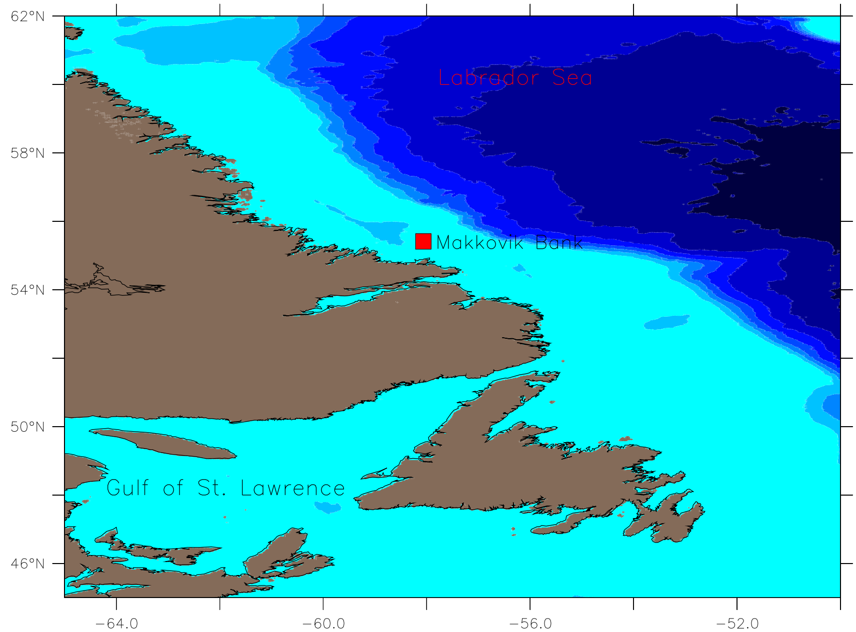

Figure 1. The location of ULS instrument.

The ULS data measured at an interval of approximately 5.5 seconds is available from the beginning of January to end of May during 2005, 2007 and 2009. The frequency histogram of the data yields a uni-modal, bi-modal or multi-modal distribution. A sample histogram is provided in Figure 2, for 10 February 2007. We assume that the first mode in the histogram corresponds to the level draft ice and the second mode corresponds to the ~~keel depth~~ ridge keel measurement. The first mode of the distribution is selected by finding a minimum between two peaks. The histogram was analyzed to derive daily averages of ice draft and keel measurements (Prasad et al., 2016).

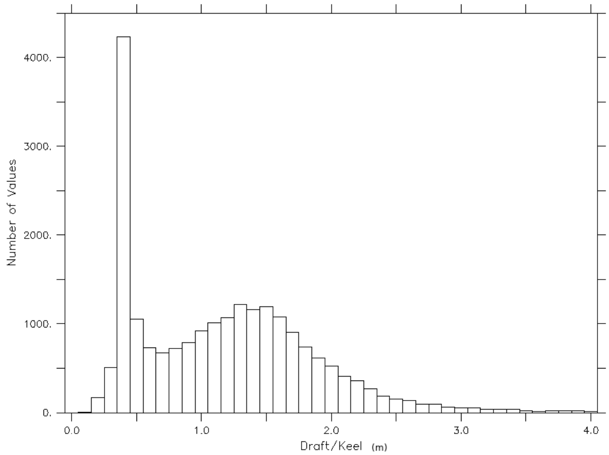

Figure 2. The histogram of the ULS measurement, 10 February 2007 for the ~~analysis~~ estimation of draft and keel (meters).

4 Data Assimilation

The assimilation module uses ~~the~~ a combined optimal interpolation and nudging technique for ice concentration ~~Lindsay and Zhang (2006);~~ (Lindsay and Zhang, 2006; Wang et al., 2013). The method can be represented generally as ~~1 Deutch (1965); Lindsay and Zhang (2006)~~ equation (1) (Deutch, 1965; Lindsay and Zhang, 2006).

$$X_a = X_b + dt\frac{K}{\tau}(X_o - X_b), \tag{1}$$

where X_a is the final analysis of the variable, X_o is the observed quantity (for ice concentration this is AMSR-E/AMSR2, for SST this is AVHRR-only OISST~~analysis~~), X_b is the background estimate of the variable (for ice concentration and SST this ~~the model background~~ is model estimate), dt is the model time step, τ is the basic nudging time scale as in ~~Wang et al. (2013)~~ (Wang et al., 2013), and K is the nudging weight with the optimal interpolation value. K is computed as

$$K = \frac{\sigma_b^\alpha}{\sigma_b^\alpha + \sigma_o^2}, \tag{2}$$

where σ_b and and σ_o are the error standard deviation of the model estimate ~~Deutch (1965)~~ (Deutch, 1965) and the observations ~~Deutch (1965)~~ (Deutch, 1965) respectively The parameters in the weighing factor given in equation (2) is defined according to ~~Lindsay and Zhang (2006)~~ (Lindsay and Zhang, 2006) as $\sigma_b = |X_o - X_b|$; $\sigma_o = 0.08$ (parameter may vary spatially), $\alpha = 6$.

When assimilation of ice concentration, $\sigma_o = 0.08$ is calculated from a long-term standard deviation to 0.08 since the AMSR-E/AMSR2 ice concentration error is depends on various atmospheric ~~factors for ice concentration~~ conditions for values less than 65%. The parameter $\alpha = 6$, is used for the present study to ensure that the coefficients for assimilation are heavily weighted towards observation only when there is large variation between the model and the observation Lindsay and Zhang (2006) (Lindsay and Zhang, 2006).

SST is also assimilated using the nudging and optimal interpolation scheme. For SST assimilation, σ_o is fixed as 0.05 to compensate for the assumption of zero mixed layer heat flux. A value α equal to 6 Lindsay and Zhang (2006) (Lindsay and Zhang, 2006) was also used for the assimilation of SST to ensure that only large differences between the model and observation are weighted heavily

The assimilation of ice concentration is then followed by a re-computation of the estimated sea ice volume. The ice volume is subtracted or added by including the increments or decrements with specified ice thickness. Since a variable drag coefficient has been used for the friction associated with an effective sea ice surface roughness at the ice-atmosphere and ice-ocean interfaces and to compute the ice to ocean heat transfer the level ice area is updated by assuming the model deformed ice area and volume represents the realistic values.

5 Results and validation

Three model results are discussed here: model ‘M0’, the non-assimilated model; ‘M1’, the model assimilated with ice concentration from AMSR-E/AMSR2; and ‘M2’, the model assimilated with ice concentration from AMSR-E/AMSR2 and SST from AVHRR-only OISSTanalysis. ‘M2’assimilates only SST whenever there is a data gap in ice concentration from AMSR-E (e.g. from 24 March 2005 to 31 March 2005), AMSR-E data are not available and, in that case, M2 assimilates only SST ‘M2’assimilates SST instead of ice in data gaps. The AMSR-E instrument stopped producing data since October 2011, and AMSRE2 data has been used for assimilation beginning August 2012. The model was spin up for 3 months before assimilation, since no coupling with ocean model is done, the spinup time of 3 months is enough to estimate the ice conditions.

5.1 Ice concentration

Figure 3 column 1 shows the absolute error mean difference of ice concentration between the non-assimilated model and the OSI SAF data, column 2 shows the absolute error mean difference of ice concentration of the model assimilated only with ice concentration and OSI SAF data, and column 3 shows the absolute error absolute mean difference of ice concentration of the model assimilated with both ice concentration and SST and OSI SAF data. Model M2 shows improvement in the ice concentration for January and March, but the results do not improve much little improvement between M1 and M2 for May 2010.

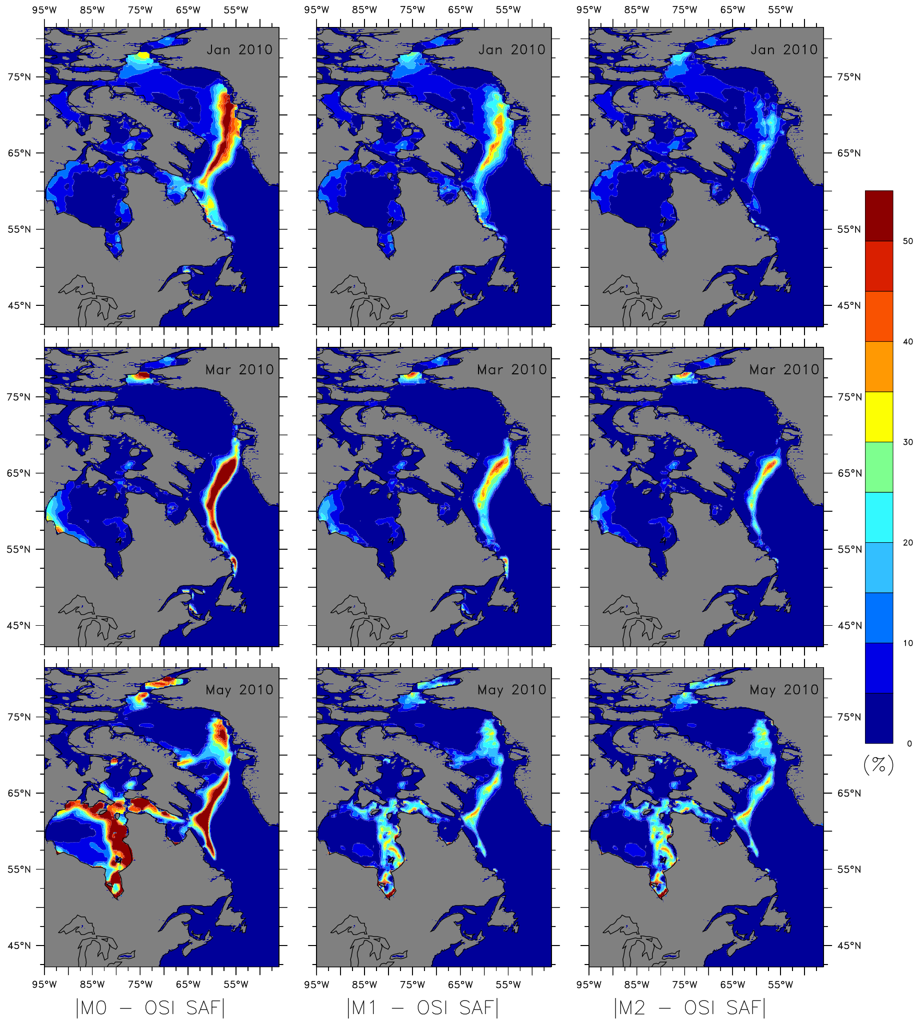

Figure 3. The absolute ~~error~~ mean difference of ice concentration of ice concentration from non-assimilated, assimilated models and OSI SAF data for Jaunary 2010, March 2010 and ~~December~~ May 2010.

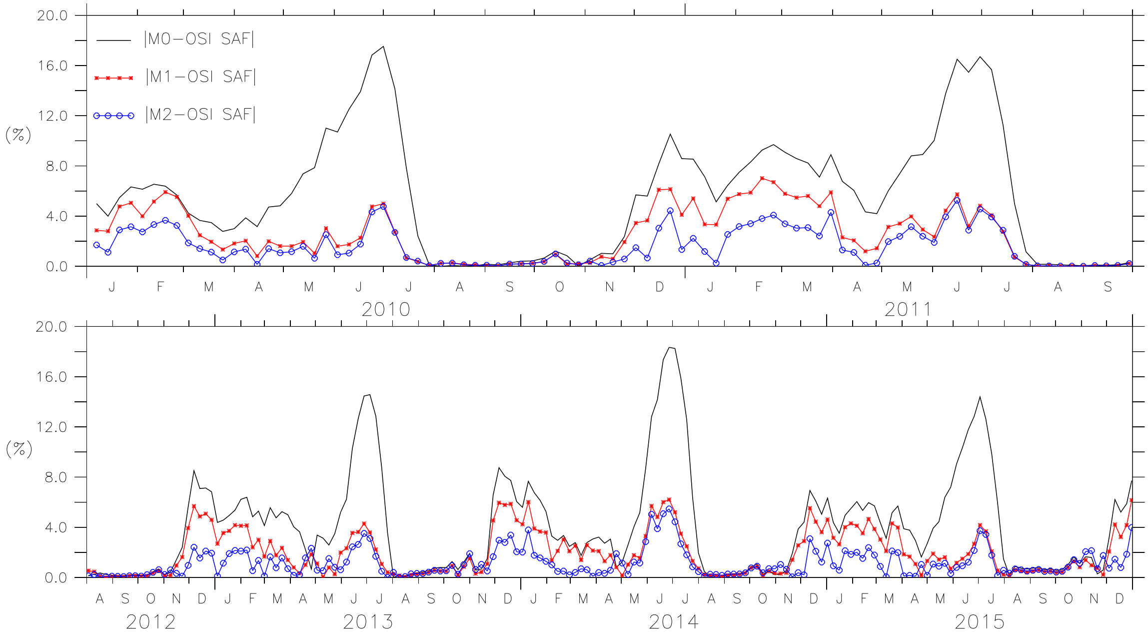

Figure 4. The absolute ~~error~~ mean difference of ice concentration for models M0, M1 and M2 from January 2010 to September 2011 is shown in row 1 and from August 2012 to December 2015 is shown in row 2.

Figure 4 shows the absolute ~~error~~ mean difference of ice concentration of the model assimilated with AMSR-E/AMSR2 and OSI SAF (SSMIS) data from January 2010 to September 2011 and the absolute ~~error~~ mean difference of ice concentration from August 2012 to December 2015. The assimilation of SST and ice concentration decreases the error between the model and the OSI SAF ice concentration. In 2010, the non-assimilated model error of 4.624% was reduced to 1.939% by assimilating ice concentration. The assimilation of SST and ice concentration decreased the error to about 1.118% in 2010.

From October 2011 to July 2012, AMSR-E data are not available for a more extended period, and model M2 was assimilated only with SST, see Figure 5. During this period, the SST assimilation decreases the error between the model and the observation by almost 3%. ~~The assimilation of ice concentration along with the assimilation of SST decreases the error in the ice concentration.~~

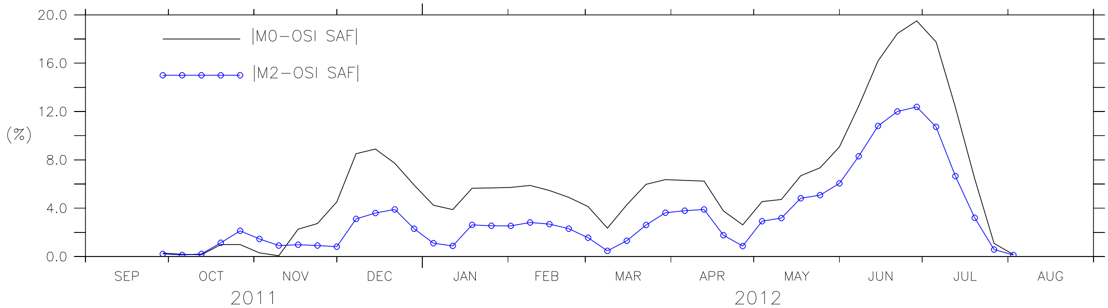

Figure 5. The absolute error mean difference of ice concentration from October 2011 to July 2012, ice concentration is was not available for assimilation and hence model M2 will be only assimilated with SST during the period.

5.2 Ice thickness

In this section, we perform the comparison of ice thickness from the model with the observation. The large unacceptable uncertainties in observations observation data derived from SMOS create difficulties for the analysis. Also, it is strictly recommended not to use the SMOS data with an uncertainty greater than one meter (Tian-Kunze and Kaleschke, 2016) for practical applications. For comparison and validation, ice thickness data from both the model and observation where the observed ice thickness has an uncertainty less than or equal to 100 cm are selected.The SMOS thickness has less uncertainty for thinner ice and higher uncertainty for thicker ice, see Table 2 for the uncertainty of SMOS ice thickness. In the case of SMOS derived thickness, the uncertainties would increase with the snow accumulation and melt onset.

Figures 6, 7, 8 shows the mean values of the thickness estimated from models M0, M1, M2 and SMOS with the uncertainty limits of the SMOS ice thickness (shaded gray)As ice thickness increases through the season, so do the uncertainty limits. The values of Model M2 are within the uncertainty limits of SMOS ice thickness from October until the end of February (except for 2014) end. In the case of SMOS derived thickness, the uncertainties would increase with the snow accumulation and melt onset. From the comparison, during March, the model results exceed the uncertainty limits. Compared with the uncertainty values, these results are in the acceptable range from October to the end of February. Figure 8 shows the results for the period October 2011 to April 2012 where AMSR-E data were missing during which M1 was not assimilated with ice concentration but used the initial conditions from the assimilated result. Model M2 used the initial conditions assimilated with both ice concentration and SST but assimilates only SST during the period. Both models, M1 and M2, with the improved initial conditions show better forecasts in the long-term analysis. One of the reasons why the model values exceed the uncertainty limits during March is the choice of $\alpha = 6$, which considers only large differences while weighing the coefficient K. Since the assimilation shows improvement in ice thickness, using a value of $\alpha = 2$, it is expected to impose the model values within the uncertainty limits.

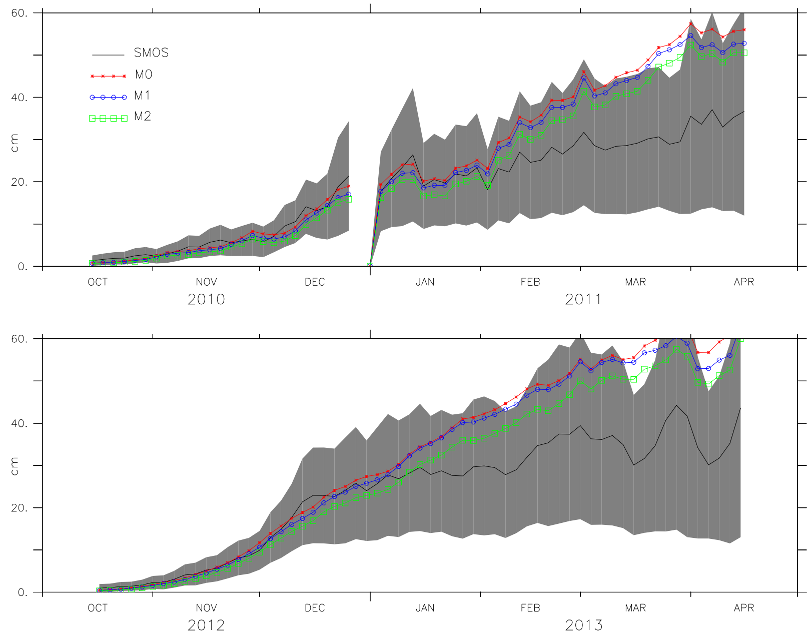

Figure 6. The ice thickness from the models M0, M1, M2, and observation (SMOS ice thickness) from October 2010 to April 2011 and October 2012 to April 2013 . The uncertainty of observation (SMOS ice thickness) is shaded in gray.

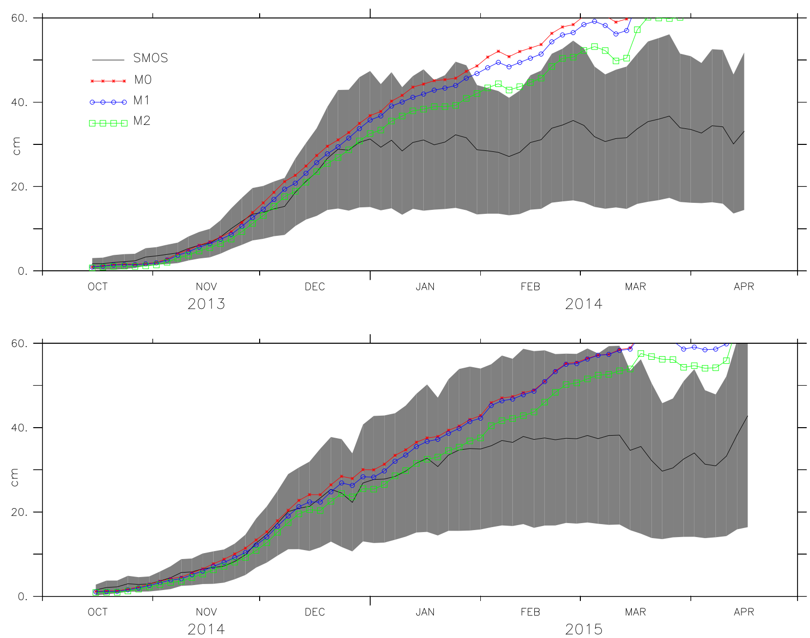

Figure 7. The ice thickness from the models M0, M1, M2, and observation (SMOS ice thickness) from October 2013 to April 2014 and October 2014 to April 2015. The uncertainty of observation (SMOS ice thickness) is shaded in gray.

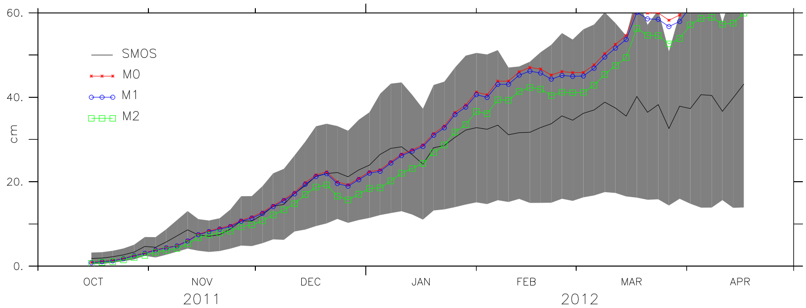

Figure 8. The ice thickness from models M0, M1(~~non assimilated~~ not assimilating ice concentration as there were no AMSRE data available, but used the initial conditions from the model assimilated with ice concentration), M2 (assimilated only with SST and used model initial conditions derived from assimilating both ice concentration and SST) and observations (SMOS ice thickness) from October 2011 to April 2012. The uncertainty of observation (SMOS ice thickness) is shaded in gray.

The Model M2 thickness, SMOS derived ice thickness, and the uncertainty of the SMOS derived measurement for 15 December 2010, 15 January 2011 and 15 March 2011 ~~is~~ are shown in Figure 9, and includes regions where observed uncertainties are larger than one meter.

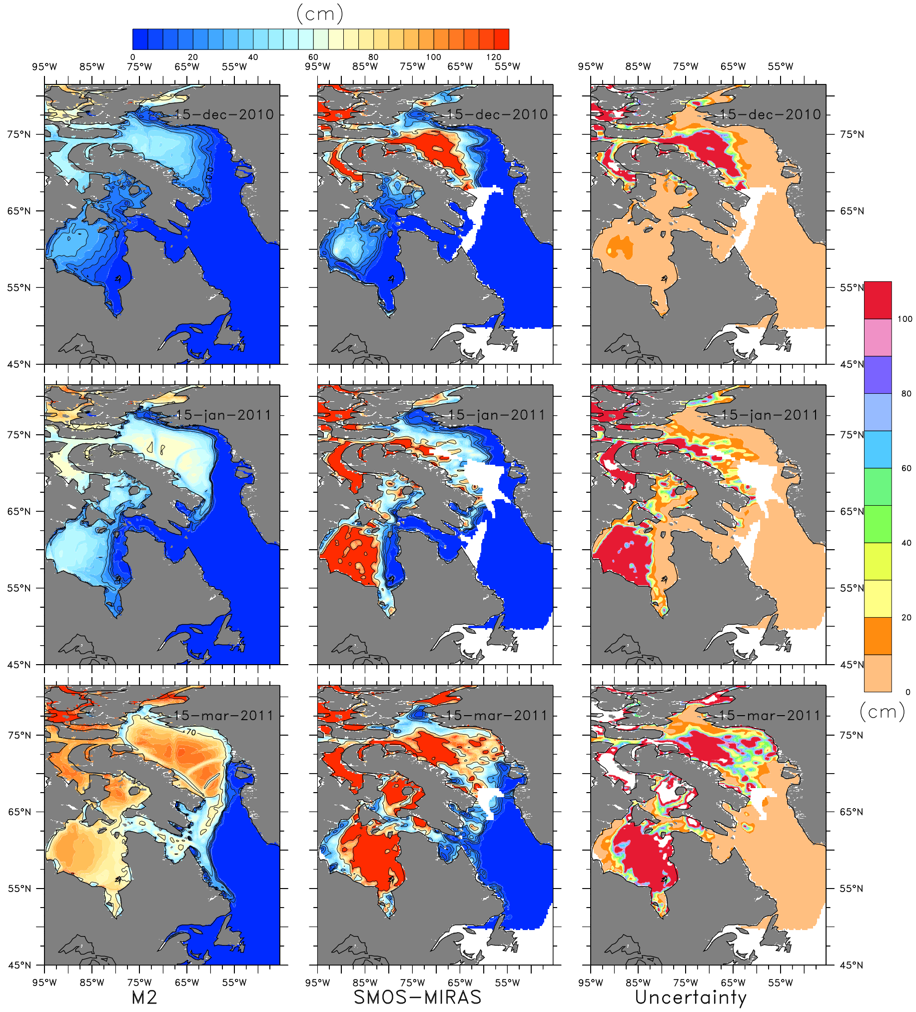

Figure 9. The model 'M2' estimated ice thickness, SMOS-MIRAS derived ice thickness, and the observation uncertainty for ~~2010-2011.~~15th December 2010, 15th January 2011 and 15th March 2011.

The thickness results for thin ice categories ($< 30cm$)from the model with SMOS are shown in Figures 10, 11, and 12. The thin ice category thicknesses are overestimated from October to November end but lies within the uncertainty limits of SMOS from December to March.

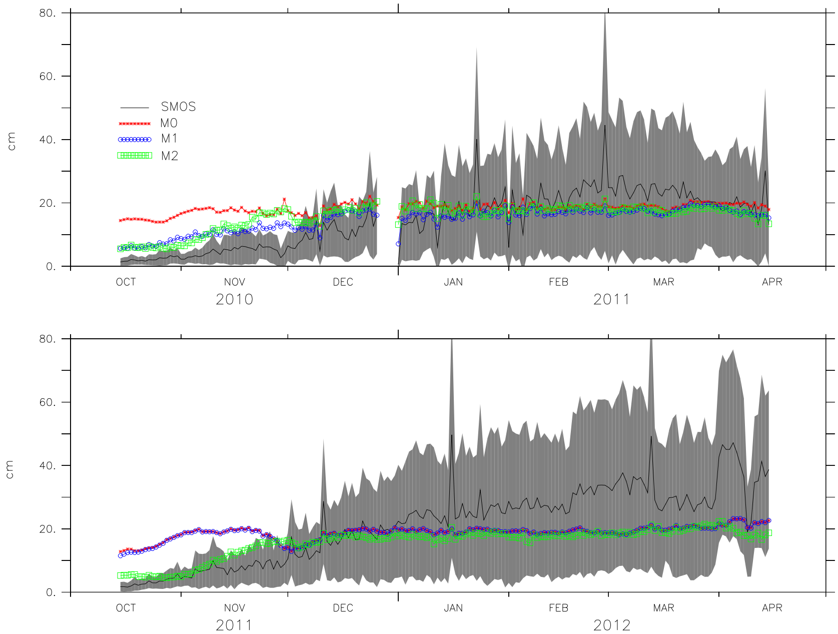

Figure 10. The ~~model 'M2' estimated~~ ice thickness from the models M0, ~~SMOS-MIRAS derived~~ M1, M2, and observation (SMOS ice thickness~~,~~) and the observation uncertainty (shaded gray) for SMOS ice thickness less than 30 cm (2010 - 2012).

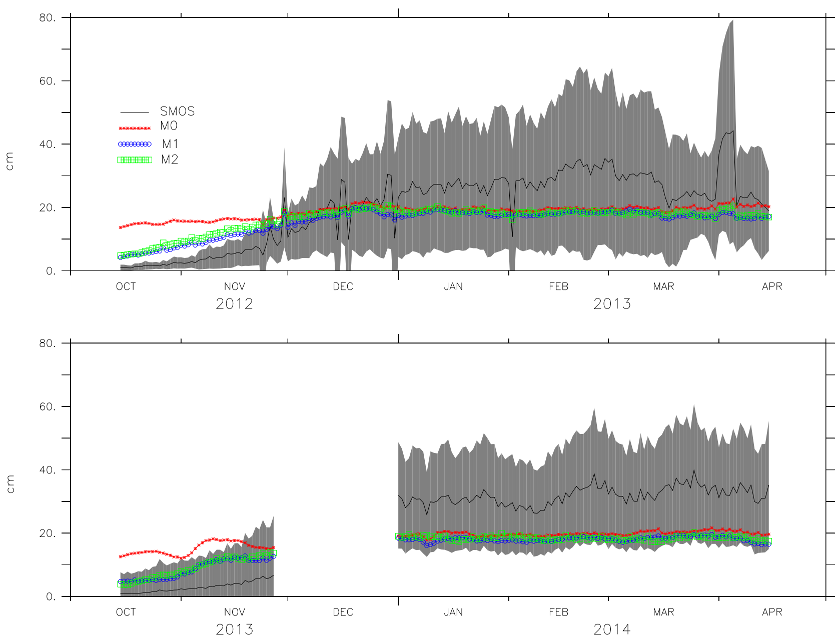

Figure 11. The ~~model 'M2' estimated~~ ice thickness from the models M0, ~~SMOS-MIRAS derived~~ M1, M2, and observation (SMOS ice thickness~~,~~) and the observation uncertainty (shaded gray) for SMOS ice thickness less than 30 cm (2012 - 2014).

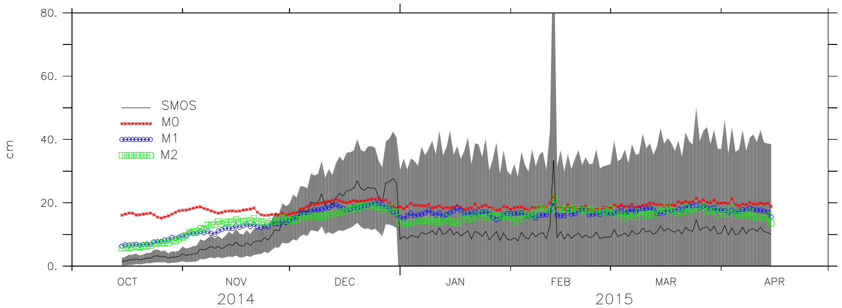

Figure 12. The ~~model 'M2' estimated~~ ice thickness from the models M0, ~~SMOS-MIRAS derived~~ M1, M2, and observation (SMOS ice thickness~~,~~) and the observation uncertainty (shaded gray) for SMOS ice thickness less than 30 cm (2014 - 2015).

Figure 13, shows the SST from AVHRR-only OISST analysis with the shaded regions representing the observation uncertainty, SST from models M0, M1 and M2. ~~The SST~~ In general, the SST from AVHRR-only OISST assimilation improves the ice concentration and ice thickness results for the model M2. The assimilated model M2 still has ~~outliers observed during the winter period. This can~~ systematic bias during the summer and winter, which may be improved by decreasing choice of α (=6, presently) and by decreasing the nudging time scale (presently for SST nudging scale is 30 days). Decreasing the nudging time scale can result in the late formation and early melt of ice (not shown here). The results can be improved with a choice of nudging time scale to be less frequent during the formation and more frequent during the winter till beginning or mid of March. Frequent nudging is also found to produce blow up for the thermodynamic model. Choice of the parameters in the assimilation has to be selected so that balance is maintained not to cause late formation and earlier melt and maintain the stability of the model thermodynamics and dynamics. For M0, non-assimilated model the results may be improved by including the mixed layer heat flux with a parametrization similar to (Petty et al., 2014). Also, note that the model still assumes a fixed salinity profile and mixed layer profile.

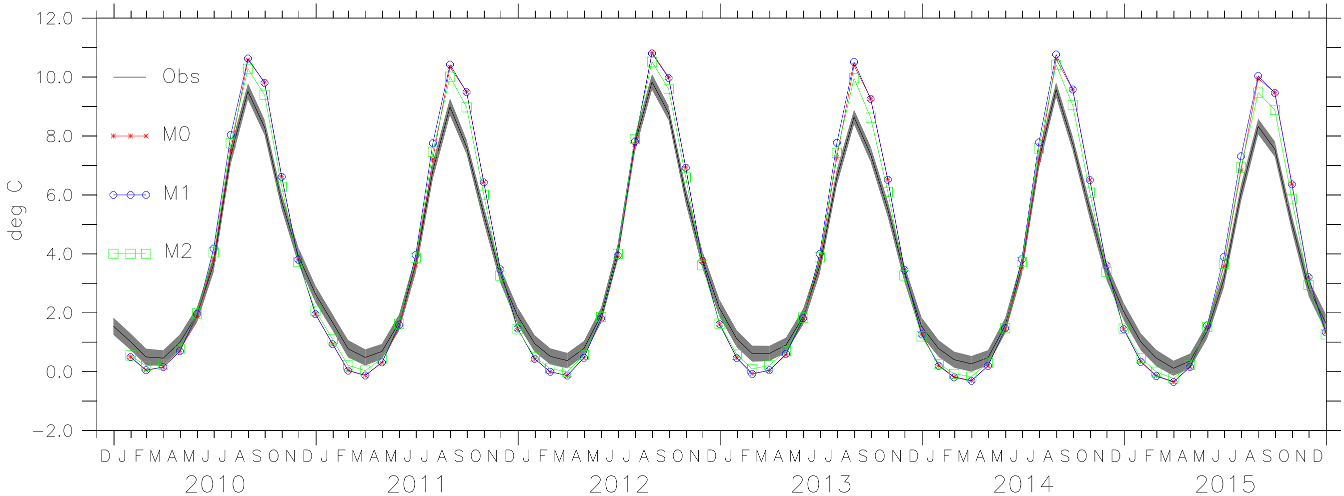

Figure 13. The SST from AVHRR-only OISST analysis with the shaded region represents the uncertainty of AVHRR-only OISST analysis, and SST from models M0, M1, M2.

5.3 Draft and keel depth

The ULS measurements were separated into level ice draft and keel depth measurement as described in Prasad et al. (2016) and also in Section 3. The level ice draft, D is computed using equation (3) (Tsamados et al., 2014). The results are shown in Figure 14.

$$D = (\rho_i v_{ice} + \rho_s v_{sno})/(A\rho_w) \quad (3)$$

Where $\rho_i = 917 kg/m^3$ is the density of ice, v_{ice} is the volume of ice, $\rho_s = 330.0 kg/m^3$ is the density of snow, v_{sno} is the volume of snow, A is ice concentration, $\rho_w = 1026 kg/m^3$ is the density of sea water.

Some deviations are noticed in the comparison of level ice draft. The estimated absolute error is about 10 cm for 2005, 2007, 2009. The error of 10cm on draft of 20 cm can be accepted ~~as a good correspondence~~ considering large difference in spatial resolution between the ULS and Model. Also, the analysis was done only for 2005, 2007, 2009 as this was when data was available.The discrepancy occurs due to the fact that ULS gives values at a particular location with high resolution (within the footprint of several meters), while the model is of 10 km resolution gives an averaged result close to the location of the ULS. Moreover, the analysis of histogram from ULS shows multi-modal distribution at certain time points which indicates the presence of rafted ice. In the present study, the rafted ice is also included and considered as the ridges which contribute towards the results achieved in this section.

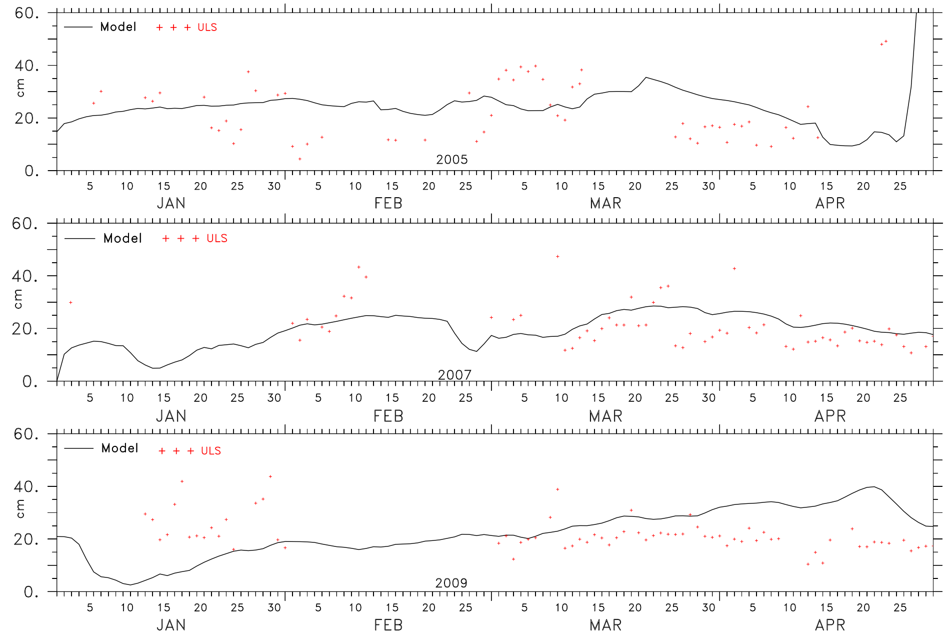

Figure 14. The level ice draft computed from the ULS measurement and the "M2" model estimated values ~~in cm~~ at Makkovik Bank for 2005, 2007 and 2009.

The keel is computed using idealized sea ice floe comprising a system of two triangular sails and keels and a single melt pond (Tsamados et al., 2014). The ridge height is given by equation (4) and the correlation between the ridge height and keel depth is given by equation (5)

$$H_r = 2\frac{V_{rdg}}{A_{rdg}}\frac{(\alpha D_k m_k + \beta C m_r)}{(\phi_r m_k D_k + \phi_k m_r C^2)} \quad (4)$$

Where ~~H_k, is the keel depth,~~ H_r is the ridge height, ~~$m_r = 0.4$ (21.8°) and $m_k = 0.5$ (26.5°) are the slopes of the ridge and the keel respectively~~ $m_r = tan(\alpha_r) = 0.4$, $\alpha_r = 21.8°$ is the slope of the sail and $m_k = tan(\alpha_k) = 0.5$, $\alpha_k = 26.5°$ is the slope of the keel, ϕ_r is the porosity of the ridges, $\phi_k = 0.14 + 0.73\phi_r$ (Shokr and Sinha, 2015) is the porosity of the keels. $D_k = 5$ is the ratio distance between ridge to distance between the keels. V_{rdg} is the volume of the ridged ice, A_{rdg} is the ridged ice area fraction, α and β are the weight functions for area of ridged ice, C is the coefficient that relates ridge to keel and

$$H_k = CH_r \quad (5)$$

gives the keel depth H_k. The Makkovik Bank where the keel measurements are estimated from ULS has high variability of ice thickness, and frequency of the formation of keels are high due to the combined effect of the Labrador currents and winds, rafted ice are common in this region (Peterson I.K., 2013). Here the model and the observation of keel depth are used to estimate the parameter C.

The coefficient, C estimated for 2005, 2007 and 2009 shows that a value between 3.00 and 4.50 gives a good estimate of keel measurement for January and February while a value between 7.00 and 8.00 gives a good estimate for keel during March, April, and May. In Figure 15 the values of the coefficient C that relates ridge to keel for January and February is 3 and $C = 7.00$ for March, April and May, see equation (5). These values are derived under the assumptions in equation (4). The sensitivity of parameters has to be further explored to determine the characteristics of each parameter and its effect on the ridge, keel relationship which may result in a different conclusion. Since the interest lies in deriving this relationship from the assimilated model, so only results from M2 is presented. For non-assimilated model, the choice of parameters vary.

During January to February the formation of ice and ridges occurs, and during March the thick ice may be contributing towards the ridging thus increasing the value of C.

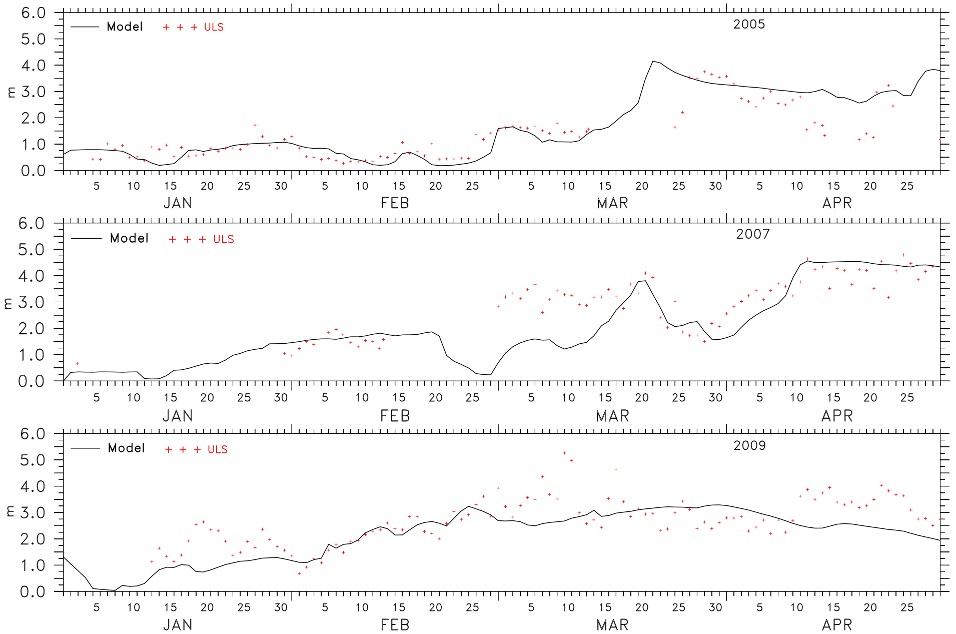

Figure 15. The keel depth computed from the ULS measurement and the "M2" model estimated values in cm for 2005, 2007 and 2009.

5.4 Freeboard

The uncertainty of freeboard measurements can arise due to the lack of leads. The presence of leads was ensured by selecting the regions where lead fraction derived from CryoSat-2 (Ricker et al., 2014) was greater than zero. In the model, freeboard is computed using equation (6) (Tsamados et al., 2014). For the region, the uncertainty of the freeboad measurements is below 40 cm (Ricker et al., 2014).

$$D_f = (v_{ice} + v_{sno})/A - D \tag{6}$$

Where v_{ice} is the volume of ice, v_{sno} is the volume of snow, A is the ice concentration, D is the draft, see equation (3).

The absolute mean difference between the model and the observation for January, February and March 2011 is shown in the Figure 16. M2 freeboard measurements are close to the observed freeboard. Figure 17 shows the RMSE of freeboard from model M2 and CryoSat-2 in the areas where the lead fraction was greater than zero. The RMSE is below the maximum uncertainty of 40 cm for the region of interest and was found to range between 4.5 cm and 11 cm. Figure 18 demonstrates the spatial estimates with M2, observation and uncertainty.

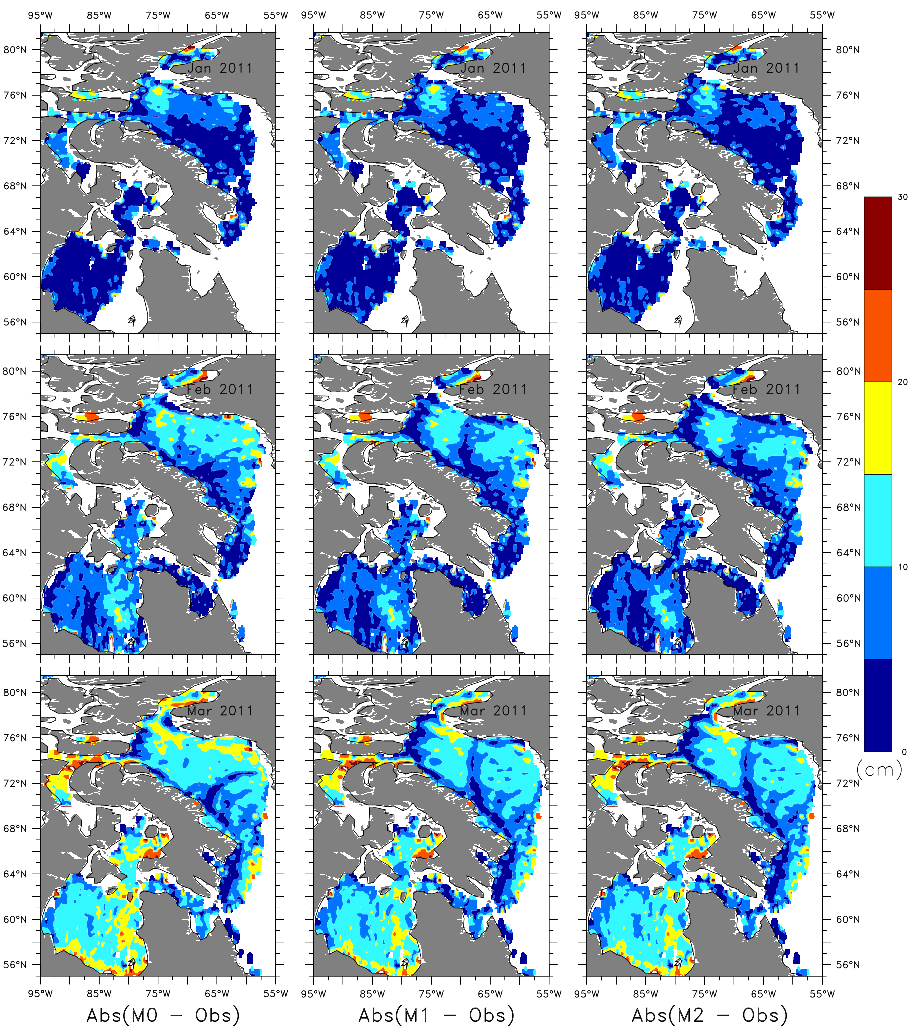

Figure 16. The absolute ~~error~~ mean difference between the model freeboard for M0, M1 and M2 and CryoSat-2 for January, February and March 2011.

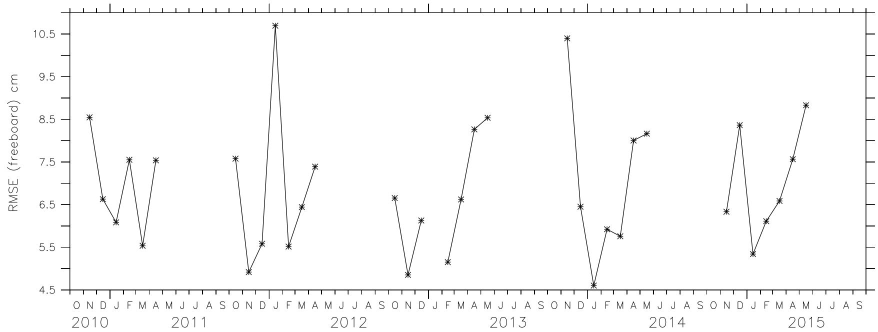

Figure 17. The RMSE of freeboard measure for the regions where the lead fraction is above 0%.

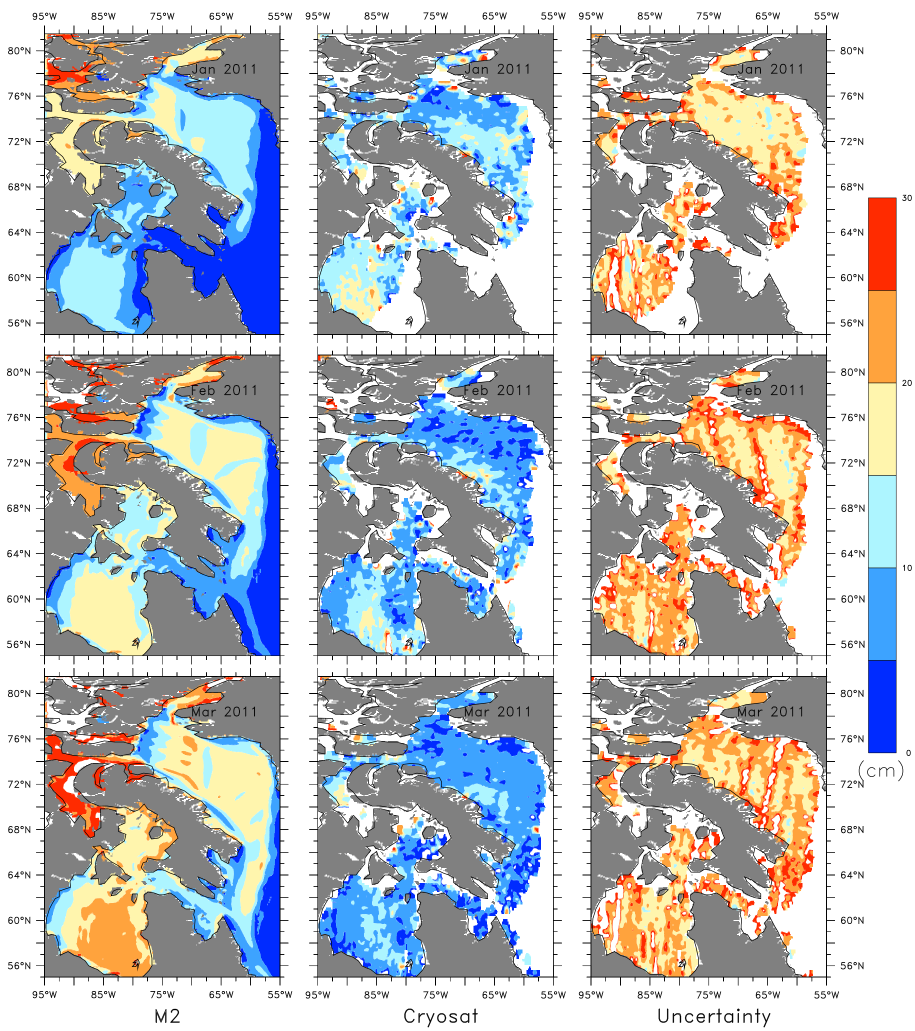

Figure 18. The Freeboard from model M2, CryoSat-2 and the uncertainty of the observations for January, February and Match 2011.

Figure 19 shows the observed freeboard from CryoSat-2, the uncertainty of observation, and the model M2. Only the model results from M2 are given since there are only slight deviations for M0 and M1 from the observation. Moreover, we are interested in the results of the assimilated model and how well it performs in the estimation of freeboard. The model values are within the uncertainty limits of the observation. Also, note that the model results are monthly averaged, while CryoSat-2 is a mosaic of daily measurements within a month. The spatial average of freeboard for the region, the observed value, and the uncertainty is shown in Figure 18. The average freeboard from the model lies within the uncertainty limits of the observation.

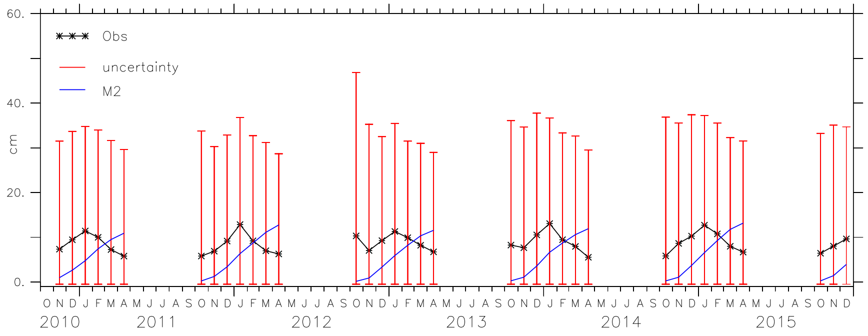

Figure 19. The freeboard from CryoSat-2, uncertainty of the observation and the model M2,

6 Conclusions

The assimilated models in the literature, and those implemented in forecasting centres use a constant drag formulation and lack the details on deriving the parameters other than ice concentration, and ice thickness (Lemieux et al., 2016; Rae et al., 2015) . In this work a variable drag formulation is used for the friction associated with an effective sea ice surface roughness at the ice-atmosphere and ice-ocean interfaces and to compute the ice to ocean heat transfer. The results from the updated model ~~are~~ were compared with satellite derived measurements to validate the ~~assimilation strategy. Moreover, the assimilated model results includes~~ model estimates of ice concentration, ice thickness, freeboard~~, and sail height, keel depthin addition to ice concentration~~. Moreover, the model results were used to estimate relationship between sail and keel depth.

The modeled ice thickness demonstrated a good correspondence with the estimates from SMOS-MIRAS, except during the period of maximum ice extent. The ~~model freeboard are compared with estimates from CryoSat-2, and the RMSE was found to range between 4.5 cm and 11 cm. The estimates of freeboard from the model are within the uncertainty values of the CryoSat-2 (below 40 cm). The~~ deviation in the results of ice thickness during March have to be further explored by tuning the parameters that contribute to the ice thickness in the non assimilated model as well as the assimilation parameters. The thin ice category thicknesses are overestimated from October to November end but lies within the uncertainty limits of SMOS from December to March. Also, the SMOS estimates are influenced by the presence of snow and also during the melt seasons the uncertainties of SMOS estimated ice thickness might increase in which case comparison with more reliable data would be required. The model freeboard are compared with estimates from CryoSat-2, and the RMSE was found to range between 4.5 cm and 11 cm. The estimates of freeboard from the model are within the uncertainty values of the CryoSat-2 (below 40 cm).

The level ice draft and keel values derived from ULS were compared with the modeled values. The coefficient that related the sail height and keel depth for the Makkovick region lies in a range $3-8$ depending on the period of the year. ~~The ULS data and model results were in agreement, except for some differences which can be explained by the difference in spatial resolution of the model and ULS data.~~

~~The assimilation methodology can be further improved by tuning the parameters, refining the error estimates derived from the observation data and combining data from several sources~~Since the variable drag formulation depends on the assimilation methodology further sensitivity studies has to be conduted for the optimisation of the model.

Competing interests.

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