

# Authors response to referees comments for manuscript tc-2017-247

*We would like to thank both reviewers for their careful reading and checking of the manuscript, and for making many thoughtful comments and valuable suggestions that helped us to improve it.*

*The numbering of pages, lines, sections and figures used in this response refers to the old version of the manuscript. Throughout our response, we use the following abbreviations:*

- *SIC - sea ice concentration*
- *SIT - sea ice thickness*
- *SST - sea surface temperature*
- *PMR - passive microwave radiometry*
- *TB - (microwave) brightness temperature*

*The manuscript and reviewer comments are published online in The Cryosphere Discussions at <https://doi.org/10.5194/tc-2017-247>.*

## 1 RC1 – comments of first referee

### 1.1 Summary and assessment

**Comment:** *The paper provides a useful story on the potential and the pitfalls of using SMOS derived sea ice thickness for the validation and assimilation with an ocean reanalysis. The paper compares SMOS sea ice thickness with ORAS5 reanalysis sea ice thickness. It finds strong correlations, considerable biases and also areas where there is little agreement between SMOS and ORAS5. Some ideas are presented why this disagreement maybe both due to retrieval and modeling errors. While those results are not conclusive, they provide some guidance on how to proceed further and how to potentially incorporate SMOS sea ice information into an ocean reanalysis. I find the paper to be well written and claims sufficiently supported by the evidence. While one may have hoped for some stronger conclusions, I think it is useful as is and provides an incremental contribution.*

**Response:** We thank the reviewer for a careful reading and assessment of the manuscript, and for suggesting several changes that helped us to improve it.

### 1.2 Specific Comments

**Comment 1.2.1:** *Page 3, Line 12 "... JRA-55...": Later JRA-25 is indicated, please clarify.*

**Response:** We have clarified this. Whereas previous versions of SMOS-SIT used JRA-25 until 2014 and JRA-55 from 2014 onwards, the version 3.1 that we are discussing uses only JRA-55.

**Comment 1.2.2:** Page 4, Line 33 “Thus the OSTIA ice concentration product can not...”: I dont understand what is stated here, I must be missing something.

**Response:** We meant to say that SIC from conventional PMR cannot be used to distinguish areas of old thick sea ice from areas of new thin sea ice because both often have sea-ice concentration of virtually 100%. In contrast, L-Band radiances can be used to make that distinction. We have rephrased P4 L32f. to make the statement more understandable.

**Comment 1.2.3:** Page 5, Line 16: Most of this is likely due to the model being unable to simulate the coastal polynya in the Laptev Sea. Why is this? I think that could be probed a little more? Is the ice too thick to be advected away from the coast and create the polynya or does it regrow too quickly? Is this a resolution effect? If ice concentrations are assimilated and they show open water there (L-Band does so, I assume the higher frequency ice concentration does too?), then why doesn't the model. I understand that this is not necessarily a model validation paper but given the uncertainty in both model and observations it would be good to tie this down a bit more, particularly since later the model seems to be favored over the observations in the case of the Laptev Sea.

**Response:** These are very good questions and suggestions thank you. Before answering, we think it is necessary to clarify two issues mentioned in the reviewer's comment first: (1) As shown very clearly in Figure 1e, SIC in the Laptev Sea polynya is close to 100%, so assimilating SIC does not help and might even be detrimental. In winter, polynyas often refreeze very quickly and are then covered by thin ice. There is a crucial difference in emissivity between higher-frequency microwave and L-Band microwave radiation for the thin ice in the refrozen polynya, which is exactly the point we are trying to make. (2) It seems to be a misunderstanding that “later the model seems to be favored over the observations in the case of the Laptev Sea” – to the contrary! Figs. 3b and 4a and their corresponding discussion in the main text quite clearly argue that the refrozen Laptev Sea polynyas are detected by L-band observations but not simulated by the reanalysis. We have rephrased sentences in the text that could lead to misunderstanding.

This leaves the question why the reanalysis does not simulate the polynya. This is an important question to tackle for model and data assimilation development, but it is not easy to answer because there are many possible reasons, and a dedicated study would be needed to narrow them down and provide a confident answer. In the light of the above, it could even be that the implied SIT increments from the SIC assimilation are responsible. We have added some discussion on this to the text on P5 L16.

**Comment 1.2.4:** Page 6, Line 18 “polynya...”: as mentioned above, why does the model not show open water areas that SMOS shows and presumably should be visible in the ice concentration data that are assimilated?

**Response:** See our reply to the previous comment. It is evident from higher-frequency PMR that the areas we are referring to are covered by thin ice. We acknowledge that a polynya in the strict sense is an area of open water surrounded by ice, and our usage of the term might therefore be misleading. We went through the entire text of the manuscript and added clarification that we are talking about refrozen polynyas (e.g. P5 L11 and L16, P6 L18, and others)

**Comment 1.2.5:** Page 6, Line 28 “under the ice”: This could use a reference to page 7, SST information cannot be used. Again, how come the model doesn't show the open water if it is there in the OSTIA ice concentrations. If there is open water, why cant you assimilate the SST (if they are available). I cant quite follow this argument. I have a sense that this may be an issue with the model which is biased thick and has excessive

*internal ice strength which keeps the ice from moving off shore. Though this doesn't explain why the assimilation doesn't create the opening. Another plausible explanation might be that excessive ice production due to excessive advection creates too much ice in this area. A look at advection and growth rates in the model might be helpful. This is particularly important since the authors seem to give the model and CryoSat measurements the upper hand while discounting EM and SMOS measurements. EM measurements aren't really discussed.*

**Response:** We have added a reference to using SST information on P6 L28. As explained in our responses to the previous comments, there is no open water in the frozen polynyas and hence SIC assimilation does not help. We agree it would be very interesting to investigate why the reanalysis does not represent the frozen-over polynyas, but as argued in our response to comment 1.2.3 we think this is a study in its own right and out of the scope of this manuscript. We have added discussion on the points mentioned by the reviewer on P5 L18.

**Comment 1.2.6:** *Page 8, Line 8: "Surface Temperature": Clarify if ice or air temperatures, I think you mean ice.*

**Response:** We did indeed mean the ice surface temperature. We have rephrased that sentence to make it clearer.

**Comment 1.2.7:** *Page 8, Line 10 "two reanalysis": Correct JRA-25/55 issue see above and remind readers how the JRA reanalysis is used in the SMOS retrievals.*

**Response:** Revised as suggested.

**Comment 1.2.8:** *Page 8, Line 26 "various thickness classes": ORAS5 has thickness classes? I thought it was a single category model?*

**Response:** Here, we refer to the diagnostic thickness classes we defined for producing the figure. It is unfortunate that this can be confused with prognostic thickness classes in the sea ice model. We have revised the sentence and use the term "thickness threshold" to avoid this ambiguity.

**Comment 1.2.9:** *Page 10, Line 3 "lack of thickness categories in combination with an artificial thickness": Please clarify, I cant follow this.*

**Response:** We have revised this sentence and provide a reference to the Section 2.1 of the main text, where we have added a detailed explanation of this issue. We have also added an appropriate literature reference.

**Comment 1.2.10:** *Page 10, Line 5 "incapable of simulating the polynyas": Is this because of the lack of thickness categories or a general bias in ice thickness and associated ice strength? How does the model do in general with respect to ice thickness in the interior pack? That information would be useful.*

**Response:** This is a recurring comment, we refer to our answer to comment 1.2.3. Regarding the general bias in ice thickness, we point out that the model does well relative to its peers, as shown in Uotila et al. (2018). We have added this reference to the model description Section 2.2.

**Comment 1.2.11:** *Page 10, Line 20 "structural limitations": Note them please.*

**Response:** In response to this and other comments, we have added a paragraph in Section 2.2 that explains the simplified treatment of thin ice in the sea-ice model and provides relevant references to the literature. Other structural limitations might be less

obvious and require further research and experimentation to corroborate, so we cannot note them here. We have rephrased the sentence on P10 L20, and have provided a reference to Section 3, where we discuss potential structural limitations.

**Comment 1.2.12:** *Figure 1: Please explain saturation ratio and where the 90% threshold comes from.*

**Response:** If an ice thickness change of 1 cm leads to a TB change of less than 0.1 K in the SMOS-SIT retrieval algorithm, the TB is considered saturated. The ice thickness at which that happens for the current values of the auxiliary fields is the maximal retrievable ice thickness  $d_{\max}$ . The saturation ratio of any other retrieved ice thickness  $d$  for the same values of the auxiliary fields can then be expressed as  $d/d_{\max}$  (Tian-Kunze et al., 2014). We have added this explanation to P3 L19ff. of the main text, and we have reworded the caption of Figure 1.

**Comment 1.2.13:** *Figure 2: “Scatter density...”: Whats the unit of density in this context. All scatter plots could use some statistics (e.g. correlation, bias, RMS error) in either the figure or caption.*

**Response:** We use scatter density as a synonym for “normalized bivariate joint frequency distribution”, so it has no units. We have added an explanation to the main text on P5 L24 and have reworded the figure caption to improve clarity.

**Comment 1.2.14:** *Fig 4: “with added and subtracted...”: Add uncertainty. Not much discussion is given to the EM data point and why this seems to be rather supporting SMOS than both CryoSat and the Model.*

**Response:** Thank you for spotting the omission of “uncertainty”. There is no discussion on the EM data point because we consider it to be a much better estimate of the truth than any satellite-derived observation or model simulation. The fact that it supports SMOS much better than the model is exactly the point we are trying to make (see several previous comments and our responses): The re-frozen polynyas are real, and they are detected by SMOS, but not simulated by the model. We have rephrased several bits of text to make this point even more clearly. The mismatch to CryoSat is a different topic and should be subject to further research. In this case, please note that the CryoSat value represents a full month of data and hence cannot be directly compared to a daily snapshot from an EM-bird overflight and a SMOS-SIT daily mean.

## 2 RC2 – comments of second referee

### 2.1 Summary and assessment

**Comment 2.1.1:** *This manuscript presents a comparison of Arctic sea ice thickness within a range of 0 – 1 m, both retrieved from SMOS satellite-based L-band brightness temperatures and from a numerical ocean-sea ice reanalysis system assimilating various observational data. It focuses on evaluating regional biases between the two products during the winter 2011-2012 season, but also touches on interannual variations and trends across the full 2011-2016 period. The premise for the study, although unfocused, is valid. Numerical sea ice forecasting systems should unequivocally be more reliable if they can assimilate a greater breadth and variety of observational data, such as low-frequency passive microwave retrievals of ice geophysical properties like those provided by SMOS.*

*Here, the authors appear to be undecided on the main purpose of their study: is the idea to verify/validate the ORAS5 forecasting system using the SMOS data? If so, given the observational uncertainties discussed in the manuscript, the SMOS data do*

not appear ready for this. Moreover, why was the enhanced sea ice thickness product incorporating SMOS and Cryosat-2 data not utilized. Alternatively, is the idea to evaluate the root causes of biases within the SMOS data? In which case, this is mostly done qualitatively. Several possible reasons are introduced to explain uncertainties in the SMOS data, but none are investigated in detail so no useful conclusions are made. Given that the premise of validating numerical sea ice forecasting systems is highly valuable, I recommend this paper could be published following major revisions. In line with comments above, the authors should decide exactly what they want the paper to be, to allow them to focus their arguments into quantitative useful conclusions.

**Response:** We thank the reviewer for their careful reading of the manuscript, for pointing out its weak points, and for making several very valuable suggestions how to improve it.

The main purpose of the study is to give an overall assessment of agreement and discrepancy between an observational product of sea-ice thickness from L-band PMR and a sea-ice ocean analysis system that does not assimilate the observational product. Observing and analyzing thin sea ice has only become possible in the last few years, so as with every new technology, initial problems are to be expected. To our knowledge, a detailed assessment of this kind covering the whole Arctic has never been done, yet we see it as an essential step to take before using the observational product for model validation, data assimilation, or forecast verification.

Perhaps we did not make our premise clear enough in the abstract and in the introduction: we do not and will never know the true ice thickness with the vast temporal and spatial coverage provided by remote sensing and reanalysis products. Both can have large errors, and it is not a-priori clear that one is superior to the other. In fact, one of the main points of the manuscript is that discrepancies between the two products compared can be attributed to errors in one or the other, depending on the region and feature considered. Hence, in many cases the fidelity of the SMOS-SIT product is not currently high enough to validate the ORAS5 reanalysis system, as pointed out by the reviewer.

We enthusiastically agree that an investigation of the root causes of potential biases in the SMOS-SIT data and the reanalysis is needed. However, this is *not* the point of this manuscript. As the reviewer points out, we offer possible reasons but can not follow up on them. Numerical experimentation with the retrieval algorithm and the ocean analysis system is beyond the scope of our study. Rather, our study provides concrete examples of discrepancies and so can provide inspiration and guidance for a future study on sensitivities and uncertainties of the retrieval algorithm and the reanalysis.

We have revised the manuscript in order to address the very valid points raised by the reviewer. We think that the new manuscript version does better in presenting the premise and purpose of the study (and thus managing the expectation of the reader), provides some deeper analysis as requested by the reviewer, and summarizes the main points of the paper in the conclusions section more pointedly. The revisions are described in more detail in our responses to the following comments.

## 2.2 General Comments

**Comment 2.2.1:** *Regarding Section 2.1, do you have quantitative component uncertainties for each of the contributing factors listed here (e.g. uncertainty contribution from the smos Tb, from the ancillary T and S data, from using assumptions for linear T-gradient, desalinization scheme etc.)? Are these provided in the SMOS product or can they be provided by the co-authors? In the context of the entire study this would be very useful, as it would allow the authors to better evaluate regional biases in the SMOS data and thus understand how likely identified bias is a product of the SMOS*

*data or forecasting system. An example of where this would be useful is around page 7 line 32.*

**Response:** Having a look at quantitative component uncertainties for SMOS-SIT is an excellent suggestion, and we agree it would be extremely useful. They are not currently available from the published SMOS-SIT product, and although they could be provided in principle, this is a non-trivial exercise, both conceptionally and computationally. An ongoing project is investigating this at the moment, and results should be left to a dedicated study which can build on this manuscript for inspiration and guidance. We have added this premise to the introduction, and have also added references to Maaß (2013) who have investigated these uncertainties/sensitivities of the retrieval model for idealized cases, and Richter et al. (2016) who perform an intercomparison of L-Band brightness temperatures calculated from reanalysis sea-ice fields.

**Comment 2.2.2:** *It would be valuable to include all or details from Appendix C in the main paper. This extra understanding of where and in what context the SMOS data could be limited would really help to interpret the validity of results from the forecasting system. This analysis could be expanded by examining scales of day-to-day variability between a fast-ice region (e.g. the Canadian Arctic Archipelago) and a dynamic region, over the same time period or scenario (like the authors rapid air T change). Equally, more depth to the analysis between ice concentration and SMOS ice thickness (also in the appendices) and on the effect of auxiliary fields on the ice thickness retrievals would be incredibly valuable and relevant, even though the authors suggest this is beyond the scope of the paper.*

**Response:** We agree that these points would be extremely valuable to investigate. However, as we have argued in our response to comment 2.1.1, we think this is better left to a dedicated study on the uncertainties and sensitivities of the retrieval model. This requires non-trivial work, as the retrieval algorithm needs to be run many times with systematic and realistic variation to the thermodynamic sea-ice model, auxiliary fields, and brightness temperatures, and possibly employing different radiative transfer models as well (coherent vs. incoherent etc.).

Given that the magnitude of the unphysical day-to-day changes discussed in Appendix C is well within the uncertainty estimate provided by SMOS-SIT, it might be a bit unfair to assign too much emphasis on them. Rather, it illustrates the fundamental need to complement remote sensing observations with physical constraints from a forecast model background in the framework of data assimilation.

**Comment 2.2.3:** *Section 5 is quite vague and unfocused. The bulk of the paper would be more useful if this was removed and replaced with more detailed investigation of regional model-obs biases, investigating particular causes for the regional biases the authors touch upon in the previous section.*

**Response:** We would like to keep this section, because it provides a positive outlook on how variability and change of thin sea ice in the Arctic can be monitored using SMOS-SIT and ORAS5, despite all their discrepancies. This positive message is one of the main points of the paper.

**Comment 2.2.4:** *You mention at Page 10 line 6 that the SMOS ice thickness algorithm relies much more on auxiliary fields when ice thickness > 0.5 m. It would therefore be useful to analyse model-obs biases for different categories of uncertainty or for different ice thickness categories. Is there a strong relationship between bias magnitude and SMOS-SIT or uncertainty?*

**Response:** The dependence of the departures on the retrieved ice thickness in SMOS-

SIT can be read off Figures 2 and 3, and we discuss the dependence in the main text. There is no apparent dependence of departures on uncertainty (see Figure 3 in this response), so we have decided not to include it in the manuscript.

**Comment 2.2.5:** *Page 11 line 2f.: I do not agree with the statement that there is “reasonable agreement” between observed and analysed ice thickness in the early freezing period. There is systematic nonlinear bias, which has not been explained or properly quantified here.*

**Response:** We agree there is systematic discrepancy even early in the freezing period. The agreement is “reasonable” only in comparison to the much larger discrepancy later in the freezing season. We have changed the wording on P11 L2. We have added discussion of this nonlinear bias to the main text after P5 L34.

**Comment 2.2.6:** *To reiterate an earlier point, it is difficult to understand whether the idea of the paper is to verify/validate the reanalysis system (in which case it would have made more sense to use the combined CS2/SMOS product from AWI and Hamburg [http://data.seaiceportal.de/gallery/index\\_new.php?active-tab1=measurement&icetype=thickness&satellite=CS&region=n&resolution=weekly&minYear=2017&minMonth=4&minDay=3&maxYear=2017&maxMonth=4&maxDay=9&showMaps=y&dateRepeat=n&submit2=display&lang=en\\_US&activetab2=thickness](http://data.seaiceportal.de/gallery/index_new.php?active-tab1=measurement&icetype=thickness&satellite=CS&region=n&resolution=weekly&minYear=2017&minMonth=4&minDay=3&maxYear=2017&maxMonth=4&maxDay=9&showMaps=y&dateRepeat=n&submit2=display&lang=en_US&activetab2=thickness)), or to verify/test SMOS (in which case it is difficult to use a highly simplified model to do this).*

**Response:** As argued in our response to comment 2.1.1, the premise of the paper is that *both* the current versions of the observational ice thickness product *and* the reanalysis product contain substantial and systematic errors. Hence, careful additional investigation and expert judgement is needed if one wants to use one of them to verify or validate the other. What can be done is to contrast them, and to use independent data and process understanding to give indication as to which of the two is probably closer to the truth for certain identified features and regimes. This is the essence of the paper. We have revised abstract, introduction and conclusions of the manuscript to clarify this point.

Regarding the suggestion to use the combined CS2SMOS product, we note that problems in a multi-sensor product like CS2SMOS are even more difficult to track down. The CS2SMOS ice thickness might be closer to the truth than SMOS-SIT alone, but at the cost of traceability. Besides, our motivation is the potential use of SMOS-SIT for data assimilation. Operational centers are extremely unlikely to assimilate a multi-sensor SIT product, which in itself already is an analysis – it is much preferable to use products individually and let the analysis system find the best fit to observational data from different sources, that can be inconsistent between themselves.

We have revised the introduction and the conclusions to explain the purpose and scope of the paper better, and to better communicate the main conclusions.

## 2.3 Minor Comments

**Comment 2.3.1:** *Page 1 Line 22: “coverage at a”*

**Response:** Fixed.

**Comment 2.3.2:** *P2 L18 requires more specific objectives for the study, beyond simply compare observations with model. What exactly are you trying to achieve here? What exactly will the study provide that is useful for future work?*

**Response:** This is a valid point and urgently needed to give the right premise for the manuscript. We have revised the introduction to address that (see also responses to the

reviewer’s general assessment and general comments).

**Comment 2.3.3:** *P5 L28: is ORAS5 SIT < 0.3m impossible? In what situations do you get very thin ice? SIC very low? A “freeze-up threshold” is referred to later on but should be explained here.*

**Response:** Here and in several other comments the simplified treatment of thin ice in the model is addressed. As alluded to by the reviewer, LIM2 has a minimal floe (or in-situ) ice thickness – new ice will grow at this thickness. This is the “freeze-up threshold” that we are referring to. However, throughout the entire manuscript we compare the *grid-cell mean* ice thickness of the model with SMOS-SIT, because SMOS-SIT also gives the *mean* ice thickness. The thickness at which new ice forms is set to 0.6 m in ORAS5, so a mean thickness of 0.3 m corresponds to exactly 50% area coverage. Mean ice thicknesses below that do exist but are not as abundant (see Figure 1). We have added a sentence on P5 L28 to explicitly state that we compare the grid cell mean ice thickness from both SMOS-SIT and ORAS5. We have also revised added text after P5 L34 that properly explains the “freeze-up threshold” and puts it into context.

**Comment 2.3.4:** *P5 L34, you need to explain this non-linear dependence here or in the discussion. Clear dependence within the LIM2 ice redistribution function? Or from the single thickness class assumption? Or is this some bias introduced from SMOS?*

**Response:** We agree this needed more explanation. We have done some further analysis, with the result that both model and observation deficits mentioned on P5 L5–9 are likely to be important. We have added these results to the text, after the paragraph starting on P5 L26.

**Comment 2.3.5:** *P6 L23, this is a very qualitative description of the relationship. . . Can you explain?*

**Response:** We do not think that this is a qualitative, it is just putting in words what can be seen in the figure. The term “functional relationship” might be poorly chosen. We mean to say that there is a high rank correlation between the two variables (product correlation could still be low due to non-linearity). This can be exploited for a-posteriori calibration. We have reworded these sentences to clarify, referring to the rank correlation instead of a “functional relationship”.

**Comment 2.3.6:** *P6 L30, where are they assimilated? Outside the ice edge presumably?*

**Response:** Correct. No SST observations are assimilated in the presence of sea ice for the simple reason that the presence of sea ice makes a satellite observation of SST virtually impossible.

**Comment 2.3.7:** *P7 L7, There is lower SIC in Baffin Bay in April, so this could be caused by the SMOS-SIT assumption of total ice concentration within a grid cell? TB is biased due to the emissivity of open water.*

**Response:** This is an intriguing hypothesis that we had considered at an earlier stage of investigation but then dropped, assuming instead that the real ice cover is 100%. The intrinsic uncertainty of sea-ice concentration from PMR is a few percent even in optimal cases (Ivanova et al., 2015), and if these few percent dominate the L-Band emissivity this invalidates the SMOS-SIT retrieval assumptions. Assuming the TB is 240 K for thick sea ice and 90 K for open water, a simple calculation shows that every percent of open water in a previously closed ice pack will lower L-Band TB by 1.5 K. In the case of the Baffin Bay shown in Figure 5, the SMOS-SIT retrieved ice thickness decreases from



1 m in January to 0.5 m in April while the SMOS TB decrease from 240 K to 230 K and the PMR SIC from close to 100% to about 95% (albeit noisy).

Thus, it is plausible that SMOS-SIT has very low mean sea-ice thickness in late winter in the Baffin Bay because it misinterpretes the open-water L-Band signature. This can in principle be tested by restricting to cases where SIC is 100% with high confidence (e.g. where sea ice velocities are convergent or where MODIS visual imagery is available). We have added this hypothesis to the text.

Testing this hypothesis rigorously is outside the scope of this manuscript. However, we can get some indication by plotting the normalized joint frequency distribution (scatter density) of OSTIA SIC and SMOS-SIT SIT for the Western Baffin Bay. Figure 4 shows that there is moderate correlation between SIC and SIT, indicating that the open-water contribution to L-band emissivity matters, but does not dominate the signal.

We have added some discussion on this to the manuscript on P7.

**Comment 2.3.8:** *P7 L8, remove also and add appropriate Tilling citation.*

**Response:** Done.

**Comment 2.3.9:** *P7 L22, this is likely owing to low SIC. Linked to the second major point above, some more involved analysis SMOS-SIT sensitivity and higher frequency emissivity/SIC would be very useful and may allow you to make much more robust arguments for causes of obs/model bias.*

**Response:** This relates to comment 2.3.7. See our response there. The SMOS-SIT sensitivity to open water is not testable given the 100% cover assumption built into the current version of the retrieval algorithm, but it can be seen that it is large by simple back-of-the-envelope calculations (our response to comment 2.3.7, also see Richter et al. (2016)). We have revised P7 of the manuscript to include some discussion on the SIC-sensitivity of L-band PMR as suggested by the reviewer.

**Comment 2.3.10:** *P8 L5, close to 100%, but not at it, whereas most other regions have total ice concentration. Another thing to consider is that sea ice in Baffin Bay is fairly low latitude so could be melting some years in April and affecting the L-band penetration depth. What do the PMR data suggest in terms of melt onset date for Baffin Bay in 2012? Crucially, do you observe this clear bias every year for Baffin Bay?*

**Response:** Agreed, SIC even a few percent lower than 100% will have an important impact on L-band TB. We have revised the text (see response to comment 2.3.7). The second hypothesis of surface melt can be safely rejected for this case, as ice surface temperatures are well below freezing throughout (see Figure 5d in the manuscript). However, it might play a role in other winters.

We have followed the advice of the reviewer to produce the time series for *all* winters, and we have also calculated them for a spatial average over the Western Baffin bay area as defined by Landy et al. (2017), in order to reduce spatial sampling uncertainty. The result is that the behaviour documented in Figure 4 of the manuscript appears in all winters for the entire Western Baffin Bay (Figure 2 in this response).

**Comment 2.3.11:** *P9 L14, change “than” to “then”.*

**Response:** Done.

**Comment 2.3.12:** *P10 L16, this would be a much stronger argument if you could provide reasonable evidence as to why this happens. Do you even see the same biases every year? Could you test the interannual persistence of your regional biases? Again*

*this would be highly valuable to the community.*

**Response:** The point of the discussion on P10 is not to claim that there *is* systematic underestimation of sea-ice thickness by SMOS-SIT, but to describe the appropriate action to take in the *scenario* that this is the case (see P10 L10).

However, we can confidently demonstrate that these regional biases robustly occur each year (see our response to several previous comments, e.g. 2.3.10). We have added this to the manuscript, by reproducing Figures 2 and 3 for *all* years available, and by plotting the time series in Figure 4 for all years available and as an area average over the western Baffin Bay (Figure 2 in this response).

**Comment 2.3.13:** *P10 L23, surely more relevant here is the need to improve the rheology and add formulations to the numerical scheme to allow for polynya development, rather than just assimilating observations and the model re-equilibrating to incorrect/overestimated ice thickness?*

**Response:** We agree, it is much preferable to remove the model bias rather than forcing the model out of its natural state by data assimilation. However, in practice model and data assimilation developments are often not well synchronized, so that data assimilation does correct for model biases. In most cases, assimilating in the presence of model bias is still preferable to not assimilating, because it leads to better time-evolving state estimates, and because forecasts are improved at least for short lead times when the model has not had time to re-develop the bias.

**Comment 2.3.14:** *P12 L18, this is an important limitation that could have been examined in greater detail within the main paper.*

**Response:** Agreed. We have added more discussion on that to the main text, also in response to comments 2.3.7 and others.

**Comment 2.3.15:** *P13 L13, this is a very useful finding that could be represented better in the main paper and given as one of the papers main conclusions.*

**Response:** This comment ties into the general comment 2.2.1, see our response there. We agree that this is an important aspect, but it is impossible to draw useful quantitative conclusions on this from a purely diagnostic point of view (which is what we do in this paper). We think it can only be a strong conclusion in a study that explicitly changes parameters of the retrieval algorithm to study its limitations and sensitivities, and it would be a rather weakly defended conclusion in the context of this manuscript.

**Comment 2.3.16:** *Fig 2, explain what unc, sic etc. mean within figure caption.*

**Response:** Done. We have also added these explanations to the main text.

**Comment 2.3.17:** *Fig 2, is it impossible to get forecast SIT below 0.3 m when SIC is low (i.e. when SMOS-SIT is around 0)? Why?*

**Response:** No it is not impossible, see Figure 1 in this response. The apparent gap is due to the filtering applied, where only data points with SIC > 30% are used.

**Comment 2.3.18:** *Fig 3, does (c) show saturation in the SMOS-SIT signal above approximately 0.5 m? Plateaus above this value, so no sensitivity from L-band signal?*

**Response:** It should not be lack of sensitivity, because all data points shown have a SMOS-SIT saturation ratio of below 90% (i.e. the retrieved SIT is 90% of the maximally retrievable SIT under these conditions). However, there could be a conceptual problem with the saturation ratio provided with the SMOS-SIT product.

**Comment 2.3.19:** *Fig 3, doing this for only one years winter enhances the possibility for anomalous ice conditions to explain the departures between observed and predicted IT. What do these look like for multiple years? Your arguments would be more convincing if similar patterns of regional biases were found in several/all years.*

**Response:** We fully agree and have taken this excellent suggestion on board. We have updated Figure 3 to include data from *all* winters, and find that the departure characteristics appear in all years.

**Comment 2.3.20:** *Fig 4, Mark on a map either here or on Fig 1. Adding a panel of SIC would be very useful for analysis.*

**Response:** We have marked the locations in Figure 1 as suggested. The SIC time series is already shown in Figure 5b, we have added a reference to the caption of Figure 4.

**Comment 2.3.21:** *Fig 4, “added and subtracted” what? Uncertainty?*

**Response:** We have added the word “uncertainty” to the caption. Apologies for the omission.

**Comment 2.3.22:** *Fig 5c, why does snow depth appear to drop considerably throughout the season?*

**Response:** It only drops in SMOS-SIT, not in ORAS5. The simple reason for the snow thickness drop in SMOS-SIT is that the retrieval algorithm assumes a snow thickness that is a piecewise linear function of ice thickness (Tian-Kunze et al., 2014). Thus, snow thickness in SMOS-SIT is not an independent parameter. In this case, one might argue that this leads to an unrealistic snow thickness. However, sensitivity of retrieved SIT to snow thickness is relatively small.

**Comment 2.3.23:** *Fig 5e, ice emissivity masked by overlying snow?*

**Response:** Dry snow is transparent in L-band and therefore does not mask the ice emissivity. Snow only enters the SMOS-SIT retrieval algorithm through its thermal insulation qualities: more snow means the ice is better insulated against the cold atmosphere, and bulk ice temperature tends to be higher, which changes the ice emissivity.

**Comment 2.3.24:** *Fig 6, remove “none”.*

**Response:** Fixed.

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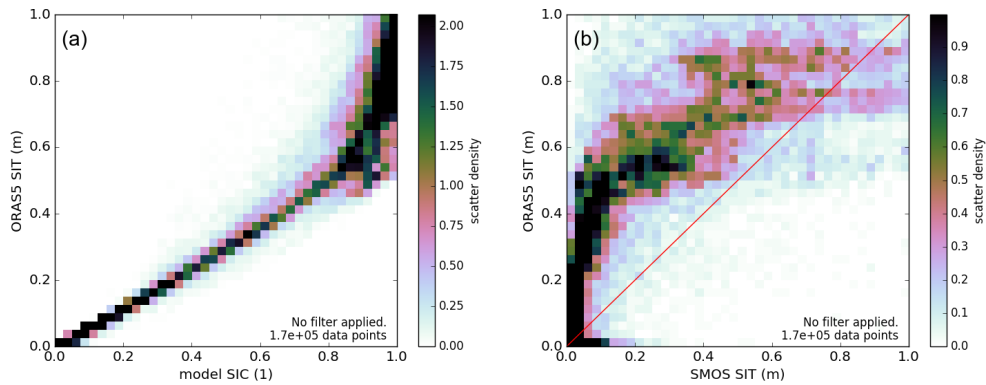


Figure 1: Joint frequency distribution of (a) ORAS5 SIC and SIT and (b) SMOS-SIT and ORAS5 SIT calculated for 15 November 2016 (the date for which the upper row of maps in Figure 1 of the manuscript is shown). All data points with a valid SMOS-SIT value have been considered, no filter was applied.

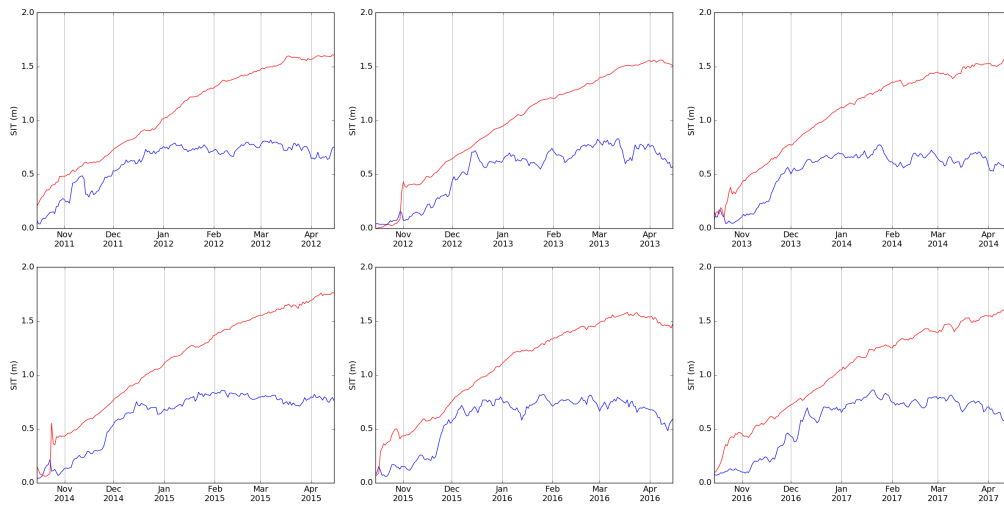


Figure 2: Time series of ice thickness in SMOS-SIT (blue line) and ORAS5 (red line) for the winters 2011/12 to 2016/17. Thickness is calculated from all data points within the box 80W–64W, 67N–75N, which corresponds to the Wester Baffin Bay area as defined in Landy et al. (2017).

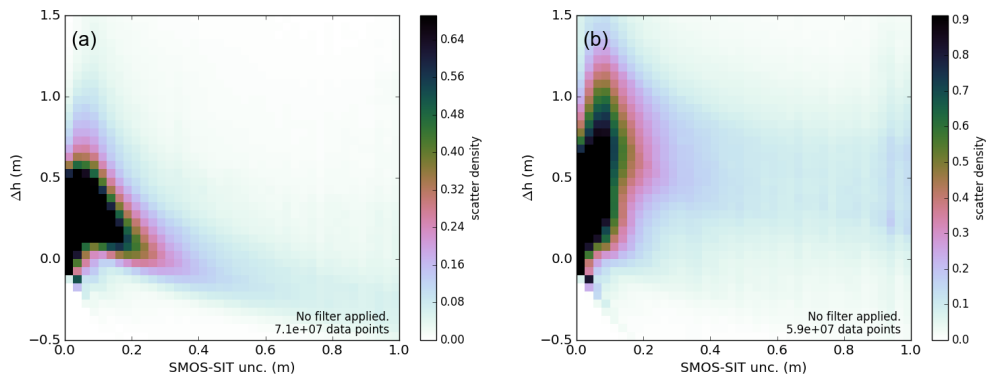


Figure 3: Normalized joint frequency distribution (scatter density) of pairs of SMOS-SIT retrieval uncertainty and SMOS-SIT-ORAS5 departures; (a) October to December 2011–2017, (b) February to April 2012–2017. All data points with a valid SMOS-SIT value have been considered, no filter was applied.

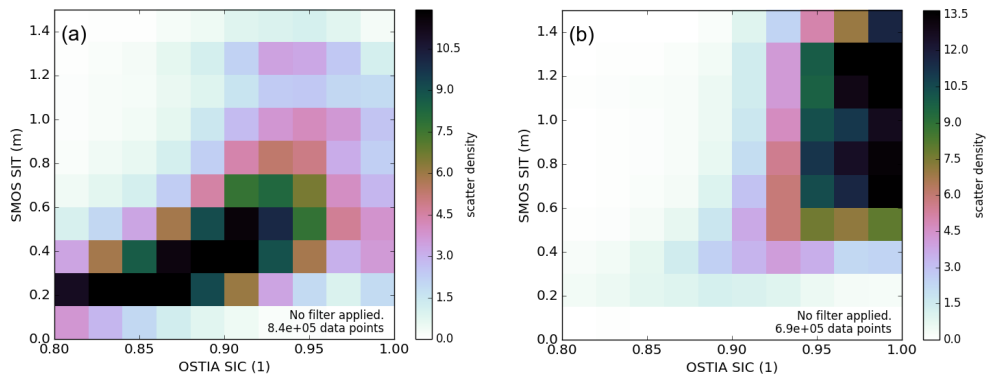


Figure 4: Normalized joint frequency distribution (scatter density) of pairs of OSTIA SIC and SMOS-SIT SIT within the box 80W–64W, 67N–75N (roughly corresponding to the Western Baffin Bay as defined by Landy et al. (2017)); (a) October to December 2011–2017, (b) February to April 2012–2017. All data points with a valid SMOS-SIT value have been considered, no filter was applied.

# Thin Arctic sea ice in [\[..\\* \]L-band \[..† \]observations and an ocean reanalysis](#)

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**Abstract.** L-band radiance measurements [of the Earth's surface](#) such as these from the SMOS satellite can be used to distinguish thin from thick ice under cold surface conditions. However, uncertainties can be large due to assumptions in the forward model that converts brightness temperatures into ice thickness, and due to uncertainties in [\[..<sup>3</sup> \]auxiliary](#) fields which need to be independently modelled or observed. It is therefore advisable to perform a critical assessment with independent observational and model data, before using [\[..<sup>4</sup> \]sea-ice thickness products from L-band radiometry](#) for model validation or data assimilation. Here, we discuss version 3.1 of the University of Hamburg [\[..<sup>5</sup> \]SMOS sea-ice thickness data set \(SMOS-SIT\)](#) from autumn [\[..<sup>6</sup> \]2011 to autumn 2017](#), and compare it to the [\[..<sup>7</sup> \]global ocean reanalysis ORAS5\[..<sup>8</sup> \]](#), which does not assimilate the SMOS-SIT data. ORAS5 currently provides the ocean and sea-ice initial conditions for all coupled weather, monthly and seasonal forecasts issued by ECMWF. It is concluded that SMOS-SIT provides valuable and unique information on thin sea ice during winter, [\[..<sup>9</sup> \]and can under certain conditions be used to expose deficiencies in the reanalysis](#). Overall, there is a promising match between [\[..<sup>10</sup> \]sea-ice thicknesses from ORAS5 and SMOS-SIT](#) early in the freezing season ([\[..<sup>11</sup> \]October–December](#)), while later in winter, sea ice is consistently modelled thicker than observed. This [\[..<sup>12</sup> \]is mostly attributable to refrozen polynyas and fracture zones, which are poorly represented in ORAS5 but well detected by SMOS-SIT](#). However, there are [\[..<sup>13</sup> \]other regions like the Baffin Bay](#), where biases in the observational data seem to

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[..<sup>14</sup>] be substantial, as comparison to independent observational data suggests. [..<sup>15</sup>] Despite considerable uncertainties and discrepancies between thin sea ice [..<sup>16</sup>] in SMOS-SIT [..<sup>17</sup>] and ORAS5 at local scales, interannual variability and trends of [..<sup>18</sup>] its large-scale distribution [..<sup>19</sup>] are in good agreement [..<sup>20</sup>]. This gives some confidence in our current capability to monitor climate variability and change of thin sea ice [..<sup>21</sup>]. With further improvements in retrieval methods, forecast models and data assimilation methods, the huge potential of L-band radiometry to derive the thickness of thin sea ice in winter will be realized and provide an important building block for improved predictions in polar regions.

## 1 Introduction

Sea ice has been regularly observed by satellites since the late 1970s. The [..<sup>22</sup>] observations most widely used in the context of large-scale weather and climate models [..<sup>23</sup>] are passive microwave radiance in the range between 6 and 90 GHz [..<sup>24</sup>]. These observations have continuous daily pan-Arctic coverage at a resolution of [..<sup>25</sup>] 50 km or better. However, because of the very small penetration depth [..<sup>26</sup>] of microwave radiation into sea ice at these frequencies, these observations only provide information about the fraction of an area covered by sea ice, not about its thickness.

Considering the importance of sea-ice thickness for [..<sup>27</sup>] atmosphere–ocean surface heat fluxes, and for predicting the further evolution of the sea-ice cover, information about it is indispensable. Substantial heat conduction occurs through thin sea ice [..<sup>28</sup>] in winter, when the temperature contrast is large between the cold surface atmosphere and the relatively warm ocean water [..<sup>29</sup>] below the ice. Approximate calculations show that surface heat fluxes resulting from heat conduction through thin sea ice can easily reach  $100 \text{ Wm}^{-2}$ . Predicting the evolution of the sea-ice cover days to months ahead also crucially depends on the sea-ice thickness: thin ice will evolve much more quickly than thick ice because it is more susceptible to dispersion or

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<sup>15</sup>removed: Both the reanalysis and the observations are provided with uncertainty estimates. While the reanalysis uncertainty estimates for the thickness of

<sup>16</sup>removed: are probably too small and do not include structural uncertainty of the simulation, these of

<sup>17</sup>removed: are often large, and do not seem to adequately characterise the complex uncertainties of the retrieval model. Therefore, careful and manual assessment of the data when using it for model evaluation and data assimilation is advisable. Interannual

<sup>18</sup>removed: the

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<sup>20</sup>removed: between SMOS-SIT and ORAS5. In summary, SMOS-SIT presents a unique source of information about

<sup>21</sup>removed: in the winter-time Arctic, and its use in sea ice modelling, assimilation and forecasting application is nascent and promising

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compression by winds, and [..<sup>30</sup>] because the larger surface heat fluxes it [..<sup>31</sup>] allows can change the mass of ice much faster.

The thickness of sea ice is much harder to derive from satellite observations than its area coverage, and each of the existing methods has its own strong limitations. Infrared emission measurements of the ice surface temperature (Wang et al., 2010; Yu and Rothrock, 1996; Mäkynen et al., 2013) only work for very thin ice without snow cover, and can only be used [..<sup>32</sup>] under cloud-free conditions. Laser and radar altimetry (Kwok and Cunningham, 2008; Laxon et al., 2013; Ricker et al., 2014) [..<sup>33</sup>] suffer from high measurement noise and narrow foot-prints, and [..<sup>34</sup>] become unfeasible for thicknesses below 0.5 m [..<sup>35</sup>] and in the presence of surface waves. Finally, the thickness of thin sea ice can be derived from L-band microwave radiance measurements (Kaleschke et al., 2012; Tian-Kunze et al., 2014; Mecklenburg et al., 2016) [..<sup>36</sup>]. This method allows daily pan-Arctic coverage for ice thickness of up to [..<sup>37</sup>] 1 m with about 30 km spatial resolution. It requires [..<sup>38</sup>], however, a complex radiative transfer model [..<sup>39</sup>], which means that calculated emissivities can be sensitive to [..<sup>40</sup>] the retrieval assumptions and auxiliary fields used.

[..<sup>41</sup>] Radiance measurements of L-Band brightness temperatures (TB) from space have for the first time become available with ESA's SMOS mission launched in 2009. There is a high sensitivity of L-Band TB to the thickness of thin sea ice, but a reliable retrieval of sea-ice thickness depends on high-quality constraints on the other parameters which the TB are sensitive to – most importantly, sea-ice concentration, and temperature and salinity profiles within the ice (Tian-Kunze et al., 2014). These external data dependencies introduce uncertainties that are often difficult to quantify. For instance, near-surface temperature over Arctic sea ice can vary by several degrees between atmospheric analyses from different centres (Bauer et al., 2016). Moreover, different radiative transfer models exist to calculate the L-band emissivity of a given sea ice slab, and the calculated L-band TB can vary considerably depending on the model chosen (Maaß, 2013; Richter et al., 2018).

For prognostic sea-ice models as included in climate and numerical weather forecasting models, simulating thin sea ice is challenging as well. Although climate models have been including prognostic sea ice for many years, two factors limit their usefulness for investigating thin sea ice. First, sea-ice thickness is often represented in a mono-category approach similar to that in Fichefet and Maqueda (1997), with very simplified treatment of thin sea ice (although in the latest generation of climate models there is a clear trend towards a multi-category approach to simulate ice thickness (Notz

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<sup>41</sup>removed: This study investigates the properties of a level-3 sea icethickness product provided by the University of Hamburg (SMOS-SIT), and compares it with the global ocean-sea ice reanalysis ORAS5 produced by

et al., 2016)). Second, thin-sea-ice features are often short-lived (a few days or less) and local in scale (smaller than 100 km). These temporal and spatial scales are usually not well resolved in climate models, whose output tends to be monthly-mean fields on grids with cell sizes of 100 km or more.

5 Prognostic sea-ice models as included in numerical weather forecasting models are usually run at higher spatial resolution (e.g. around 10-15 km in the Arctic for the setup discussed in this study), and usually their output is analysed based on daily-mean or instantaneous values. Thus, they clearly resolve many of the small-scale, short-lived thin sea ice features. However, they often use the same simplified mono-category approach towards simulating ice thickness, and hence suffer from the same structural problems as the sea-ice component in climate models.

10 These prognostic models are combined with observations using data assimilation, to arrive at the best estimate of the true state, the so-called analysis. If the same system is applied to observations spanning multiple years, it is usually called a re-analysis, a convention which we will follow here. State-of-the-art ocean reanalyses employ prognostic sea-ice models at relatively high spatial resolution as suitable for numerical weather prediction. These ocean reanalyses have many users (see e.g. (Le Traon and Others, 2017)), who might not all have the resources to carry out an assessment how the reanalysis product compares to observations. Such overall assessments of several reanalyses have been carried out  
15 in the past (Balmaseda et al., 2015; Chevallier et al., 2016; Uotila et al., 2018), but have not addressed the specific issue of thin sea ice.

This study aims to provide an overview assessment of agreements and discrepancies of sea-ice thickness between an observational product from L-band radiometry on the one hand, and a ocean reanalysis that does not assimilate these observations on the other hand. This assessment is a first necessary step towards the [..<sup>42</sup>] eventual assimilation of [..<sup>43</sup>  
20 ]these observational data, because large systematic errors in either the observations or the forecast model will make successful data assimilation difficult. Previous studies report overall slightly positive results when assimilating L-band sea-ice thickness observations (Yang et al., 2014; Xie et al., 2016), but without doubting the validity of the observational data. As we will show here, both reanalysis and observations can contain large and systematic errors. We argue that these need to be characterized, understood, and properly treated in any future data assimilation system in order to obtain  
25 an improved estimate of the true sea-ice thickness.

Being an overview assessment, this study provides guidance and inspiration for future research by identifying the characteristic main agreements and discrepancies between sea-ice thickness from L-band retrievals and an ocean reanalysis. We offer plausible hypotheses for the identified discrepancies and are able to verify some of them quantitatively. However, due to the nature of our methods, there are many discrepancies where we cannot offer conclusive evidence of their root  
30 causes. This would require systematic numerical experimentation with the retrieval and reanalysis models, a substantial technical, computational and analytical effort that is beyond the scope of the diagnostic overview study presented here. First steps in this direction have already been taken by Maaß (2013) and Richter et al. (2018), who perform sensitivity

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<sup>42</sup>removed: European Centre for Medium-Range Weather Forecasts (ECMWF). Non-trivial model-observation departures are reported, which change with region, time of the year, and thickness range considered. Routine monitoring of the departures has been implemented at ECMWF, and this investigation is a step towards

<sup>43</sup>removed: the data, although successful assimilation will require further improvements in the model, observation retrievals,

experiments with the retrieval model, and by Zuo et al. (2015) and Shi and Lohmann (2017), who perform sensitivity experiments with the forecast model and data assimilation methods.

The remainder of the paper is structured as follows: we start with a description of the methods used to produce the observational sea-ice thickness product SMOS-SIT in Section 2.1, and the ocean reanalysis system ORAS5 in Section 2.2. The pan-Arctic reanalysis–observation departures are discussed in Section 3, followed by a more detailed discussion of the regional differences in Section 4. Section 5 makes the point that, despite often large reanalysis–observation departures, climate variability and trend of the thin sea-ice area are in broad agreement between reanalysis and observations. A discussion of the results is presented in Section 6, and Section 7 summarizes the main results. More detailed technical information and discussion of the limits of SMOS-SIT can be found in Appendices A–D.

## 2 Model and data

### 2.1 SMOS-SIT sea ice thickness product

Thin sea ice thickness (nominal cut-off at 1.5 m) has been retrieved at the University of Hamburg from L-band brightness temperatures (TB) at 1.4 GHz measured by the MIRAS radiometer on board of SMOS. The retrieval algorithm consists of a thermodynamic sea ice model and a one-ice-layer radiative transfer model (Kaleschke et al., 2012; Tian-Kunze et al., 2014).

The resulting plane layer thickness is multiplied by a correction factor assuming a log-normal thickness distribution (Tian-Kunze et al., 2014). The algorithm has been used for the [..<sup>44</sup>] production of a SMOS-based sea ice thickness data set in polar-stereographic projection in 12.5 km grid resolution from 2010 on (<http://icdc.cen.uni-hamburg.de/1/daten/cryosphere/13c-smos-sit.html>) (Tian-Kunze et al., 2014). In this study, we use the most up-to-date version (v3.1, based on v620 L1C brightness temperatures), which has been produced operationally since October 2016. The v3.1 data for the previous winter seasons had been reprocessed using the same algorithm. [..<sup>45</sup>] In the beginning two years of SMOS operation, the signals were strongly influenced by Radio Frequency Interference (RFI), so we exclude the winter 2010/2011 from our discussion. Previous versions of the algorithm have been described in [..<sup>46</sup>] Kaleschke et al. (2012), Tian-Kunze et al. (2014), and Kaleschke et al. (2016), who also provide comparison to EM-bird measurements, infrared-derived, and modelled sea ice thickness.

Brightness temperature used in the algorithm is the daily mean intensity, which is the average of horizontal and vertical polarization. Over sea ice, the intensity is almost independent of incidence angle. The average over the incidence angles 0–40° is taken, in order to reduce the brightness temperature uncertainty to about 0.5 K. In the [..<sup>47</sup>] algorithms prior to v3.1, RFI contaminated snapshots have been discarded using a threshold value of 300 K, applied either to horizontal or vertical polarization. However, in v3.1 the new quality flags given in the v620 L1C data have been implemented to identify the data contaminated not only by RFI but also by sun, or by geometric effects.

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The retrieval method needs additional auxiliary data as boundary conditions for the thermodynamic as well as the radiation model: bulk ice temperature is estimated from surface air temperature extracted from the JRA-55 atmospheric reanalysis [..<sup>48</sup>](Ebita et al., 2011). Bulk sea-ice salinity is calculated with the methods described in Tian-Kunze et al. (2014) based on a weekly climatology of sea surface salinity from a simulation with the MIT General Circulation Model (Marshall et al., 5 1997) covering the years [..<sup>49</sup> ]2002–2009. Brightness temperatures over sea ice depend on the dielectric properties of the ice layer, which vary with ice temperature and ice salinity (Menashi et al., 1993; Kaleschke et al., 2010, 2012). [..<sup>50</sup> ]The temperature profile within the ice [..<sup>51</sup> ]is assumed to be linear, which is a good approximation for thin ice and slow changes in the meteorological conditions. The retrieval algorithm works only under cold conditions: the presence of surface melting invalidates the retrieval assumptions.

10 Ice thickness retrieval uncertainties are given pixel-wise each day in the data set. There are several factors that cause uncertainties in the sea ice thickness retrieval: the uncertainty of the SMOS [..<sup>52</sup> ]TB, the uncertainties [..<sup>53</sup> ]of the auxiliary data sets, the uncertainties in ice temperature and ice salinity, and the assumptions made for the radiation and thermodynamic models, for example 100% ice coverage. [..<sup>54</sup> ]

15 The uncertainty of daily mean TB is mostly less than 0.5 K, except for the years 2010 and 2011, when, due to RFI problems, the percentage of RFI contaminated TB measurements was relatively high near the coasts of Russia and Greenland. The uncertainties caused by bulk ice temperature and bulk ice salinity depend on the uncertainties of surface air temperature and sea surface salinity, which are the boundary conditions in the retrieval [..<sup>55</sup> ] [..<sup>56</sup> ]. As a first approximation, a sea-ice surface temperature uncertainty of 1 K has been assumed. The uncertainty of sea surface salinity is estimated from standard deviation of an ocean simulation for the years 2002-2009 (Tian-Kunze et al., 2014).

20 In addition to the uncertainty factors discussed above, version 3.1 of SMOS-SIT also considers the uncertainty in the fitted parameter  $\sigma$  of the assumed log-normal distribution for the subgrid-scale sea-ice thickness (Kaleschke et al., 2017). The fit uncertainty is the standard deviation of the natural logarithm  $\ln \sigma$ , and it is derived from six years of NASA OIB airborne observations of ice thickness (Kurtz et al., 2013). The average ice thickness uncertainty from this contribution is less than 0.1 m.

25 The total ice thickness uncertainty provided in SMOS-SIT is the sum of the above-mentioned uncertainties of TB, ice temperature and salinity, and ice thickness distribution function. Errors caused by assumptions on heat fluxes and snow thickness have not yet been included. The radiation model used in the retrieval is a one-layer model. Thus, with this radiative transfer model, it is not possible to discuss the impact of ice temperature and salinity profiles on the ice thickness

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retrieval. Generally, the uncertainty increases with increasing ice thickness. For thinner ice the relationship between ice thickness and ice thickness uncertainty is almost linear. A fit function between ice thickness and ice thickness uncertainty is derived from one winter period of SMOS data. This function is then implemented in the retrieval for the calculation of ice thickness uncertainty.

- 5 In addition to the retrieval uncertainty, the data set contains the so-called saturation ratio for each SMOS pixel, which gives a useful estimate of the sensitivity of SMOS brightness temperature to ice thickness for the values of the auxiliary fields valid for the SMOS pixel. The saturation ratio is defined as the ratio of the retrieved ice thickness to the maximal retrievable ice thickness, which is reached when SMOS brightness temperature changes less than 0.1 K per cm ice thickness change (Tian-Kunze et al., 2014).
- 10 For more detailed technical information and a discussion of the limits of SMOS-SIT please refer to the Appendices. Appendix A shows that there are some substantial differences in the SMOS-SIT data set between the current version 3.1 and the previous version 2.3. In Appendix B, the fundamental limits of retrieving sea-ice thickness from SMOS brightness temperatures are touched upon, and evidence for these limits from the data themselves is presented. Appendix C discusses unrealistic day-to-day fluctuations in retrieved sea-ice thickness, and Appendix D demonstrates that using SMOS-SIT without removing
- 15 high-uncertainty data points can lead to wrong conclusions when studying year-to-year variability of thin sea ice.

## 2.2 ORAS5 sea-ice–ocean reanalysis

The ECMWF ocean reanalysis system 5 (ORAS5) is a state estimate of the global ocean and sea ice from [..<sup>57</sup>]1979 to today, and is being used to provide ocean and sea ice initial conditions for operational forecasts at ECMWF (Zuo et al., 2017).

- 20 The NEMO ocean model version 3.4.1 (Madec, 2008) has been used for ORAS5 in a global configuration with a tripolar grid with a resolution of 1/4 degree at the equator. One of the poles of the grid is located on the Antarctic continent, and the other two are in Central Asia and North Canada. Horizontal resolution in northern high latitudes ranges from less than 5 km (Canadian Archipelago south of Victoria Island) to about 17 km (Bering Sea and Sea of Okhotsk). There are 75 vertical levels, with level spacing increasing from 1 m at the surface to 200 m in the deep ocean.

- 25 ORAS5 contains the dynamic-thermodynamic sea ice model LIM2 (Fichefet and Maqueda, 1997). The sea ice model is run with a viscous-plastic rheology. LIM2 has fractional ice cover, a single ice thickness category (Hibler III, 1979), and calculates vertical heat flux within the ice according to the three-layer Semtner scheme (Semtner, 1976). Snow on sea ice is modelled, but melt ponds are not.

- 30 The single-thickness approach of LIM2 necessitates a very simplified treatment of open-water sea-ice formation: as in Hibler III (1979), a critical ice thickness  $h_0$  is introduced that distinguishes “thin” from “thick” ice. In ORAS5,  $h_0$  is equal to 0.6 m in the Arctic. The critical ice thickness determines how fast the ice concentration increases under freezing conditions, and is therefore also called the lead-close parameter (see Smedsrud and Martin (2015)). In a model grid cell that was previously ice-free, new sea ice forms thermodynamically at a constant actual floe thickness that is equal to  $h_0$ . This is obviously an overly simplistic representation of how sea ice really forms from open water: by formation and solidification

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<sup>57</sup>removed: 1975

of grease ice (Smedsrud and Martin, 2015). This modelling assumption introduces an artificially increased frequency of occurrence of grid-cell mean ice thickness around  $h_0$  under freezing conditions because growth rates for grid-cell mean ice thicknesses below  $h_0$  are over-estimated. New generations of sea-ice models, for instance LIM3 (Vancoppenolle et al., 2009) or CICE5 (Hunke et al., 2015) have a much smaller and state-dependent  $h_0$ , which avoids this problem.

5 Forcing fields for ORAS5 are derived from the atmospheric reanalysis ERA-Interim (Dee et al., 2011) until the end of 2014, and from the operational ECMWF atmospheric analysis from the beginning of 2015 on. Sea surface temperature for years from 2008 on is constrained to observations from the UK Met Office Operational Sea Surface Temperature and Sea Ice Analysis (OSTIA) by a strong restoring term. Assimilation of subsurface ocean temperature and salinity, of sea ice concentration and sea level anomalies is performed using a 3DVar-FGAT procedure (Daget et al., 2008). The length of the data assimilation window  
10 is 5 days.

Sea-ice concentration in ORAS5 is assimilated from the level-4 OSTIA product (Donlon et al., 2012). <sup>[.58]</sup>OSTIA sea-ice concentration is created by interpolating <sup>[.59]</sup>and in-filling the sea-ice concentration product of the EUMETSAT Ocean and Sea Ice Satellite Application Facility (<http://osisaf.met.no/p/ice>) to a global regular grid with 1/20 degree resolution and filling in missing values. The sea-ice concentration assimilation is univariate with no direct impact on the floe ice thickness. However,  
15 grid-cell mean ice thickness <sup>[.60]</sup><sup>[.61]</sup>is directly affected by the assimilation increments (see Tietsche et al. (2013) for details). There is no assimilation of sea-ice thickness observations in ORAS5, so it is completely independent of SMOS-SIT.

ORAS5 consists of five ensemble members which are obtained by perturbing <sup>[.62]</sup>the surface forcing, and by assimilating <sup>[.63]</sup>perturbed observations (see Zuo et al. (2017) for details).

For a full description of the immediate predecessor of ORAS5, see the documentation of ORAP5 in Zuo et al. (2015);  
20 Tietsche et al. (2017). ORAP5 has been found to simulate well the overall ice thickness in the Arctic in comparison with other state-of-the-art ocean reanalyses (Uotila et al., 2018).

### 3 Pan-Arctic reanalysis–observation departures

The SMOS-SIT data <sup>[.64]</sup>provide essential information about sea ice that is complementary to observation of sea ice concentration <sup>[.65]</sup>using higher-frequency passive microwave channels. To illustrate that, Figure 1 shows SMOS-SIT sea-ice  
25 thickness together with observed sea-ice concentration from the OSTIA product for a day early in the freezing season, and for a day late in the freezing season. Please not that here and elsewhere, sea-ice thickness denotes the grid-cell mean sea-ice thickness for both SMOS-SIT and ORAS5. Early in the freezing season, there are large areas of newly-formed sea ice that

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<sup>58</sup>removed: Sea-ice concentration in OSTIA

<sup>59</sup>removed: the OSI-SAF sea ice products

<sup>60</sup>removed: (i.e.

<sup>61</sup>removed: ice volume per area) is directly impacted

<sup>62</sup>removed: forcing fields according to uncertainties derived from inter-product differences

<sup>63</sup>removed: observations that were sampled in a slightly different way for each ensemble member

<sup>64</sup>removed: provides

<sup>65</sup>removed: by

is thin. Figure 1(a) shows that [sea ice thickness of 0.6 – 0.7 m dominates](#) in the Beaufort and Chukchi Seas, as well as [\[.66\]](#) part of the [central](#) Arctic Ocean adjacent to them [\[.67\]](#). In the Baffin Bay, sea ice thickness from SMOS-SIT is even thinner, at around 0.2 – 0.3 m. All these regions exhibit [\[.68\]](#) sea-ice [\[.69\]](#) concentrations of virtually 100% (Figure 1b) [\[.70\]](#), which demonstrates that sea-ice concentration [\[.71\]](#) observational products like OSTIA can not be used to [\[.72\]](#) distinguish areas with thin new sea ice from areas of old thick sea ice; sea-ice thickness observational products like SMOS-SIT are needed to do that.

[Figure 1 about here.]

Sea-ice thickness in ORAS5 in early winter is comparable with that of SMOS-SIT (Figure 1c). However, the model tends to simulate thicker ice on average. Note that the departures in Figures 1c,f are only shown for SMOS-SIT data points with a saturation ratio less than 90% and total retrieval uncertainty of less than 1 m (see Section 2.1 for definitions of these). Positive departures dominate, especially close to regions of thick ice. There are a few places in the Beaufort and the Siberian Shelf Seas with negative departures, but in most of the thin-ice areas ORAS5 simulates ice around 0.4 m thicker than retrieved by SMOS-SIT. [\[.73\]](#) [\[.74\]](#)

As the freezing season progresses, the ice edge moves further south outside of the Arctic Basin, and previously formed thin ice in the Arctic Basin becomes thicker. Polynyas and fracture zones begin to form. [These re-freeze very quickly, which is evident by the near-100% sea-ice concentration but greatly reduced sea-ice thickness in these features.](#) Figure 1(d) shows [\[.75\]](#) extensive refrozen polynyas in the Kara and Laptev Seas, as well as a fracture zone covering the whole Beaufort Sea. In the Baffin Bay, sea-ice thickness derived by SMOS-SIT is mostly below 0.3 m. Again, none of these features within the ice pack are picked up by the sea-ice OSTIA concentration product, which shows homogeneously high ice concentration throughout the ice pack (Figure 1e).

The departures between ORAS5 and SMOS-SIT in late winter are large and positive throughout (Figure 1 [\[.76\]](#) f), with values of 1m or more dominating. Most of this is [\[.77\]](#) due to the [\[.78\]](#) failure of the reanalysis to simulate relevant features like the

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<sup>66</sup>removed: the

<sup>67</sup>removed: , sea ice thickness of 0.6 – 0.7 m dominates

<sup>68</sup>removed: high

<sup>69</sup>removed: concentration of above 90

<sup>70</sup>removed: . Thus, the OSTIA

<sup>71</sup>removed: product

<sup>72</sup>removed: differentiate them from the areas of older ice in the Central Arctic

<sup>73</sup>removed: Part of the reason for this might be the simplified representation of thin ice in ORAS5, which tends to drive modelled sea-ice thickness towards 0.6

<sup>74</sup>removed: m during the freeze-up, as can be seen in Figure 8 (see also discussion in Tietsche et al. (2014)). At the same time, ice thickness in SMOS-SIT is calculated under the assumption of 100% sea ice concentration; under the presence of only partial ice cover the SMOS-SIT ice thickness are known to be biased thin (Tian-Kunze et al., 2014).

<sup>75</sup>removed: large

<sup>76</sup>removed: (f)

<sup>77</sup>removed: likely

<sup>78</sup>removed: model being unable

refrozen coastal polynya in the Laptev Sea, or [..<sup>79</sup>]refrozen fracture zones like the one visible in the SMOS-SIT data for the Beaufort Sea. [..<sup>80</sup>]

There are multiple plausible reasons for the poor representation of refrozen polynyas and fracture zones in the reanalysis: various deficiencies in the ocean and sea-ice models (e.g. too thick ice, inappropriate rheology, insufficient modelling of open-water ice growth, too strong upper-ocean stratification), the data assimilation methods (e.g. inappropriate background error covariance between ice concentration and ice volume), or deficiencies in the atmospheric forcing (e.g. too weak off-shore winds). Further investigation of this reanalysis deficit is clearly needed, but for the most part this requires dedicated experimentation and is therefore out of the scope of this study. However, it can be said that there are conspicuous features in maps of sea-ice concentration increments (not shown), which directly affect grid-cell mean ice thickness through implied ice volume increments as discussed by Tietsche et al. (2013). For the day in question, 15 April 2016, the sea-ice concentration increments are large and positive in the refrozen polynyas and fracture zones. This would suggest that the model dynamics tend to produce the features, but the assimilation increments suppress them in the reanalysis.

In the Barents Sea there is good agreement between ORAS5 and SMOS-SIT, with a positive departure of 20 cm or less. Finally, the Baffin Bay stands out as having extensive thin ice cover in SMOS-SIT, but thick ice in ORAS5. The [..<sup>81</sup>]North Water Polynya at the northern end of Baffin Bay is captured both by SMOS-SIT and ORAS5.

The previous example maps show typical conditions in early and late winter, and typical departures between ORAS5 and SMOS-SIT. For a more quantitative assessment, we calculate departures for [..<sup>82</sup>]co-located daily sea-ice thickness [..<sup>83</sup>] in (a) the early-winter period 15 October to 15 [..<sup>84</sup>] December for the years 2011–2017, and (b) the late-winter period 15 [..<sup>85</sup>] February to 15 [..<sup>86</sup>] April for the years 2012–2017. We exclude data points where the SMOS-SIT retrieval is known to be unreliable: data points with a retrieval uncertainty of more than 1 m, a saturation ratio of above 90%, or a sea-ice concentration below 30% are not considered (see Section 2.1 for explanations of retrieval uncertainty and saturation ratio).

From these co-located pairs of observed and modelled daily sea-ice thicknesses we calculate the normalized bivariate joint frequency distribution, which we will call *scatter density* in the following for the sake of brevity. Scatter density plots give a quite complete picture of the departure statistics. For a good match, density should be high on the one-to-one line and low elsewhere. High density above the one-to-one line indicates positive bias, high density below the one-to-one line indicates negative bias. Conditional departure characteristics e.g. for a certain range of observed values can also easily be derived visually.

[Figure 2 about here.]

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<sup>79</sup>removed: fraction

<sup>80</sup>removed: Interestingly, in the

<sup>81</sup>removed: well-known polynya

<sup>82</sup>removed: collocated

<sup>83</sup>removed: for each day in

<sup>84</sup>removed: December 2015, and for each day in

<sup>85</sup>removed: February 2016

<sup>86</sup>removed: April 2016. The scatter density of the resulting set of observation-analysis pairs is shown in Figure 2.



As can be seen from the scatter density in Figure 2a, in early winter the agreement between SMOS-SIT and ORAS5 sea ice thickness is quite promising [..<sup>87</sup>] as the distribution is close to the one-to-one line. However, the overestimation of sea-ice thickness by ORAS5, which was already visually apparent from the maps in Figure 1, is confirmed. For observed sea-ice thickness between 0 and 0.3 m, ORAS5 sea-ice thickness is about 0.3 m higher. The agreement becomes better for higher  
5 observed sea-ice thickness in the range 0.5-1 m. Note that the scatter density distribution has wide tails [..<sup>88</sup>]. For instance, for an ice thickness of 0.4 m in SMOS-SIT, ORAS5 [..<sup>89</sup>] values of up to 1.5 m exist. This is not so obvious in the scatter density, but is clearly visible in the corresponding scatter plot that tends to highlight outlier data points (not shown). [..<sup>90</sup>]

Part of the reason for ORAS5 having higher ice thickness than SMOS-SIT early in the freezing season is the [..<sup>91</sup>] simplified representation of thin ice in LIM2, the sea-ice component of ORAS5 (see Section 2.2): thermodynamic formation of  
10 new ice in LIM2 happens at a fixed actual (floe) thickness of 0.6 m, a value that has been chosen to approximate growth processes in the presence of thick sea ice (Hibler III, 1979). Quite obviously, this is not a good representation of how sea ice forms from open water, which is the dominant regime at the ice edge early in the freezing season. As can be seen in Figure 8c, the simplified LIM2 treatment of thin sea ice leads to an artificially high frequency of occurrence of grid-cell mean ice thickness around 0.6 m, because ice growth rates are artificially enhanced for grid-cell mean ice thicknesses  
15 below that value (see Mellor and Kantha (1989), Tietsche et al. (2017) and Shi and Lohmann (2017) for further discussion on this).

A second reason for higher ice thickness in ORAS5 than SMOS-SIT early in the freezing season is that SMOS-SIT retrieves sea-ice thickness under the assumption of 100% sea ice concentration. If the area captured by a SMOS pixel has only partial ice cover, the SMOS-SIT ice thickness retrieval is biased thin (Tian-Kunze et al., 2014). As can be seen from  
20 Figure 9b, there is an almost perfect linear relationship between SMOS TB and sea-ice concentration for intermediate sea-ice concentration values, which clearly indicates that geometrical averaging of open-water and sea-ice emissivity within a SMOS pixel is playing a role. When excluding data points from Figure 2a where sea-ice concentration is below 95% (not shown), the scatter density conditional on SMOS-SIT thickness being below 0.2 m is almost zero, which is good indication that all thickness retrievals at least up to this thickness are likely to be biased low due to neglecting the  
25 open-water contribution to L-band emissivity.

In late winter, ORAS5 has much higher sea-ice thickness than SMOS-SIT (Figure 2b). Departures between 0.5m and 1m are common throughout the SMOS-SIT thickness range of [..<sup>92</sup>] 0–1m. There is a more linear shape of the scatter density distribution – this is promising in principle, but could result from compensating errors in different regions, which would make

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<sup>87</sup>removed: . The distribution is roughly along

<sup>88</sup>removed: in the ORAS5-SIT

<sup>89</sup>removed: SIT

<sup>90</sup>removed: It is worth noting the curved shape of

<sup>91</sup>removed: scatter density distribution, which highlights the non-linear dependence of typical analysis-observation departures on the thickness range observed.

<sup>92</sup>removed: 0-1m

the relationship less relevant. The scatter distribution is also much wider than for [..<sup>93</sup> ]early winter, indicating larger and more uncertain [..<sup>94</sup> ]

reanalysis–observation differences. The larger discrepancy in later winter has several causes. Figure 1([..<sup>95</sup> ]d-f) illustrate the most obvious one: the [..<sup>96</sup> ]ocean reanalysis does not simulate polynyas and fracture zones well. But there are other  
5 causes, some of which are related to the properties of SMOS-SIT data. In the following Section, we [..<sup>97</sup> ]analyse the late-winter departures in more detail.

#### 4 Regional contrasts

There is considerable regional dependence of the departures in late winter (February to April). Figure 3 shows the SMOS-SIT/ORAS5 scatter density as in Figure 2b), but for three key regions separately: the Barents and Kara Seas, the Laptev Sea,  
10 and the Baffin Bay.

For the Barents and Kara Seas (Figure 3a), the departure statistics are almost as good as for the pan-Arctic in early winter (Figure 2a). We can conclude that this region has relatively good agreement between ORAS5 and SMOS-SIT sea ice thickness throughout the winter.

In the Laptev Sea (Figure 3b), ORAS5 has no ice thickness below [..<sup>98</sup> ]1 m, whereas SMOS-SIT detects a lot of ice thinner  
15 than [..<sup>99</sup> ]1 m. There is [..<sup>100</sup> ]a very low correlation between ORAS5 and SMOS-SIT ice thickness[..<sup>101</sup> ]. This behaviour is consistent with our earlier assessment that refrozen polynyas do occur frequently in the Laptev sea in late winter, and that they are detected by SMOS-SIT but not well represented in ORAS5.

Finally, Figure 3c shows the late-winter scatter density for the Baffin Bay, which again has characteristics that are very different from the other two regions. In general, ORAS5 simulates much thicker ice than retrieved by SMOS-SIT, but in  
20 contrast to the Laptev-Sea case, there is a quite [..<sup>102</sup> ]high rank correlation between SMOS-SIT and ORAS5[..<sup>103</sup> ], i.e. higher SMOS-SIT values are often associated with higher ORAS5 values but the correspondence is not necessary linear. This suggests systematic rather than random sources for the departures[..<sup>104</sup> ].

[Figure 3 about here.]

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<sup>93</sup>removed: early-winter

<sup>94</sup>removed: analysis-observation differences.

<sup>95</sup>removed: c-f

<sup>96</sup>removed: numerical sea-ice model

<sup>97</sup>removed: analyze

<sup>98</sup>removed: 1m

<sup>99</sup>removed: 1m

<sup>100</sup>removed: hardly any

<sup>101</sup>removed: , as the features of the scatter density are mostly horizontal

<sup>102</sup>removed: well-defined concave downwards functional relationship

<sup>103</sup>removed: . This signals

<sup>104</sup>removed: , and would in principle allow for a successfully bias correction when mapping model equivalent to observations

An interpretation of the results in Figure 3 needs to start from the appreciation that the regions shown have quite different physical characteristics: in the Barents and Kara Seas, sea ice is strongly affected by warm Atlantic water being advected towards and under the ice, **which means the ice cover is constrained by SST**. At the same time, prevailing winds modulate the location of the ice edge by transporting the ice. Both processes are expected to be reasonably well simulated by ORAS5, because winds are prescribed as forcing, and the SST are ingested from an observational product. From the observational side, most of the calibration and validation campaigns for SMOS-SIT have been carried out in this area <sup>[..<sup>105</sup> ]</sup>(Kaleschke et al., 2016). Thus, the Barents and Kara Seas can be expected to be the region where the <sup>[..<sup>106</sup> ]</sup>**reanalysis-observation** agreement is best.

In the Laptev Sea, **sea** ice is still relatively well observed when it comes to SMOS-SIT validation, but it is more difficult to simulate in ORAS5. Because there is no ice edge in the Laptev Sea, SST information cannot be used to constrain the ice cover. Furthermore, as clearly visible in Figure 1, extensive polynyas form there in <sup>[..<sup>107</sup> ]</sup>**February to April**, mainly when offshore winds push back the ice from land or land-fast sea ice. These processes are not well simulated by the <sup>[..<sup>108</sup> ]</sup>**reanalysis**, which tends to keep a compact thick sea ice cover even in the presence of offshore winds. As a result, major departures can be expected.

<sup>[..<sup>109</sup> ]</sup>In the Baffin Bay, the occurrence of thinner ice of varying thickness is modelled and observed, but the modelled ice is roughly twice as thick. There is independent information that suggests that SMOS ice thickness is biased low there (see <sup>[..<sup>110</sup> ]</sup>Laxon et al. (2013); Landy et al. (2017); Tilling et al. (2015)). CryoSat2 estimates (<sup>[..<sup>111</sup> ]</sup><http://www.cpom.ucl.ac.uk/csopr/seaice.html>) indicate that between February and April, the ice in this region is typically 1.5 m thick. This is confirmed by independent expert judgement by ice <sup>[..<sup>112</sup> ]</sup>analysts, who estimate that ice in this region and this season would typically be at least 1m thick (Nick Hughes, personal communication).

To further illustrate and consolidate the findings from Figure 3, we plot time series for two representative locations in the Laptev Sea and the Baffin Bay in Figure 4. Both show the typical behaviour of <sup>[..<sup>113</sup> ]</sup>**reanalysis–observation** departures: SMOS-SIT <sup>[..<sup>114</sup> ]</sup>and ORAS5 <sup>[..<sup>115</sup> ]</sup>match well early in winter, but later on <sup>[..<sup>116</sup> ]</sup>**ORAS5** ice keeps getting thicker while SMOS-SIT thickness saturates, albeit with some strong fluctuations. We choose to present a full freezing season in the winter 2011/2012, because this allows <sup>[..<sup>117</sup> ]</sup>**co-location with** independent data in both locations. For the Laptev Sea (Figure 4a),

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<sup>105</sup>removed: Kaleschke et al. (2016)

<sup>106</sup>removed: analysis-observation

<sup>107</sup>removed: Feb-Apr

<sup>108</sup>removed: sea-ice model

<sup>109</sup>removed: Finally, in

<sup>110</sup>removed: also Landy et al. (2017)

<sup>111</sup>removed: Laxon et al. (2013),

<sup>112</sup>removed: chart

<sup>113</sup>removed: analysis-observation

<sup>114</sup>removed: observations

<sup>115</sup>removed: simulation

<sup>116</sup>removed: the analyzed

<sup>117</sup>removed: collocation with some

there was <sup>[.118]</sup> a campaign in April that measured the ice thickness using a so-called EM-bird<sup>[.119]</sup>. This measurement method has demonstrated uncertainties of less than 0.1 m (Haas et al., 2009), hence we can use it as the “ground truth” to benchmark remote sensing observations and reanalysis results. The EM-bird measurement confirms that the ice was indeed only about 0.5 m thick, which indicates the presence of new thin ice in the <sup>[.120]</sup>Laptev-Sea Polynya (Tian-Kunze et al., 2014). The <sup>[.121]</sup>reanalysis is not able to simulate that. The CryoSat2 estimate for this location is around 1m averaged over March <sup>[.122]</sup>and April, halfway between ORAS5 and SMOS-SIT.

For a representative location in the Baffin Bay (Figure 4b), there is reasonable match between <sup>[.123]</sup>reanalysis and observations until January. After that, the sea ice in <sup>[.124]</sup>ORAS5 keeps growing to reach thicknesses of 1.5 <sup>[.125]</sup>– 2 m in mid-April, whereas SMOS-SIT observations level off between 0.5 and 1m until mid-April. The CryoSat2 estimate for this location and averaged over March/April 2012 is 1.8m. This behaviour is generic: it occurs in all years, and also when considering an area average over the Western Baffin Bay as defined by Landy et al. (2017)

When judging compatibility of observational and model-based estimates of sea ice thickness, their uncertainties should be taken into account. The available uncertainty estimates are indicated in Figure 4 in the form of five perturbed ensemble members of the ORAS5 reanalysis, and in the form of lower and upper bounds of the SMOS-SIT uncertainty estimate provided with the data set. The estimated ORAS5 uncertainty is very small – well below 0.3 m most of the time. It is almost certainly too small, as it does not account for structural uncertainty in the model and data assimilation methods. By contrast, the SMOS-SIT uncertainty range (see Section 2.1) is very variable, and often very large. Sometimes it covers the whole range of fathomable values; sometimes it is small, but independent evidence suggests that the truth lies far outside the uncertainty range provided. An example of the former case is the SMOS-SIT ice thickness in the Laptev Sea (Figure 4a) in February: the retrieved value is 1.2 m, but the uncertainty range goes from 0m to more than 2m. An example for the latter case is the SMOS-SIT ice thickness in the Baffin Bay in April 2012 (Figure 4b): the retrieved value is 0.5 m with an uncertainty estimate of only 0.1 m. As argued before, the true sea ice thickness was very likely much higher than that.

[Figure 4 about here.]

Given that ORAS5, CryoSat2, and expert judgement agree that sea ice in the Baffin Bay in this time of the year should be considerably thicker than SMOS-derived thicknesses, we tentatively suggest that there is a problem with the retrieval assumption of SMOS-SIT in this region. From Figures 5 (a),(e) it can be seen that the slight decrease in SMOS TB from February onwards

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<sup>118</sup>removed: an

<sup>119</sup>removed: overflight in April , confirming

<sup>120</sup>removed: well-known

<sup>121</sup>removed: model

<sup>122</sup>removed: /

<sup>123</sup>removed: analysis

<sup>124</sup>removed: the analysis

<sup>125</sup>removed: - 2m

is interpreted as a <sup>126</sup>strong decrease in retrieved sea-ice thickness in SMOS-SIT, in disagreement with the ORAS5 <sup>127</sup>reanalysis and independent observations.

A sea ice concentration slightly below 100% <sup>128</sup>(Figure 5b) might also play a role: For the high SMOS TB typical of late-winter conditions in the Baffin Bay, even a few percent of open water within the SMOS footprint will lower TB significantly by geometrical averaging (note that differences of open-water fraction of a few percent are difficult if not impossible to observe reliably (Ivanova et al., 2015)). The assumption of 100% sea-ice cover made by SMOS-SIT will then lead to a thickness retrieval that is biased low. The scatter density of OSTIA sea-ice concentration versus SMOS-SIT sea-ice thickness for the Western Baffin Bay in late winter (not shown) shows moderate correlation between the two, i.e. there was open water present and it was usually associated with lower ice thicknesses in the SMOS-SIT retrievals. This is an indication – but not proof – that SMOS-SIT might systematically underestimate ice thickness in the Baffin Bay because of non-negligible amounts of open water. <sup>129</sup>

<sup>130</sup>Sea-ice surface temperature (Figure 5d) is <sup>131</sup>almost always colder in ORAS5 than in SMOS-SIT. This is <sup>132</sup>consistent with the ice being thicker in ORAS5 than in SMOS-SIT: the thicker the ice, the smaller the surface heating by conductive heat flux from the relatively warm ocean water below the ice to the relatively cold surface of the ice. However, different <sup>133</sup>near-surface temperatures in the two reanalyses used (<sup>134</sup>JRA-55 and ERA-Interim,) might also play a role (see Bauer et al. (2016)), because they will have a direct impact on the implied sea-ice bulk temperature. Note that there is an apparent artefact in the ice surface temperature in the SMOS-SIT product: it has a constant value of around -4°C for extended periods in November and December. Differences in snow thicknesses (Figure 5c) mirror differences in the ice thickness, because SMOS-SIT assumes an empirical piecewise linear relationship between the two (Tian-Kunze et al., 2014). <sup>135</sup>Furthermore, sensitivity studies by Maaß (2013) suggest that the decrease in TB could be the result of the sea ice becoming fresher at a different rate than assumed by the empirical rate assumed by SMOS-SIT. Testing <sup>136</sup>all these hypothesis in detail is beyond the scope of this paper, because neither does SMOS-SIT deliver the assumed sea ice salinity as part of the data product, nor does the ORAS5 sea ice model have a good treatment of ice salinity. Further investigation should be undertaken, and we suggest that the assumed sea ice salinity be made part of the SMOS-SIT data product.

25 \_\_\_\_\_ [Figure 5 about here.]

<sup>126</sup>removed: slight decrease in SIT by

<sup>127</sup>removed: analysis. Sea ice concentration is unlikely to play a role, as it is close to

<sup>128</sup>removed: in both model and observations

<sup>129</sup>removed: There was a considerable and varying amount of radio-frequency interference (Figure 5f) , but it seems that its impact is successfully removed by the processing chain when calculating the brightness temperatures.

<sup>130</sup>removed: Surface

<sup>131</sup>removed: consistently

<sup>132</sup>removed: linked with the thicker ice which reduces conductive heat fluxes through the ice that warm the surface

<sup>133</sup>removed: meteorological conditions

<sup>134</sup>removed: JRA-25

<sup>135</sup>removed: Perhaps more importantly than all previous considerations

<sup>136</sup>removed: this hypothesis

## 5 Interannual variability

Despite the uncertainties at a local scale discussed in the previous sections, there is good agreement in the large-scale distribution of thin sea ice and its interannual variability. Figure 6 shows time series of the area covered by sea ice with thickness above various thresholds in November from 2011 to <sup>[..<sup>137</sup>]</sup>2017. The uppermost curve is the area of sea ice with at least 0.1 m thickness. The 0.1 m curve corresponds quite well to the NSIDC sea ice extent if the observational gap around the North Pole is taken into account. The lowermost curve is the area of sea ice with at least 0.9 m thickness.

<sup>[..<sup>138</sup>]</sup>The overall magnitude, variability and trend of the area <sup>[..<sup>139</sup>]</sup>for the various ice thickness thresholds generally agree quite well between ORAS5 and <sup>[..<sup>140</sup>]</sup>SMOS-SIT. The extreme summer minimum in 2012 is visible as reduced sea ice area in November for all thickness classes. In 2013, there was a marked recovery. Since then, there has been a downward trend in all classes<sup>[..<sup>141</sup>]</sup>, with a small uptick in November 2017. Importantly, this indicates that the well-established summer sea ice decline in recent years has started to affect the winter-time state. These signals of interannual variability are in good agreement with ice volume estimates derived from CryoSat2 radar altimetry (Tilling et al., 2015).

It is important to recall that, in the thickness range 0.9 m and above, SMOS-SIT <sup>[..<sup>142</sup>]</sup>relies heavily on auxiliary fields to retrieve the sea-ice thickness from SMOS brightness temperature. To produce Figure 6 it was necessary to consider all SMOS-SIT data points, even those with high uncertainty and/or saturation ratio close to 100%. As shown in Appendix D, the resulting maps and scatter densities are not realistic, and one should be cautious when interpreting the lowermost curve in Figure 6a. Nevertheless, it is encouraging to see that overall the same interannual variability and trends of thin sea ice area are derived from ORAS5 and SMOS-SIT.

[Figure 6 about here.]

Interannual variability and trends for sea ice in the Arctic do not occur <sup>[..<sup>143</sup>]</sup>in synchrony in different regions. Figure 6 shows November conditions, when sea ice is present not only in the central Arctic Ocean, but also in the adjacent Seas, in the Canadian Archipelago, The Baffin Bay, Labrador Sea and the Hudson Bay. All these regions are exposed to regional climate variability and change that is not necessarily aligned: the Barents, Kara and Laptev Seas are heavily influenced by the North Atlantic inflow. In the East Siberian, Chukchi and Beaufort Seas the role of the North Atlantic diminishes, and other processes related to the Siberian High and <sup>[..<sup>144</sup>]</sup>Pacific climate are more important.

In the East Siberian, Chukchi, and Beaufort Seas (Figure 7a,b), interannual variability of area cover is higher for thicker ice than it is for thinner ice. This feature is detected by both SMOS-SIT and ORAS5; it is more pronounced in ORAS5, where

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<sup>137</sup>removed: 2016. the

<sup>138</sup>removed: There is generally good agreement between the

<sup>139</sup>removed: of the various thickness classes as simulated by

<sup>140</sup>removed: observed by SMOS

<sup>141</sup>removed: .

<sup>142</sup>removed: heavily relies

<sup>143</sup>removed: homogeneously

<sup>144</sup>removed: inflow Pacific climate become

the area covered by ice thicker than 0.7 m more than doubled between 2012 and 2013, and [..<sup>145</sup> ]then decreased in each subsequent to reach the same level as 2012 in 2016.

The Barents, Kara and Laptev Seas (Figure 7c,d), also exhibit a strongly reduced area coverage in 2012 for all thickness categories. However, ice cover continued to increase until 2014, by which time the area covered was almost twice as high as  
5 2012 in some categories. The unusually high area cover in 2014 might at least in parts be due to an unusual circulation in autumn 2014: anomalously high pressure over Scandinavia combined with low pressure over Siberia in September-November led to anomalous high northerly components in the winds in these seas, which would have both encouraged thermodynamic ice growth and spreading of the ice by advection.

Another interesting feature in the Barents, Kara, and Laptev Seas is the increasing area of ice thicker than 0.9 m simulated  
10 by ORAS5. The year-to-year changes in thicker ice area as seen by SMOS-SIT are very different, but we would advise caution when interpreting the SMOS-SIT time series for these thicker ice categories for the reasons detailed in Appendix D.

Finally, in Canadian waters, the Baffin Bay, and the Labrador Sea (Figure 7e,f), no decrease in ice area for any category is detected, neither by SMOS-SIT nor by ORAS5. Relative year-to-year variations in ice area also tend to be much smaller than in the other two areas.

15 The consistency in the time series presented in this section demonstrates that large-scale variability and trend of thin sea ice early in the freezing season can be monitored by both SMOS-SIT and ORAS5 with relative confidence. Both products indicate that year-to-year variability in the pan-Arctic area of thin sea ice is currently strong enough to mask any expected negative trend, and that different regions show distinct –even opposed– variability and trends. These can be related to specific regional anomalies in atmospheric circulation and surface conditions for any given year.

20 [Figure 7 about here.]

## 6 Discussion

In light of the previously discussed shortcomings and uncertainties both in the current version of the SMOS-SIT data and the current version of the [..<sup>146</sup> ]ocean reanalysis, we suggest to proceed with caution. It is clear that there is a generic trend for analysed sea ice to be thicker than what is retrieved from SMOS. Indications are that both problems in the model and in the  
25 observations contribute to this.

On the model side, [..<sup>147</sup> ]an overly simplistic treatment of open-water sea-ice growth (see Sections 2.2 and 3 and Smedsrud and Martin (2015)) leads to overestimation of ice thicknesses during freeze-up season ([..<sup>148</sup> ]October–December). Later in winter, the [..<sup>149</sup> ]reanalysis is mostly incapable of simulating the polynyas and fracture zones present in the interior of the ice pack.

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<sup>145</sup>removed: than

<sup>146</sup>removed: ECMWF sea ice model

<sup>147</sup>removed: the lack of ice thickness categories in combination with an artificial threshold of minimum ice thickness while freezing

<sup>148</sup>removed: October-December

<sup>149</sup>removed: model

On the observational side, low sensitivity of the SMOS brightness temperatures for ice thicknesses larger than 0.5 m is compensated in the SMOS-SIT retrieval algorithm by heavily relying on auxiliary fields from external sources, such as 2 m temperature and winds, sea ice salinity, and snow thickness on sea ice. These have considerable and poorly quantified uncertainties associated with them (e.g. Bauer et al. (2016)), which reflects in uncertainty in the retrieved ice thickness. For ice

5 thicknesses below 0.5 m, the assumption of 100% sea-ice concentration becomes questionable.

The previous example illustrates that [..<sup>150</sup>]reanalysis–observation departures have several distinct root causes, and future data assimilation studies using SMOS should treat each of the following scenarios differently:

1. The model over- or underestimates large-scale ice thickness in the areas of first-year ice. Typical is an overestimation in [..<sup>151</sup>]October–December in the Arctic Shelf Seas. Sea-ice thickness as derived by SMOS is within the range of

10 the unconstrained sea-ice model, so that data assimilation will unequivocally provide a better estimate of the truth than model or observations alone.

2. SMOS-SIT systematically underestimates ice thickness. We argue that this typically occurs in the Baffin Bay and Labrador Sea during late winter. Assimilating SMOS-SIT data here would deteriorate the simulated state. We would argue that the quality of the observational product in this region needs to be improved before using it for data assimila-

15 tion.

3. SMOS-SIT detects the presence of thin ice in fracture zones and polynyas, but [..<sup>152</sup>]there are fundamental structural deficits in the reanalysis (see discussion in Section 3) that prevent it from simulating these. Here, SMOS-SIT can contribute to model validation and improvement. Assimilating SMOS-SIT data would lead to a better state estimate, but would force the model outside the range of states it would normally occupy. Assimilation is probably beneficial to arrive

20 at better state estimates and initial conditions, but investigation is needed to ensure no undesired unphysical side-effects are triggered during the assimilation.

With further progress in the retrieval algorithms and the modelling for thin sea ice, the distinction between the above three departure scenario might become obsolete, and [..<sup>153</sup>]unqualified use of the data for model validation and data assimilation will become possible, without the need for manual intervention and interpretation. Until then, we suggest to use SMOS-SIT

25 data as a means of detecting the presence of thin sea ice, and design data assimilation studies with the above three departure scenarios in mind.

## 7 Summary and Conclusions

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<sup>150</sup>removed: analysis-observation departures have different fundamental reasons

<sup>151</sup>removed: October-December

<sup>152</sup>removed: the model has structural limitations

<sup>153</sup>removed: direct,



[..<sup>154</sup> ]

In this study, we carry out an overall assessment of agreement and discrepancies between SMOS-SIT, an observational product of sea-ice thickness derived from L-band radiances, and ORAS5, an ocean reanalysis that does not assimilate the SMOS-SIT data. We start from the premise that neither the observational product nor the reanalysis can be unequivocally trusted to be closer to the truth, because both of them contain systematic errors that are dependent on the region and feature under consideration. Thus, a careful overall assessment of agreements and discrepancies is advisable before using the observational data routinely for model validation, data assimilation, and forecast verification.

[..<sup>155</sup> ] We find that SMOS-SIT [..<sup>156</sup> ] and ORAS5 are broadly consistent in distinguishing between areas of newly-formed thin sea ice and areas of old thick sea-ice early in the freezing season. This is true regarding the spatial distribution, but also regarding regional and pan-Arctic interannual variability and trends. However, in terms of reanalysis–observation departures, it is evident that ORAS5 almost always simulates sea-ice thicker than observed in SMOS-SIT. This happens to a greater or lesser degree, and with various unrelated root causes, depending on the region [..<sup>157</sup> ] and feature under consideration.

Early in the freezing season (October–December), there is reasonable [..<sup>158</sup> ] correspondence between sea-ice thickness from SMOS-SIT and ORAS5, but sea ice is thicker in ORAS5 than in SMOS-SIT. We suggest that this discrepancy is explained to roughly equal parts by known systematic deficiencies in both products: SMOS-SIT underestimates the true ice thickness because it ignores the open-water contribution to L-band emissivity, and ORAS5 overestimates the true sea-ice thickness because of exaggerated ice growth rates due to limitations inherent to the mono-category approach to modelling the sea-ice thickness distribution.

As the freezing season progresses, ice thicknesses are continuously growing [..<sup>159</sup> ] in ORAS5 almost everywhere, but are stagnating and often even decreasing in SMOS-SIT. This stagnation and saturation of sea-ice growth in SMOS-SIT occurs even when [..<sup>160</sup> ] only considering data that is [..<sup>161</sup> ] deemed to be reliable according to the diagnostic uncertainty parameters provided with the product. The result of this are large discrepancies between SMOS-SIT [..<sup>162</sup> ]

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<sup>154</sup>removed: It has been demonstrated here that there is huge potential for sea ice thickness from SMOS to be useful for validation of and data assimilation in prognostic ocean /sea ice models, but that there are outstanding questions on the uncertainty of the retrieved ice thickness

<sup>155</sup>removed: Departures of ice thickness between the ice-ocean analysis ORAS5 and the

<sup>156</sup>removed: observational product have a complex structure and depend

<sup>157</sup>removed: , season, and thickness range considered. In general

<sup>158</sup>removed: agreement between observed and analysed ice thickness early in the freezing season from October to November. Later on, in most regions the analysis shows ice thickness that

<sup>159</sup>removed: , whereas SMOS ice thickness saturates. This saturation

<sup>160</sup>removed: filtering out

<sup>161</sup>removed: flagged as having a low uncertainty in the

<sup>162</sup>removed: data product.

[..<sup>163</sup> ]and ORAS5 sea-ice thickness late in the freezing season (February–April) for all regions except the central Arctic and the Barents and Kara Seas. In the central Arctic Ocean (excluding the surrounding marginal Seas), both SMOS-SIT [..<sup>164</sup> ]

5 [..<sup>165</sup> ]and ORAS5 agree that there is no thin sea ice [..<sup>166</sup> ]ice late in the freezing season. In the Barents and Kara Seas, the departures are moderate throughout the freezing season.

The large positive reanalysis–observation departures late in the freezing season [..<sup>167</sup> ]fall into two distinct categories. The first category is prevalent in the Laptev, East Siberian, Chukchi, and Beaufort Seas, where extensive refrozen polynyas and fracture zones exist, as evidenced by independent observations from campaigns and visual imagery. These are well detected by SMOS-SIT[..<sup>168</sup> ], but ORAS5 [..<sup>169</sup> ]

10 [..<sup>170</sup> ]

[..<sup>171</sup> ]is mostly unable to simulate them. In this case, the discrepancy can be attributed to errors in the model and data assimilation methods. The second category of large positive departures is most apparent in the Baffin Bay: here, SMOS-SIT ice thickness saturates at values around 0.7 m, whereas simple energy budget considerations, ORAS5 as well as independent observations from radar altimetry suggest values closer to 1.5 m. Hence, it seems that SMOS-SIT 15 is systematically biased low in this case. We suggest several plausible hypothesis for the bias, the most appealing being that SMOS-SIT misinterprets the contribution of appreciable area fractions of open water to L-band [..<sup>172</sup> ]emissivity.

[..<sup>173</sup> ]

20 [..<sup>174</sup> ]The discrepancies described above illustrate that a robust and reliable quantification of the thickness of thin sea ice is from L-band observations and ocean reanalysis is an open challenge. Meeting it will require improvements in the observational methods, but also in the forecast model and data assimilation [..<sup>175</sup> ]methods. It should be kept in mind that

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<sup>163</sup>removed: Some large late-winter departures are due to the occurrence of fracture zones and polynyas within the ice pack. These are well-detected by

<sup>164</sup>removed: , but only poorly simulated by the model. Other late-winter departures, for instance in the Baffin Bay region, seem to be caused by SMOS-SIT data being biased low. Some hypotheses for the low bias have been suggested, but further investigation is needed here.

<sup>165</sup>removed: Despite the local uncertainties, there is good agreement in the large-scale distribution of

<sup>166</sup>removed: , and in its interannual variability and trends. Early

<sup>167</sup>removed: ,

<sup>168</sup>removed: and

<sup>169</sup>removed: consistently show a marked depletion of thin ice in 2012, a temporary recovery in 2013/14, and a marked subsequent decrease after that, leading to a thin ice area in 2016 that is as low or lower than that in 2012.

<sup>170</sup>removed: Thin sea ice is a fast-changing moderator of air-sea heat fluxes in the cold season, with clear relevance for numerical prediction of weather and climate. However, its properties are difficult to model, and difficult to observe in-situ and remotely.

<sup>171</sup>removed: Sea-ice thickness retrievals from

<sup>172</sup>removed: missions like SMOS are novel and innovative, and we are only just beginning to harness its unique benefits. However, it needs to be kept in mind that this remote sensing technique is fundamentally limited to thin sea ice, and careful investigations are required to quantify this limit

<sup>173</sup>removed: By contrasting L-Band sea-ice thickness retrievals with sea-ice thickness from an independent ocean reanalysis over seven winters 2010 to 2016, the present study explores the limits of both data sets. There is encouraging agreement in some aspects, but systematic discrepancies in other aspects. A case-by-case consideration is necessary to determine whether the truth most likely lies closer to the observational or the reanalysis data set.

<sup>174</sup>removed: In the light of these findings, we advise caution when using sea-ice thickness from SMOS for model validation

<sup>175</sup>removed: . To make progress in reconciling observation and model data, it would be beneficial to integrate the retrieval model better with the systems that are used to produce the ancillary data for the retrieval, most importantly the meteorological and oceanographic surface parameters. This integration would

our capacity to observe and model the <sup>[..176]</sup> thickness of thin sea ice on a pan-Arctic scale is less than a decade old, and many improvements are already imminent. In this light, the consistencies that do already exist are encouraging. We hope that the discrepancies described here will provide inspiration and guidance to future in-depth studies addressing current deficiencies of observational, modelling, and data assimilation methods, so that subsequent improvements can

5 unlock the full potential of L-band radiometry for measuring the thickness of thin sea ice and contributing to an improved characterization and prediction of polar regions.

## Appendix A: Changes from the previous <sup>[..177]</sup> SMOS-SIT version

In the previous <sup>[..178]</sup> SMOS-SIT version 2.1, look-up tables were used in the retrieval algorithm to speed up processing. The resulting discretisation leads to <sup>[..179]</sup> substantial retrieval artefacts. As Figure 8 demonstrates, the frequency distribution of

10 retrieved sea ice thickness (SIT) has an unphysical multi-mode structure, with local minima at around 15, 25, 45 and 80 cm. These modes are very strong, for instance SMOS-SIT has four times more sea ice at 30cm than at 25cm. This artefact could potentially cause major problems in correct geophysical interpretation of the data, and could cause spurious results when using SMOS-SIT for data assimilation. In the current version 3.1 of the data, the problem has been addressed by introducing more entries in the look-up table with a finer spacing. Furthermore, in the process of converting plane-layer ice thickness into

15 heterogeneous mean ice thickness, instead of using a look-up table <sup>[..180]</sup>, a parametrized <sup>[..181]</sup> conversion function is applied, which avoid the abrupt transition caused by dividing the ice thickness into discrete entries.

[Figure 8 about here.]

## Appendix B: Ambiguities when retrieving sea-ice thickness from SMOS TB

<sup>[..182]</sup> Sea-ice thickness (SIT) retrieved from L-band microwave radiance is limited by penetration depth of the radiation in

20 sea ice. The maximum retrievable ice thickness is reached when the L-band brightness temperature has no useful sensitivity to SIT any more, or when it is dominated by <sup>[..183]</sup> uncertainty in the ice bulk salinity and temperature (Tian-Kunze et al., 2014). Figure 9 shows that for SMOS-SIT, throughout the data set, there is a strong functional relationship between retrieved SIT and <sup>[..184]</sup> brightness temperature (TB). TB is very sensitive to SIT of up to 50cm or so, but beyond that the slope TB/SIT

allow a systematic analysis of the uncertainties and sensitivities of retrieved sea ice thickness, which in turn is an essential step towards assimilation of sea-ice thickness within a well-balanced data assimilation system. Eventually, a full exploitation of

<sup>176</sup> removed: information about sea-ice thickness contained in L-Band radiometry will lead to a better sea-ice analysis, and hence to better forecasts in polar regions from days to seasons

<sup>177</sup> removed: data

<sup>178</sup> removed: data

<sup>179</sup> removed: a substantial retrieval artefact

<sup>180</sup> removed: method

<sup>181</sup> removed: converting

<sup>182</sup> removed: SIT

<sup>183</sup> removed: uncertain ice salinity and ice

<sup>184</sup> removed: TB

of the relationship is small, meaning that SIT is only poorly constrained by TB, and auxiliary data become more important to determine the retrieved SIT.

Unfortunately, for footprints which are partially open water, SMOS-SIT does not take into account the emission of the open water. As shown in Figure 9 (middle and right), in the range [..<sup>185</sup> ]up to 0.5m, there is typically a sizeable open water fraction, and there is a linear relationship between ice concentration and SMOS TB. This suggest that SMOS-SIT erroneously ascribes [..<sup>186</sup> ]lower TB to thinner ice instead of [..<sup>187</sup> ]open water, and hence below 50cm we must expect SMOS to be biased low (see also Tian-Kunze et al. (2014)). However, this might be compensated by the fact that retrievals for sea ice concentration are often also biased low for areas of thin sea (Kwok et al., 2007). For retrieved ice thicknesses above [..<sup>188</sup> ]0.5m, the open water fraction is usually low so does not contribute much to the TB; however, in this range the retrieved thickness is dominated by [..<sup>189</sup> ]potentially uncertain assumptions about snow, ice temperature and ice salinity.

[Figure 9 about here.]

### Appendix C: Day-to-day variability

Sea ice thickness at a particular location retrieved from SMOS-SIT varies much more from one day to the next than analysed by ORAS5[..<sup>190</sup> ]. Figure 10 [..<sup>191</sup> ]shows that the distribution of daily SIT changes is much broader for SMOS-SIT than for ORAS5. Extreme daily thickness changes of more than 0.2 m occur around 6% of the time in SMOS-SIT, but less than 1% of the time in ORAS5. These changes can have either thermodynamic causes (ice mass changes) or advective causes (ice is moved in/out of grid cell). A SMOS-SIT grid cell has a width of 12.5km. [..<sup>192</sup> ]For reference, an advective change of 0.2 m would require a nearby step change of 0.2 m in the ice thickness, combined with strong winds or ocean currents that are able to move the ice by 12.5 km in a day. Alternatively, if the change was thermodynamic, a surface heat flux of [..<sup>193</sup> ]700Wm<sup>2</sup> over that day for the whole 12.5 km grid cell would be required. These extreme conditions should only be expected to occur near the ice edge, and in polynyas and fracture zones, and therefore daily changes of 0.2 m or more should be rare.

[Figure 10 about here.]

Inspection of maps of daily changes reveals that large [..<sup>194</sup> ]sea-ice thickness (SIT) changes in SMOS-SIT are not restricted to the ice edge, polynyas and fracture zones, but occur over extended large-scale areas that correspond to changing synoptic weather patterns. An example is given in Figure 11. On 16 Nov 2015, ice surface temperatures derived by SMOS-SIT were

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<sup>185</sup>removed: 0-50cm

<sup>186</sup>removed: low

<sup>187</sup>removed: to the open watercontribution

<sup>188</sup>removed: 50cm

<sup>189</sup>removed: poorly constrained

<sup>190</sup>removed: (

<sup>191</sup>removed: ). Note

<sup>192</sup>removed: That means, for references,

<sup>193</sup>removed: 700 Wm<sup>2</sup>

<sup>194</sup>removed: SIT

around  $-15^{\circ}\text{C}$  in the Laptev Sea and SMOS-derived ice thicknesses ranged between 0.5 and 1 m. The next day, SMOS-derived ice surface temperatures in this region increased by 5 K in a very coherent and homogeneous structure, while brightness temperatures decreased only slightly and with less spatial coherence. The SMOS-derived SIT over the Laptev Sea [..<sup>195</sup>] **thinned** coherently by more than 0.2 m in some areas. Given that it is impossible for the ice to change that way in reality, taking into  
5 account both thermodynamic and advective forcing, it must be concluded that this wide-spread ice thinning by 0.2 m from one day to the next is an error in the retrieval algorithm: strong changes in the ice surface temperature, in reality caused by synoptic changes, together with unremarkable change in brightness temperatures, are erroneously interpreted as a strong thinning of the ice.

The unrealistic strong day-to-day fluctuations in the SMOS-SIT data are likely due to either errors in the [..<sup>196</sup>] **auxiliary**  
10 fields, or due to the assumption of a linear temperature profile within the ice. If there are relevant errors in the [..<sup>197</sup>] **auxiliary** fields, a quick change in the field will lead to a quick change in the retrieved ice thickness that is not realistic. The limits to the validity of the assumption of a linear temperature profile has been investigated in detail by Maaß (2013). They found that, after abrupt changes in the meteorological conditions, the temperature profile within the ice can take several days to adjust. Based on these results, we tentatively suggest that the assumption of the linear temperature profile within the ice is responsible for the  
15 unrealistic day-to-day changes in the SMOS-SIT data.

However, this question can only be answered satisfyingly by further research which has full control both over the SMOS-SIT retrieval model and the [..<sup>198</sup>] **auxiliary** meteorological and oceanographic fields. [..<sup>199</sup>] **Most of these auxiliary fields are the output of complex data assimilation systems**, and therefore advanced and well-studied uncertainty estimates are available. It would be a valuable first step towards assimilation of SMOS brightness temperatures for SIT, if the SMOS-SIT retrieval model  
20 could be installed at one of the [..<sup>200</sup>] centres who produces the [..<sup>201</sup>] **auxiliary** fields, and test sensitivity of the retrieved SIT to their known uncertainties.

[Figure 11 about here.]

## Appendix D: Representation of thicker ice

When interpreting sea-ice thicknesses of 0.5 m or higher from SMOS-SIT, it is essential to inspect the provided uncertainties.  
25 Neglecting to do so easily results in wrong conclusions. As an example, Figure 12 shows sea-ice thickness on a single day (15 Nov 2012) as seen by SMOS-SIT and ORAS5. When considering all data from SMOS-SIT (Figure 12a), a false impression of almost uniformly 1 m thick sea ice throughout the Arctic Ocean is given, which is unrealistic given the well-known fact that the multi-year ice north of Greenland and the Canadian Archipelago is several meters thick, whereas the newly formed first-year

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<sup>195</sup>removed: changed

<sup>196</sup>removed: ancillary

<sup>197</sup>removed: ancillary

<sup>198</sup>removed: ancillary

<sup>199</sup>removed: At production, these ancillary fields form part of an data assimilation system

<sup>200</sup>removed: operational

<sup>201</sup>removed: ancillary

ice in the marginal seas of the Arctic Ocean is probably thinner than 1 m. Sea-ice thickness in ORAS5 (Figure 12b) clearly shows the expected structure, in good agreement with other observations and modelling results (Kwok and Cunningham, 2008; Schweiger et al., 2011; Laxon et al., 2013).

5 Figure 12c shows the corresponding scatter density between SMOS-SIT and ORAS5 sea ice thickness for the freeze-up season 15 Oct - 15 Dec 2012. It is evident that SMOS-SIT, without any filtering, has lots of ice thickness in the 1-1.5 m range, which do not correlate at all with the ORAS5 ice thickness.

[Figure 12 about here.]

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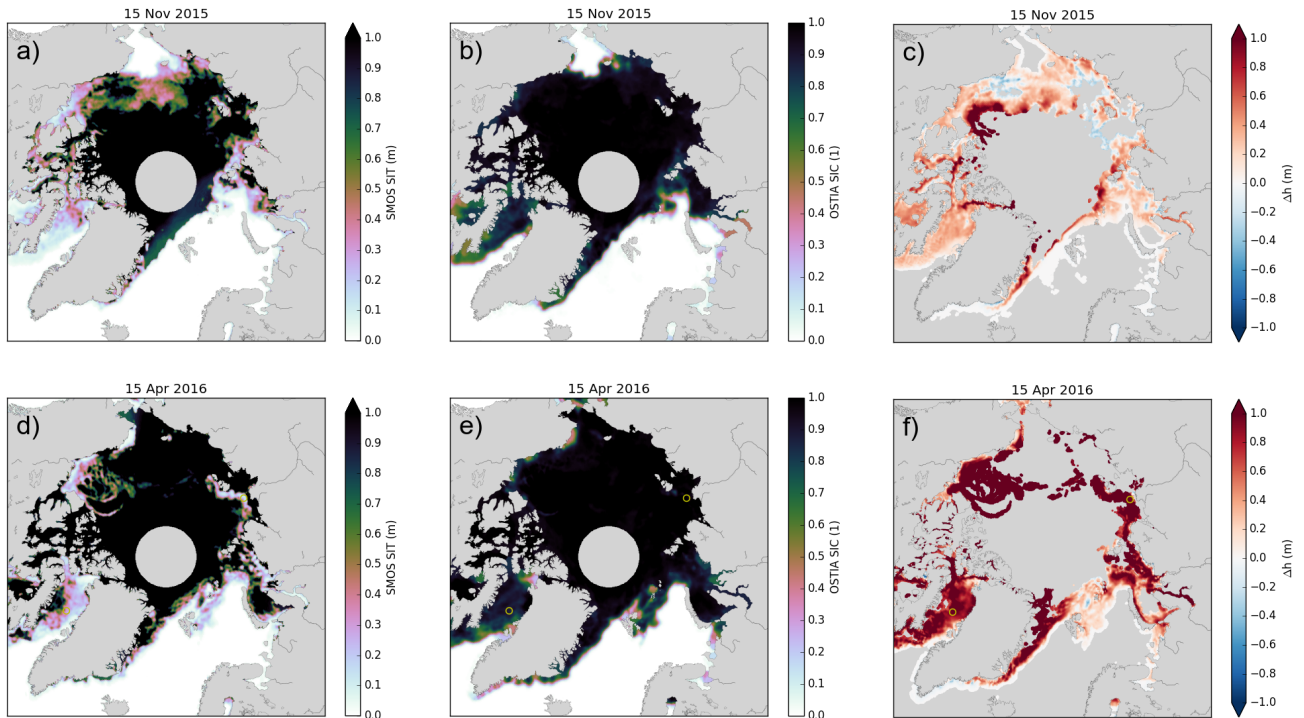


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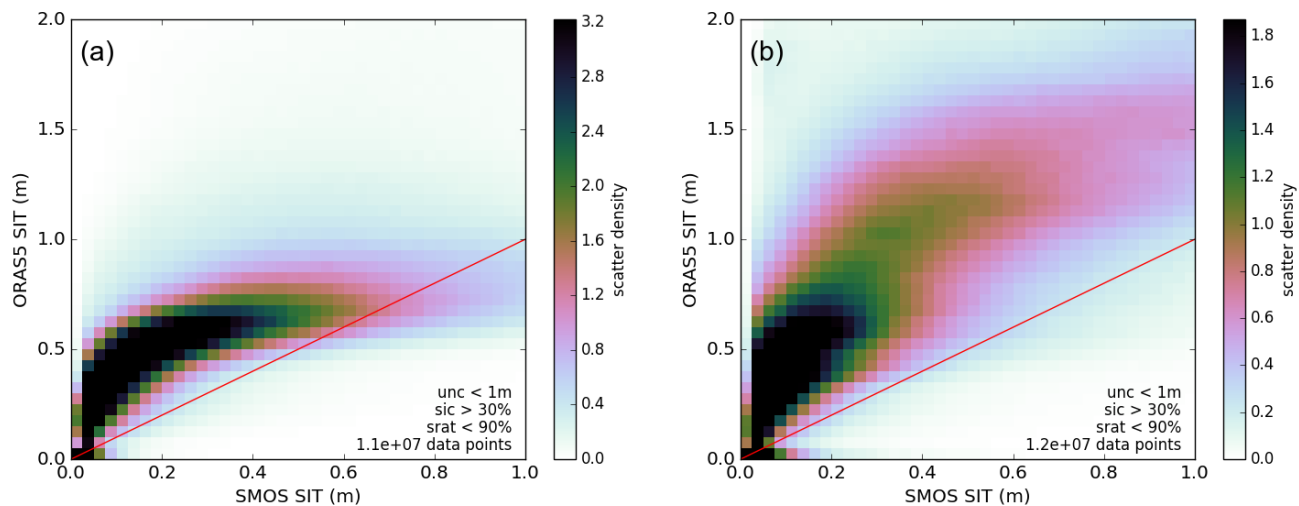
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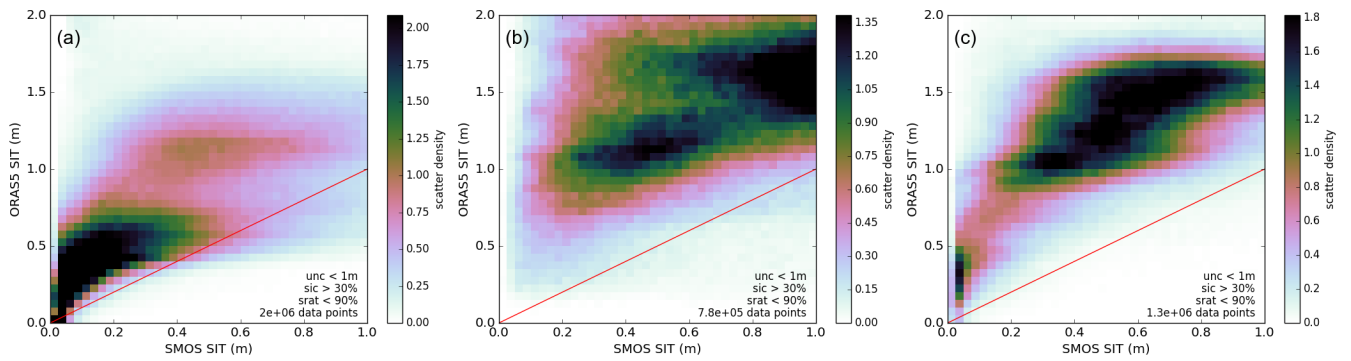
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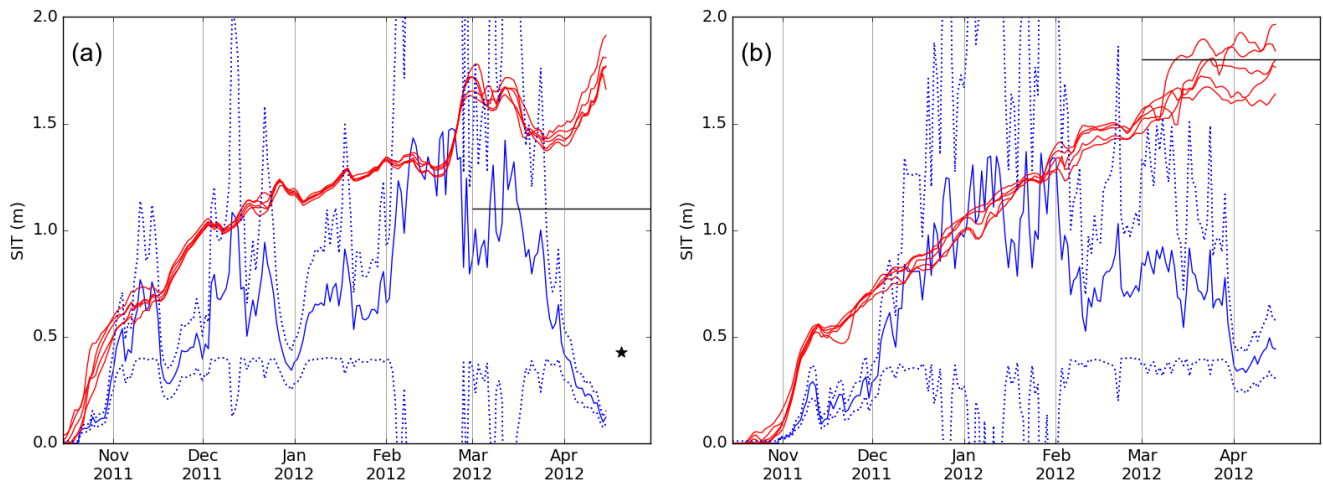
**Figure 1.** Thin sea ice for two selected days representing typical conditions in early and late winter: 15 Nov 2015 (a)–(c) and 15 April 2016 (d)–(f). Subfigures (a) and (d) show the sea ice thickness retrieved by SMOS-SIT. The colours saturate at 1m, because ice thicknesses beyond that can normally not be retrieved. Subfigures (b) and (e) show sea ice concentration from the OSTIA product. The difference between sea ice thickness [..<sup>202</sup>] analysed in ORAS5 and retrieved by SMOS-SIT is shown in (c) and (f). [..<sup>203</sup>] The difference [..<sup>204</sup>] is only shown for data points where the retrieved SMOS-SIT [..<sup>205</sup>] ice thickness is lower than 90% [..<sup>206</sup>] of the maximal retrievable thickness (see Tian-Kunze et al. (2014) for details) and where the SMOS-SIT total retrieval uncertainty [..<sup>207</sup>] is less than 1m [..<sup>208</sup>]. The yellow circles in the Laptev Sea and Baffin Bay in (d)–(f) indicate the representative locations discussed in Section 4.



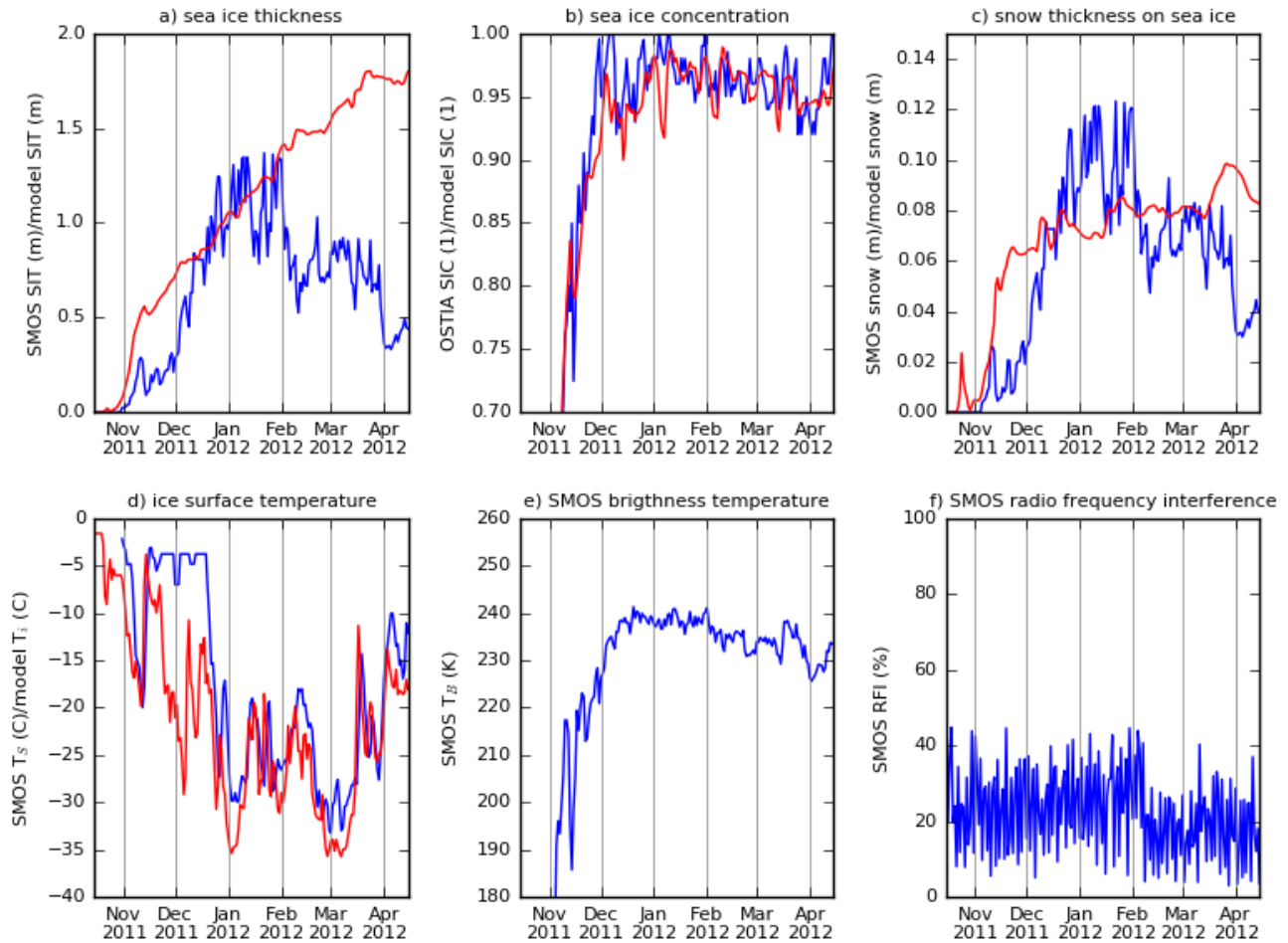
**Figure 2.** [..<sup>209</sup>] Normalized joint frequency distribution (scatter density) of co-located pairs of daily observed and analysed thin sea ice [..<sup>210</sup>]; (a) October to December [..<sup>211</sup>] 2011–2017, (b) February to April [..<sup>212</sup>] 2012–2017. The text insets in the lower-right corner give information on the pre-filtering of the data before producing the scatter density: data points are only considered if the retrieval uncertainty is below 1 m ( $unc < 1\text{ m}$ ), the sea-ice concentration from OSTIA is above 30% ( $sic > 30\%$ ) and the saturation ratio is below 90% ( $srat < 90\%$ ). The last line of the text inset gives the total number of data points for which the scatter density was calculated.



**Figure 3.** [..<sup>213</sup>] Normalized joint frequency distribution (scatter density) of observed and analysed thin sea ice in late winter, February to April [..<sup>214</sup>] 2012–2017: (a) Barents and Kara Seas (15E–90E, 70–85N), (b) Laptev Sea (90E–150E, 70–85N), and (c) Baffin Bay (75W–53W, 65N–80N). For an explanation of the text insets, see caption of Figure 2.

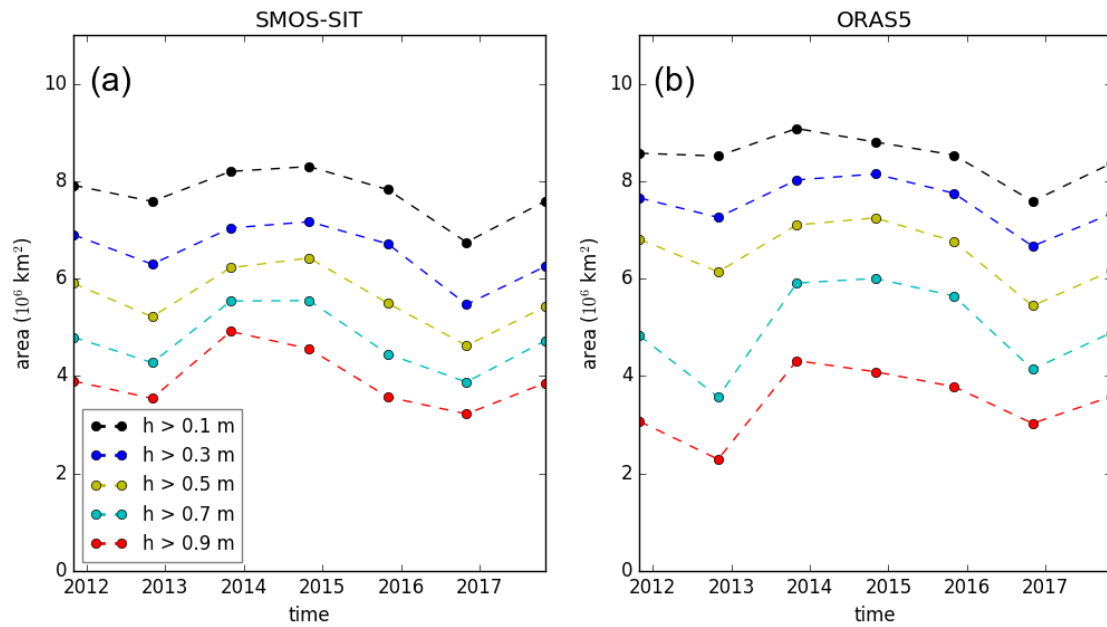


**Figure 4.** Time series of daily sea ice thickness during the 2011/2012 winter at (a) a representative location in the Laptev Sea at 74.5N,127E and (b) a representative location in the Baffin Bay at 72N,62W. Blue is SMOS-SIT (full line) with added and subtracted [uncertainty standard deviation](#) (dotted lines); Red are the five realisations of ORAS5; Black horizontal lines are the CryoSat2 average thickness for March/April provided by CPOM; black star is an EM-Bird overfly for the Laptev Sea on 20 April 2012. [The corresponding time series of sea-ice concentration are shown in Figure 5b.](#)

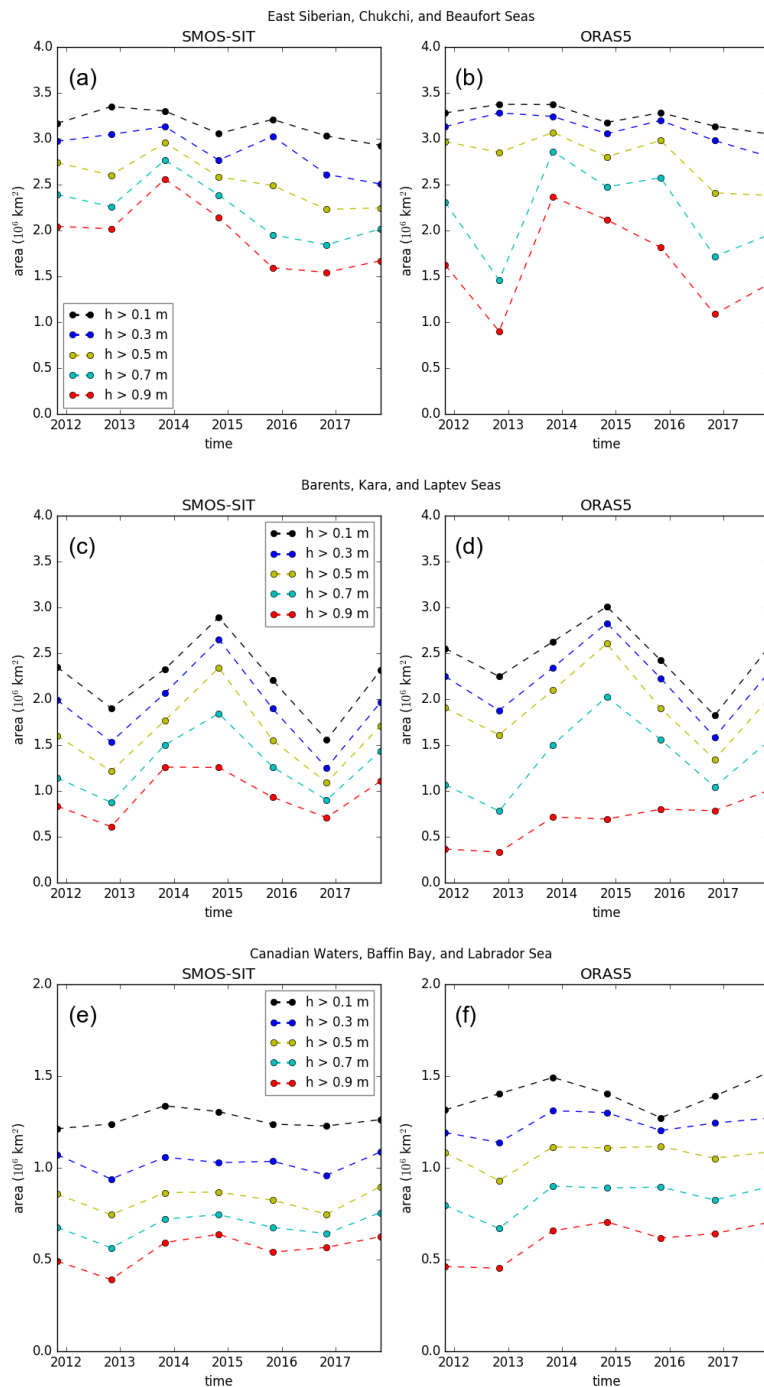


**Figure 5.** Time series for relevant SMOS-SIT and ORAS5 parameters for the Baffin Bay location 72N,<sup>[.215]</sup>62W for the full freezing season 2011/2012. Blue curves are SMOS-SIT parameters (except in (b), where blue is observed ice concentration from OSTIA), red curves are model parameters.

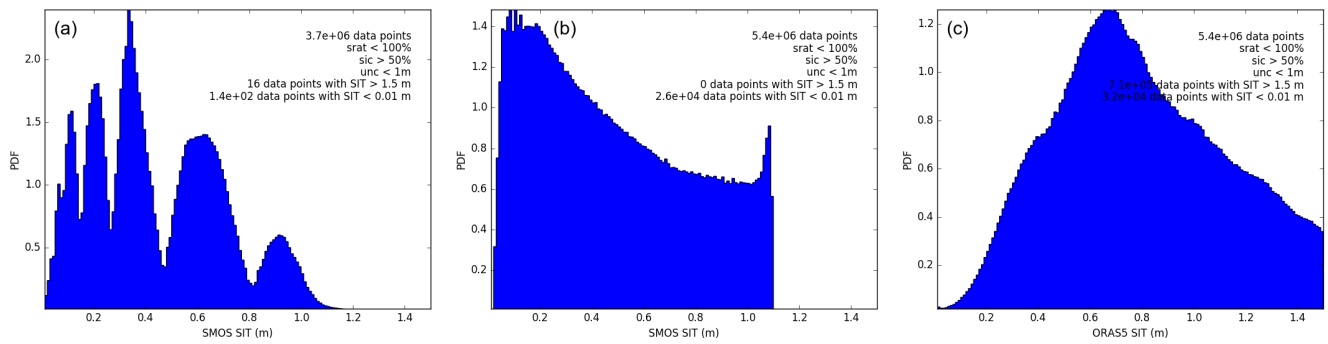




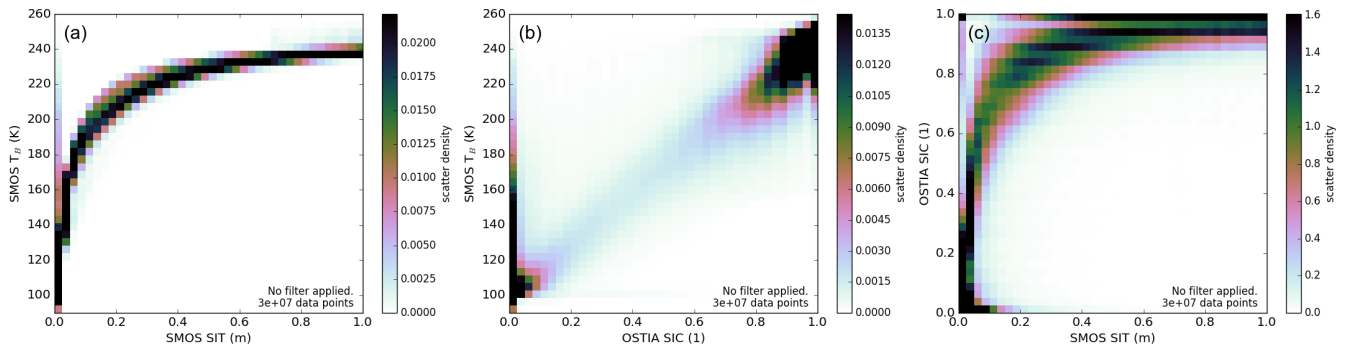
**Figure 6.** Monthly November means of the pan-Arctic area covered by ice thicker than given thresholds in SMOS-SIT (a) and ORAS5 (b).



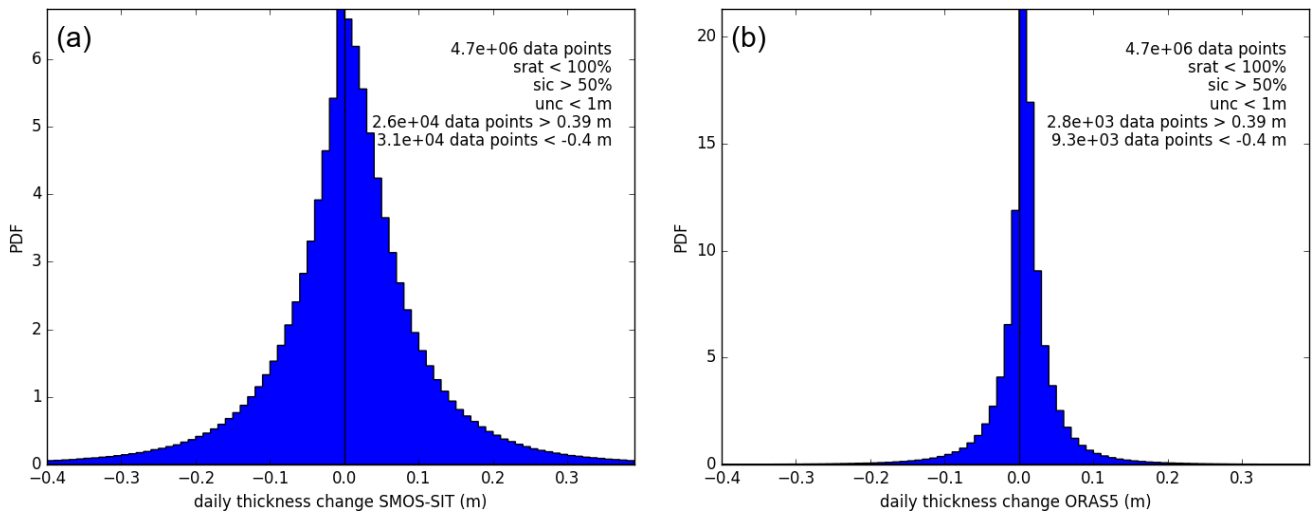
**Figure 7.** Monthly November means of the regional area covered by ice thicker than given thresholds in SMOS-SIT (left) and ORAS5 (right). The boundaries of the longitude-latitude boxes are 0-150E, 70-90N for (a) and (b); 150E-120W, 70-90N for (c) and (d); and 120-70W, 55-83N for (e) and (f).



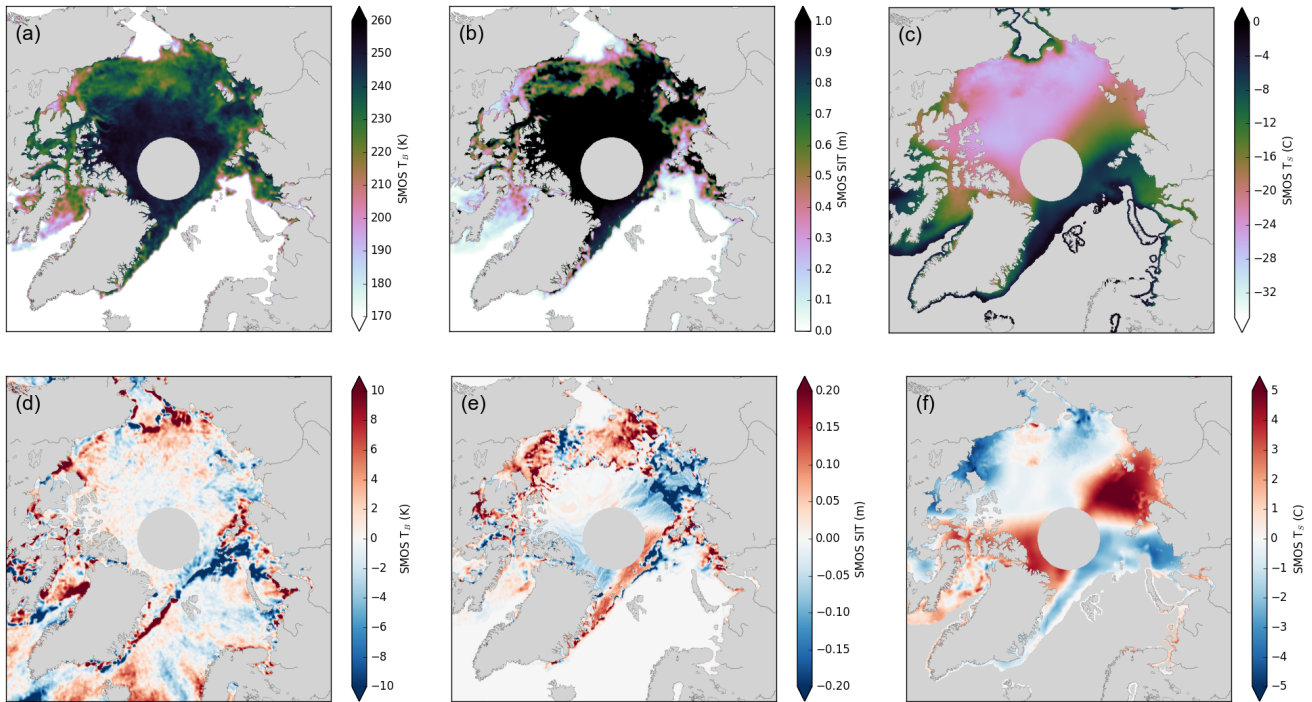
**Figure 8.** SMOS-SIT thickness frequency distribution for the winter 2015/2016 for (a) SMOS-SIT version 2.1, ([..<sup>216</sup>] b) [..<sup>217</sup>] SMOS-SIT version 3.1 [..<sup>218</sup>], and (c) the ORAS5 ocean/sea ice reanalysis [..<sup>219</sup>].



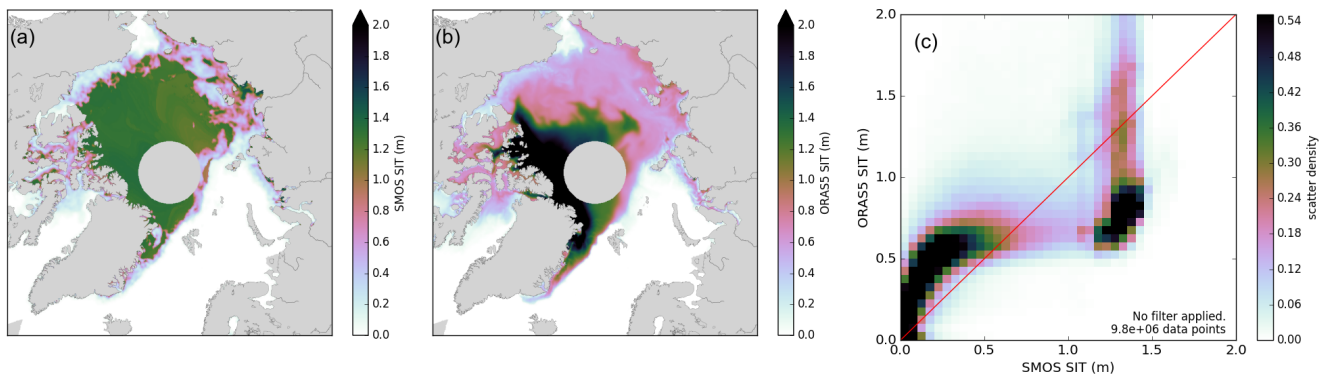
**Figure 9.** Scatter density of (a) SMOS TB and SMOS-SIT-derived sea ice thickness, (b) SMOS TB and sea-ice concentration, (c) sea-ice concentration and SMOS-SIT sea-ice thickness. The scatter density is calculated from all SMOS-SIT data points over the period 15 Oct 2015 to 15 Apr 2016, no filtering has been applied.



**Figure 10.** Frequency distribution of [..<sup>220</sup>] daily sea ice thickness changes from (a) SMOS-SIT and (b) ORAS5 in the period 15 Oct 2015 to 15 Apr 2016. To produce these histograms, only those differences between consecutive days at the same location have been taken into account where the uncertainty diagnostics provided with SMOS-SIT for both days indicate a reliable retrieval (saturation ration < 100%, uncertainty < 1 m, sea-ice concentration > 50%). Day-to-day thickness changes are outside  $\pm 0.4$  m in less than 1% of the cases.



**Figure 11.** SMOS-derived information on 15 November 2015 (top panels) and daily difference between 16 and 15 November 2015 (bottom panels) for SMOS TB (a,d), SMOS-SIT ice thickness (b,e) and SMOS-SIT ice surface temperature (c,f). Correspondence between unrealistic SMOS-derived changes in ice thickness (e) and changes in ice surface temperatures ([..<sup>221</sup>]f) are evident.



**Figure 12.** Representation of thicker ice in SMOS-SIT and ORAS5. (a) and (b) show sea-ice thickness on 15 Nov 2012 in the range [0–2 m derived from (a) SMOS-SIT and (b) ORAS5. (c) shows the scatter density of ice thickness from SMOS-SIT and ORAS5 for all observation points without any filtering from 15 Oct to 15 Dec 2012.

# Authors response to referees comments for manuscript tc-2017-247

*We would like to thank both reviewers for their careful reading and checking of the manuscript, and for making many thoughtful comments and valuable suggestions that helped us to improve it.*

*The numbering of pages, lines, sections and figures used in this response refers to the old version of the manuscript. Throughout our response, we use the following abbreviations:*

- *SIC - sea ice concentration*
- *SIT - sea ice thickness*
- *SST - sea surface temperature*
- *PMR - passive microwave radiometry*
- *TB - (microwave) brightness temperature*

*The manuscript and reviewer comments are published online in The Cryosphere Discussions at <https://doi.org/10.5194/tc-2017-247>.*

## 1 RC1 – comments of first referee

### 1.1 Summary and assessment

**Comment:** *The paper provides a useful story on the potential and the pitfalls of using SMOS derived sea ice thickness for the validation and assimilation with an ocean reanalysis. The paper compares SMOS sea ice thickness with ORAS5 reanalysis sea ice thickness. It finds strong correlations, considerable biases and also areas where there is little agreement between SMOS and ORAS5. Some ideas are presented why this disagreement maybe both due to retrieval and modeling errors. While those results are not conclusive, they provide some guidance on how to proceed further and how to potentially incorporate SMOS sea ice information into an ocean reanalysis. I find the paper to be well written and claims sufficiently supported by the evidence. While one may have hoped for some stronger conclusions, I think it is useful as is and provides an incremental contribution.*

**Response:** We thank the reviewer for a careful reading and assessment of the manuscript, and for suggesting several changes that helped us to improve it.

### 1.2 Specific Comments

**Comment 1.2.1:** *Page 3, Line 12 "... JRA-55...": Later JRA-25 is indicated, please clarify.*

**Response:** We have clarified this. Whereas previous versions of SMOS-SIT used JRA-25 until 2014 and JRA-55 from 2014 onwards, the version 3.1 that we are discussing uses only JRA-55.



**Comment 1.2.2:** Page 4, Line 33 “Thus the OSTIA ice concentration product can not...”: I dont understand what is stated here, I must be missing something.

**Response:** We meant to say that SIC from conventional PMR cannot be used to distinguish areas of old thick sea ice from areas of new thin sea ice because both often have sea-ice concentration of virtually 100%. In contrast, L-Band radiances can be used to make that distinction. We have rephrased P4 L32f. to make the statement more understandable.

**Comment 1.2.3:** Page 5, Line 16: Most of this is likely due to the model being unable to simulate the coastal polynya in the Laptev Sea. Why is this? I think that could be probed a little more? Is the ice too thick to be advected away from the coast and create the polynya or does it regrow too quickly? Is this a resolution effect? If ice concentrations are assimilated and they show open water there (L-Band does so, I assume the higher frequency ice concentration does too?), then why doesn't the model. I understand that this is not necessarily a model validation paper but given the uncertainty in both model and observations it would be good to tie this down a bit more, particularly since later the model seems to be favored over the observations in the case of the Laptev Sea.

**Response:** These are very good questions and suggestions thank you. Before answering, we think it is necessary to clarify two issues mentioned in the reviewer's comment first: (1) As shown very clearly in Figure 1e, SIC in the Laptev Sea polynya is close to 100%, so assimilating SIC does not help and might even be detrimental. In winter, polynyas often refreeze very quickly and are then covered by thin ice. There is a crucial difference in emissivity between higher-frequency microwave and L-Band microwave radiation for the thin ice in the refrozen polynya, which is exactly the point we are trying to make. (2) It seems to be a misunderstanding that “later the model seems to be favored over the observations in the case of the Laptev Sea” – to the contrary! Figs. 3b and 4a and their corresponding discussion in the main text quite clearly argue that the refrozen Laptev Sea polynyas are detected by L-band observations but not simulated by the reanalysis. We have rephrased sentences in the text that could lead to misunderstanding.

This leaves the question why the reanalysis does not simulate the polynya. This is an important question to tackle for model and data assimilation development, but it is not easy to answer because there are many possible reasons, and a dedicated study would be needed to narrow them down and provide a confident answer. In the light of the above, it could even be that the implied SIT increments from the SIC assimilation are responsible. We have added some discussion on this to the text on P5 L16.

**Comment 1.2.4:** Page 6, Line 18 “polynya...”: as mentioned above, why does the model not show open water areas that SMOS shows and presumably should be visible in the ice concentration data that are assimilated?

**Response:** See our reply to the previous comment. It is evident from higher-frequency PMR that the areas we are referring to are covered by thin ice. We acknowledge that a polynya in the strict sense is an area of open water surrounded by ice, and our usage of the term might therefore be misleading. We went through the entire text of the manuscript and added clarification that we are talking about refrozen polynyas (e.g. P5 L11 and L16, P6 L18, and others)

**Comment 1.2.5:** Page 6, Line 28 “under the ice”: This could use a reference to page 7, SST information cannot be used. Again, how come the model doesn't show the open water if it is there in the OSTIA ice concentrations. If there is open water, why cant you assimilate the SST (if they are available). I cant quite follow this argument. I have a sense that this may be an issue with the model which is biased thick and has excessive

*internal ice strength which keeps the ice from moving off shore. Though this doesn't explain why the assimilation doesn't create the opening. Another plausible explanation might be that excessive ice production due to excessive advection creates too much ice in this area. A look at advection and growth rates in the model might be helpful. This is particularly important since the authors seem to give the model and CryoSat measurements the upper hand while discounting EM and SMOS measurements. EM measurements aren't really discussed.*

**Response:** We have added a reference to using SST information on P6 L28. As explained in our responses to the previous comments, there is no open water in the frozen polynyas and hence SIC assimilation does not help. We agree it would be very interesting to investigate why the reanalysis does not represent the frozen-over polynyas, but as argued in our response to comment 1.2.3 we think this is a study in its own right and out of the scope of this manuscript. We have added discussion on the points mentioned by the reviewer on P5 L18.

**Comment 1.2.6:** *Page 8, Line 8: "Surface Temperature": Clarify if ice or air temperatures, I think you mean ice.*

**Response:** We did indeed mean the ice surface temperature. We have rephrased that sentence to make it clearer.

**Comment 1.2.7:** *Page 8, Line 10 "two reanalysis": Correct JRA-25/55 issue see above and remind readers how the JRA reanalysis is used in the SMOS retrievals.*

**Response:** Revised as suggested.

**Comment 1.2.8:** *Page 8, Line 26 "various thickness classes": ORAS5 has thickness classes? I thought it was a single category model?*

**Response:** Here, we refer to the diagnostic thickness classes we defined for producing the figure. It is unfortunate that this can be confused with prognostic thickness classes in the sea ice model. We have revised the sentence and use the term "thickness threshold" to avoid this ambiguity.

**Comment 1.2.9:** *Page 10, Line 3 "lack of thickness categories in combination with an artificial thickness": Please clarify, I cant follow this.*

**Response:** We have revised this sentence and provide a reference to the Section 2.1 of the main text, where we have added a detailed explanation of this issue. We have also added an appropriate literature reference.

**Comment 1.2.10:** *Page 10, Line 5 "incapable of simulating the polynyas": Is this because of the lack of thickness categories or a general bias in ice thickness and associated ice strength? How does the model do in general with respect to ice thickness in the interior pack? That information would be useful.*

**Response:** This is a recurring comment, we refer to our answer to comment 1.2.3. Regarding the general bias in ice thickness, we point out that the model does well relative to its peers, as shown in Uotila et al. (2018). We have added this reference to the model description Section 2.2.

**Comment 1.2.11:** *Page 10, Line 20 "structural limitations": Note them please.*

**Response:** In response to this and other comments, we have added a paragraph in Section 2.2 that explains the simplified treatment of thin ice in the sea-ice model and provides relevant references to the literature. Other structural limitations might be less

obvious and require further research and experimentation to corroborate, so we cannot note them here. We have rephrased the sentence on P10 L20, and have provided a reference to Section 3, where we discuss potential structural limitations.

**Comment 1.2.12:** *Figure 1: Please explain saturation ratio and where the 90% threshold comes from.*

**Response:** If an ice thickness change of 1 cm leads to a TB change of less than 0.1 K in the SMOS-SIT retrieval algorithm, the TB is considered saturated. The ice thickness at which that happens for the current values of the auxiliary fields is the maximal retrievable ice thickness  $d_{\max}$ . The saturation ratio of any other retrieved ice thickness  $d$  for the same values of the auxiliary fields can then be expressed as  $d/d_{\max}$  (Tian-Kunze et al., 2014). We have added this explanation to P3 L19ff. of the main text, and we have reworded the caption of Figure 1.

**Comment 1.2.13:** *Figure 2: “Scatter density...”: Whats the unit of density in this context. All scatter plots could use some statistics (e.g. correlation, bias, RMS error) in either the figure or caption.*

**Response:** We use scatter density as a synonym for “normalized bivariate joint frequency distribution”, so it has no units. We have added an explanation to the main text on P5 L24 and have reworded the figure caption to improve clarity.

**Comment 1.2.14:** *Fig 4: “with added and subtracted...”: Add uncertainty. Not much discussion is given to the EM data point and why this seems to be rather supporting SMOS than both CryoSat and the Model.*

**Response:** Thank you for spotting the omission of “uncertainty”. There is no discussion on the EM data point because we consider it to be a much better estimate of the truth than any satellite-derived observation or model simulation. The fact that it supports SMOS much better than the model is exactly the point we are trying to make (see several previous comments and our responses): The re-frozen polynyas are real, and they are detected by SMOS, but not simulated by the model. We have rephrased several bits of text to make this point even more clearly. The mismatch to CryoSat is a different topic and should be subject to further research. In this case, please note that the CryoSat value represents a full month of data and hence cannot be directly compared to a daily snapshot from an EM-bird overflight and a SMOS-SIT daily mean.

## 2 RC2 – comments of second referee

### 2.1 Summary and assessment

**Comment 2.1.1:** *This manuscript presents a comparison of Arctic sea ice thickness within a range of 0 – 1 m, both retrieved from SMOS satellite-based L-band brightness temperatures and from a numerical ocean-sea ice reanalysis system assimilating various observational data. It focuses on evaluating regional biases between the two products during the winter 2011-2012 season, but also touches on interannual variations and trends across the full 2011-2016 period. The premise for the study, although unfocused, is valid. Numerical sea ice forecasting systems should unequivocally be more reliable if they can assimilate a greater breadth and variety of observational data, such as low-frequency passive microwave retrievals of ice geophysical properties like those provided by SMOS.*

*Here, the authors appear to be undecided on the main purpose of their study: is the idea to verify/validate the ORAS5 forecasting system using the SMOS data? If so, given the observational uncertainties discussed in the manuscript, the SMOS data do*

not appear ready for this. Moreover, why was the enhanced sea ice thickness product incorporating SMOS and Cryosat-2 data not utilized. Alternatively, is the idea to evaluate the root causes of biases within the SMOS data? In which case, this is mostly done qualitatively. Several possible reasons are introduced to explain uncertainties in the SMOS data, but none are investigated in detail so no useful conclusions are made. Given that the premise of validating numerical sea ice forecasting systems is highly valuable, I recommend this paper could be published following major revisions. In line with comments above, the authors should decide exactly what they want the paper to be, to allow them to focus their arguments into quantitative useful conclusions.

**Response:** We thank the reviewer for their careful reading of the manuscript, for pointing out its weak points, and for making several very valuable suggestions how to improve it.

The main purpose of the study is to give an overall assessment of agreement and discrepancy between an observational product of sea-ice thickness from L-band PMR and a sea-ice ocean analysis system that does not assimilate the observational product. Observing and analyzing thin sea ice has only become possible in the last few years, so as with every new technology, initial problems are to be expected. To our knowledge, a detailed assessment of this kind covering the whole Arctic has never been done, yet we see it as an essential step to take before using the observational product for model validation, data assimilation, or forecast verification.

Perhaps we did not make our premise clear enough in the abstract and in the introduction: we do not and will never know the true ice thickness with the vast temporal and spatial coverage provided by remote sensing and reanalysis products. Both can have large errors, and it is not a-priori clear that one is superior to the other. In fact, one of the main points of the manuscript is that discrepancies between the two products compared can be attributed to errors in one or the other, depending on the region and feature considered. Hence, in many cases the fidelity of the SMOS-SIT product is not currently high enough to validate the ORAS5 reanalysis system, as pointed out by the reviewer.

We enthusiastically agree that an investigation of the root causes of potential biases in the SMOS-SIT data and the reanalysis is needed. However, this is *not* the point of this manuscript. As the reviewer points out, we offer possible reasons but can not follow up on them. Numerical experimentation with the retrieval algorithm and the ocean analysis system is beyond the scope of our study. Rather, our study provides concrete examples of discrepancies and so can provide inspiration and guidance for a future study on sensitivities and uncertainties of the retrieval algorithm and the reanalysis.

We have revised the manuscript in order to address the very valid points raised by the reviewer. We think that the new manuscript version does better in presenting the premise and purpose of the study (and thus managing the expectation of the reader), provides some deeper analysis as requested by the reviewer, and summarizes the main points of the paper in the conclusions section more pointedly. The revisions are described in more detail in our responses to the following comments.

## 2.2 General Comments

**Comment 2.2.1:** *Regarding Section 2.1, do you have quantitative component uncertainties for each of the contributing factors listed here (e.g. uncertainty contribution from the smos Tb, from the ancillary T and S data, from using assumptions for linear T-gradient, desalinization scheme etc.)? Are these provided in the SMOS product or can they be provided by the co-authors? In the context of the entire study this would be very useful, as it would allow the authors to better evaluate regional biases in the SMOS data and thus understand how likely identified bias is a product of the SMOS*

*data or forecasting system. An example of where this would be useful is around page 7 line 32.*

**Response:** Having a look at quantitative component uncertainties for SMOS-SIT is an excellent suggestion, and we agree it would be extremely useful. They are not currently available from the published SMOS-SIT product, and although they could be provided in principle, this is a non-trivial exercise, both conceptionally and computationally. An ongoing project is investigating this at the moment, and results should be left to a dedicated study which can build on this manuscript for inspiration and guidance. We have added this premise to the introduction, and have also added references to Maaß (2013) who have investigated these uncertainties/sensitivities of the retrieval model for idealized cases, and Richter et al. (2016) who perform an intercomparison of L-Band brightness temperatures calculated from reanalysis sea-ice fields.

**Comment 2.2.2:** *It would be valuable to include all or details from Appendix C in the main paper. This extra understanding of where and in what context the SMOS data could be limited would really help to interpret the validity of results from the forecasting system. This analysis could be expanded by examining scales of day-to-day variability between a fast-ice region (e.g. the Canadian Arctic Archipelago) and a dynamic region, over the same time period or scenario (like the authors rapid air T change). Equally, more depth to the analysis between ice concentration and SMOS ice thickness (also in the appendices) and on the effect of auxiliary fields on the ice thickness retrievals would be incredibly valuable and relevant, even though the authors suggest this is beyond the scope of the paper.*

**Response:** We agree that these points would be extremely valuable to investigate. However, as we have argued in our response to comment 2.1.1, we think this is better left to a dedicated study on the uncertainties and sensitivities of the retrieval model. This requires non-trivial work, as the retrieval algorithm needs to be run many times with systematic and realistic variation to the thermodynamic sea-ice model, auxiliary fields, and brightness temperatures, and possibly employing different radiative transfer models as well (coherent vs. incoherent etc.).

Given that the magnitude of the unphysical day-to-day changes discussed in Appendix C is well within the uncertainty estimate provided by SMOS-SIT, it might be a bit unfair to assign too much emphasis on them. Rather, it illustrates the fundamental need to complement remote sensing observations with physical constraints from a forecast model background in the framework of data assimilation.

**Comment 2.2.3:** *Section 5 is quite vague and unfocused. The bulk of the paper would be more useful if this was removed and replaced with more detailed investigation of regional model-obs biases, investigating particular causes for the regional biases the authors touch upon in the previous section.*

**Response:** We would like to keep this section, because it provides a positive outlook on how variability and change of thin sea ice in the Arctic can be monitored using SMOS-SIT and ORAS5, despite all their discrepancies. This positive message is one of the main points of the paper.

**Comment 2.2.4:** *You mention at Page 10 line 6 that the SMOS ice thickness algorithm relies much more on auxiliary fields when ice thickness > 0.5 m. It would therefore be useful to analyse model-obs biases for different categories of uncertainty or for different ice thickness categories. Is there a strong relationship between bias magnitude and SMOS-SIT or uncertainty?*

**Response:** The dependence of the departures on the retrieved ice thickness in SMOS-

SIT can be read off Figures 2 and 3, and we discuss the dependence in the main text. There is no apparent dependence of departures on uncertainty (see Figure 3 in this response), so we have decided not to include it in the manuscript.

**Comment 2.2.5:** *Page 11 line 2f.: I do not agree with the statement that there is “reasonable agreement” between observed and analysed ice thickness in the early freezing period. There is systematic nonlinear bias, which has not been explained or properly quantified here.*

**Response:** We agree there is systematic discrepancy even early in the freezing period. The agreement is “reasonable” only in comparison to the much larger discrepancy later in the freezing season. We have changed the wording on P11 L2. We have added discussion of this nonlinear bias to the main text after P5 L34.

**Comment 2.2.6:** *To reiterate an earlier point, it is difficult to understand whether the idea of the paper is to verify/validate the reanalysis system (in which case it would have made more sense to use the combined CS2/SMOS product from AWI and Hamburg [http://data.seaiceportal.de/gallery/index\\_new.php?active-tab1=measurement&icetype=thickness&satellite=CS&region=n&resolution=weekly&minYear=2017&minMonth=4&minDay=3&maxYear=2017&maxMonth=4&maxDay=9&showMaps=y&dateRepeat=n&submit2=display&lang=en\\_US&activetab2=thickness](http://data.seaiceportal.de/gallery/index_new.php?active-tab1=measurement&icetype=thickness&satellite=CS&region=n&resolution=weekly&minYear=2017&minMonth=4&minDay=3&maxYear=2017&maxMonth=4&maxDay=9&showMaps=y&dateRepeat=n&submit2=display&lang=en_US&activetab2=thickness)), or to verify/test SMOS (in which case it is difficult to use a highly simplified model to do this).*

**Response:** As argued in our response to comment 2.1.1, the premise of the paper is that *both* the current versions of the observational ice thickness product *and* the reanalysis product contain substantial and systematic errors. Hence, careful additional investigation and expert judgement is needed if one wants to use one of them to verify or validate the other. What can be done is to contrast them, and to use independent data and process understanding to give indication as to which of the two is probably closer to the truth for certain identified features and regimes. This is the essence of the paper. We have revised abstract, introduction and conclusions of the manuscript to clarify this point.

Regarding the suggestion to use the combined CS2SMOS product, we note that problems in a multi-sensor product like CS2SMOS are even more difficult to track down. The CS2SMOS ice thickness might be closer to the truth than SMOS-SIT alone, but at the cost of traceability. Besides, our motivation is the potential use of SMOS-SIT for data assimilation. Operational centers are extremely unlikely to assimilate a multi-sensor SIT product, which in itself already is an analysis – it is much preferable to use products individually and let the analysis system find the best fit to observational data from different sources, that can be inconsistent between themselves.

We have revised the introduction and the conclusions to explain the purpose and scope of the paper better, and to better communicate the main conclusions.

## 2.3 Minor Comments

**Comment 2.3.1:** *Page 1 Line 22: “coverage at a”*

**Response:** Fixed.

**Comment 2.3.2:** *P2 L18 requires more specific objectives for the study, beyond simply compare observations with model. What exactly are you trying to achieve here? What exactly will the study provide that is useful for future work?*

**Response:** This is a valid point and urgently needed to give the right premise for the manuscript. We have revised the introduction to address that (see also responses to the

reviewer’s general assessment and general comments).

**Comment 2.3.3:** *P5 L28: is ORAS5 SIT < 0.3m impossible? In what situations do you get very thin ice? SIC very low? A “freeze-up threshold” is referred to later on but should be explained here.*

**Response:** Here and in several other comments the simplified treatment of thin ice in the model is addressed. As alluded to by the reviewer, LIM2 has a minimal floe (or in-situ) ice thickness – new ice will grow at this thickness. This is the “freeze-up threshold” that we are referring to. However, throughout the entire manuscript we compare the *grid-cell mean* ice thickness of the model with SMOS-SIT, because SMOS-SIT also gives the *mean* ice thickness. The thickness at which new ice forms is set to 0.6 m in ORAS5, so a mean thickness of 0.3 m corresponds to exactly 50% area coverage. Mean ice thicknesses below that do exist but are not as abundant (see Figure 1). We have added a sentence on P5 L28 to explicitly state that we compare the grid cell mean ice thickness from both SMOS-SIT and ORAS5. We have also revised added text after P5 L34 that properly explains the “freeze-up threshold” and puts it into context.

**Comment 2.3.4:** *P5 L34, you need to explain this non-linear dependence here or in the discussion. Clear dependence within the LIM2 ice redistribution function? Or from the single thickness class assumption? Or is this some bias introduced from SMOS?*

**Response:** We agree this needed more explanation. We have done some further analysis, with the result that both model and observation deficits mentioned on P5 L5–9 are likely to be important. We have added these results to the text, after the paragraph starting on P5 L26.

**Comment 2.3.5:** *P6 L23, this is a very qualitative description of the relationship. . . Can you explain?*

**Response:** We do not think that this is a qualitative, it is just putting in words what can be seen in the figure. The term “functional relationship” might be poorly chosen. We mean to say that there is a high rank correlation between the two variables (product correlation could still be low due to non-linearity). This can be exploited for a-posteriori calibration. We have reworded these sentences to clarify, referring to the rank correlation instead of a “functional relationship”.

**Comment 2.3.6:** *P6 L30, where are they assimilated? Outside the ice edge presumably?*

**Response:** Correct. No SST observations are assimilated in the presence of sea ice for the simple reason that the presence of sea ice makes a satellite observation of SST virtually impossible.

**Comment 2.3.7:** *P7 L7, There is lower SIC in Baffin Bay in April, so this could be caused by the SMOS-SIT assumption of total ice concentration within a grid cell? TB is biased due to the emissivity of open water.*

**Response:** This is an intriguing hypothesis that we had considered at an earlier stage of investigation but then dropped, assuming instead that the real ice cover is 100%. The intrinsic uncertainty of sea-ice concentration from PMR is a few percent even in optimal cases (Ivanova et al., 2015), and if these few percent dominate the L-Band emissivity this invalidates the SMOS-SIT retrieval assumptions. Assuming the TB is 240 K for thick sea ice and 90 K for open water, a simple calculation shows that every percent of open water in a previously closed ice pack will lower L-Band TB by 1.5 K. In the case of the Baffin Bay shown in Figure 5, the SMOS-SIT retrieved ice thickness decreases from

1 m in January to 0.5 m in April while the SMOS TB decrease from 240 K to 230 K and the PMR SIC from close to 100% to about 95% (albeit noisy).

Thus, it is plausible that SMOS-SIT has very low mean sea-ice thickness in late winter in the Baffin Bay because it misinterpretes the open-water L-Band signature. This can in principle be tested by restricting to cases where SIC is 100% with high confidence (e.g. where sea ice velocities are convergent or where MODIS visual imagery is available). We have added this hypothesis to the text.

Testing this hypothesis rigorously is outside the scope of this manuscript. However, we can get some indication by plotting the normalized joint frequency distribution (scatter density) of OSTIA SIC and SMOS-SIT SIT for the Western Baffin Bay. Figure 4 shows that there is moderate correlation between SIC and SIT, indicating that the open-water contribution to L-band emissivity matters, but does not dominate the signal.

We have added some discussion on this to the manuscript on P7.

**Comment 2.3.8:** *P7 L8, remove also and add appropriate Tilling citation.*

**Response:** Done.

**Comment 2.3.9:** *P7 L22, this is likely owing to low SIC. Linked to the second major point above, some more involved analysis SMOS-SIT sensitivity and higher frequency emissivity/SIC would be very useful and may allow you to make much more robust arguments for causes of obs/model bias.*

**Response:** This relates to comment 2.3.7. See our response there. The SMOS-SIT sensitivity to open water is not testable given the 100% cover assumption built into the current version of the retrieval algorithm, but it can be seen that it is large by simple back-of-the-envelope calculations (our response to comment 2.3.7, also see Richter et al. (2016)). We have revised P7 of the manuscript to include some discussion on the SIC-sensitivity of L-band PMR as suggested by the reviewer.

**Comment 2.3.10:** *P8 L5, close to 100%, but not at it, whereas most other regions have total ice concentration. Another thing to consider is that sea ice in Baffin Bay is fairly low latitude so could be melting some years in April and affecting the L-band penetration depth. What do the PMR data suggest in terms of melt onset date for Baffin Bay in 2012? Crucially, do you observe this clear bias every year for Baffin Bay?*

**Response:** Agreed, SIC even a few percent lower than 100% will have an important impact on L-band TB. We have revised the text (see response to comment 2.3.7). The second hypothesis of surface melt can be safely rejected for this case, as ice surface temperatures are well below freezing throughout (see Figure 5d in the manuscript). However, it might play a role in other winters.

We have followed the advice of the reviewer to produce the time series for *all* winters, and we have also calculated them for a spatial average over the Western Baffin bay area as defined by Landy et al. (2017), in order to reduce spatial sampling uncertainty. The result is that the behaviour documented in Figure 4 of the manuscript appears in all winters for the entire Western Baffin Bay (Figure 2 in this response).

**Comment 2.3.11:** *P9 L14, change “than” to “then”.*

**Response:** Done.

**Comment 2.3.12:** *P10 L16, this would be a much stronger argument if you could provide reasonable evidence as to why this happens. Do you even see the same biases every year? Could you test the interannual persistence of your regional biases? Again*



*this would be highly valuable to the community.*

**Response:** The point of the discussion on P10 is not to claim that there *is* systematic underestimation of sea-ice thickness by SMOS-SIT, but to describe the appropriate action to take in the *scenario* that this is the case (see P10 L10).

However, we can confidently demonstrate that these regional biases robustly occur each year (see our response to several previous comments, e.g. 2.3.10). We have added this to the manuscript, by reproducing Figures 2 and 3 for *all* years available, and by plotting the time series in Figure 4 for all years available and as an area average over the western Baffin Bay (Figure 2 in this response).

**Comment 2.3.13:** *P10 L23, surely more relevant here is the need to improve the rheology and add formulations to the numerical scheme to allow for polynya development, rather than just assimilating observations and the model re-equilibrating to incorrect/overestimated ice thickness?*

**Response:** We agree, it is much preferable to remove the model bias rather than forcing the model out of its natural state by data assimilation. However, in practice model and data assimilation developments are often not well synchronized, so that data assimilation does correct for model biases. In most cases, assimilating in the presence of model bias is still preferable to not assimilating, because it leads to better time-evolving state estimates, and because forecasts are improved at least for short lead times when the model has not had time to re-develop the bias.

**Comment 2.3.14:** *P12 L18, this is an important limitation that could have been examined in greater detail within the main paper.*

**Response:** Agreed. We have added more discussion on that to the main text, also in response to comments 2.3.7 and others.

**Comment 2.3.15:** *P13 L13, this is a very useful finding that could be represented better in the main paper and given as one of the papers main conclusions.*

**Response:** This comment ties into the general comment 2.2.1, see our response there. We agree that this is an important aspect, but it is impossible to draw useful quantitative conclusions on this from a purely diagnostic point of view (which is what we do in this paper). We think it can only be a strong conclusion in a study that explicitly changes parameters of the retrieval algorithm to study its limitations and sensitivities, and it would be a rather weakly defended conclusion in the context of this manuscript.

**Comment 2.3.16:** *Fig 2, explain what unc, sic etc. mean within figure caption.*

**Response:** Done. We have also added these explanations to the main text.

**Comment 2.3.17:** *Fig 2, is it impossible to get forecast SIT below 0.3 m when SIC is low (i.e. when SMOS-SIT is around 0)? Why?*

**Response:** No it is not impossible, see Figure 1 in this response. The apparent gap is due to the filtering applied, where only data points with SIC > 30% are used.

**Comment 2.3.18:** *Fig 3, does (c) show saturation in the SMOS-SIT signal above approximately 0.5 m? Plateaus above this value, so no sensitivity from L-band signal?*

**Response:** It should not be lack of sensitivity, because all data points shown have a SMOS-SIT saturation ratio of below 90% (i.e. the retrieved SIT is 90% of the maximally retrievable SIT under these conditions). However, there could be a conceptual problem with the saturation ratio provided with the SMOS-SIT product.

**Comment 2.3.19:** *Fig 3, doing this for only one years winter enhances the possibility for anomalous ice conditions to explain the departures between observed and predicted IT. What do these look like for multiple years? Your arguments would be more convincing if similar patterns of regional biases were found in several/all years.*

**Response:** We fully agree and have taken this excellent suggestion on board. We have updated Figure 3 to include data from *all* winters, and find that the departure characteristics appear in all years.

**Comment 2.3.20:** *Fig 4, Mark on a map either here or on Fig 1. Adding a panel of SIC would be very useful for analysis.*

**Response:** We have marked the locations in Figure 1 as suggested. The SIC time series is already shown in Figure 5b, we have added a reference to the caption of Figure 4.

**Comment 2.3.21:** *Fig 4, “added and subtracted” what? Uncertainty?*

**Response:** We have added the word “uncertainty” to the caption. Apologies for the omission.

**Comment 2.3.22:** *Fig 5c, why does snow depth appear to drop considerably throughout the season?*

**Response:** It only drops in SMOS-SIT, not in ORAS5. The simple reason for the snow thickness drop in SMOS-SIT is that the retrieval algorithm assumes a snow thickness that is a piecewise linear function of ice thickness (Tian-Kunze et al., 2014). Thus, snow thickness in SMOS-SIT is not an independent parameter. In this case, one might argue that this leads to an unrealistic snow thickness. However, sensitivity of retrieved SIT to snow thickness is relatively small.

**Comment 2.3.23:** *Fig 5e, ice emissivity masked by overlying snow?*

**Response:** Dry snow is transparent in L-band and therefore does not mask the ice emissivity. Snow only enters the SMOS-SIT retrieval algorithm through its thermal insulation qualities: more snow means the ice is better insulated against the cold atmosphere, and bulk ice temperature tends to be higher, which changes the ice emissivity.

**Comment 2.3.24:** *Fig 6, remove “none”.*

**Response:** Fixed.

## References

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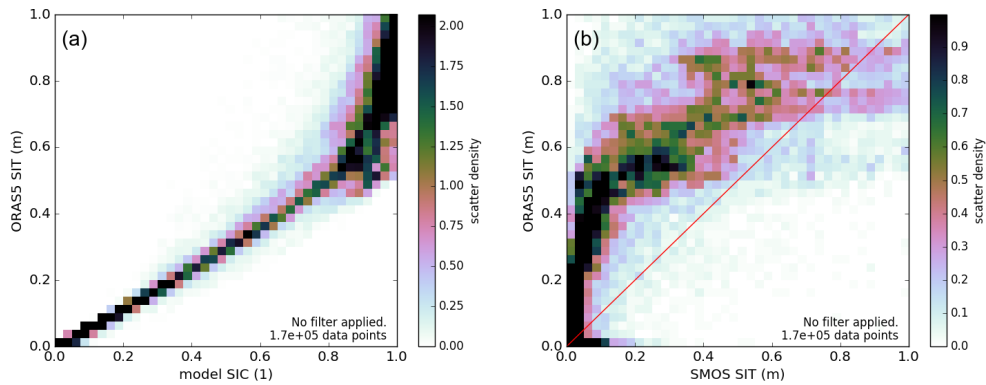


Figure 1: Joint frequency distribution of (a) ORAS5 SIC and SIT and (b) SMOS-SIT and ORAS5 SIT calculated for 15 November 2016 (the date for which the upper row of maps in Figure 1 of the manuscript is shown). All data points with a valid SMOS-SIT value have been considered, no filter was applied.

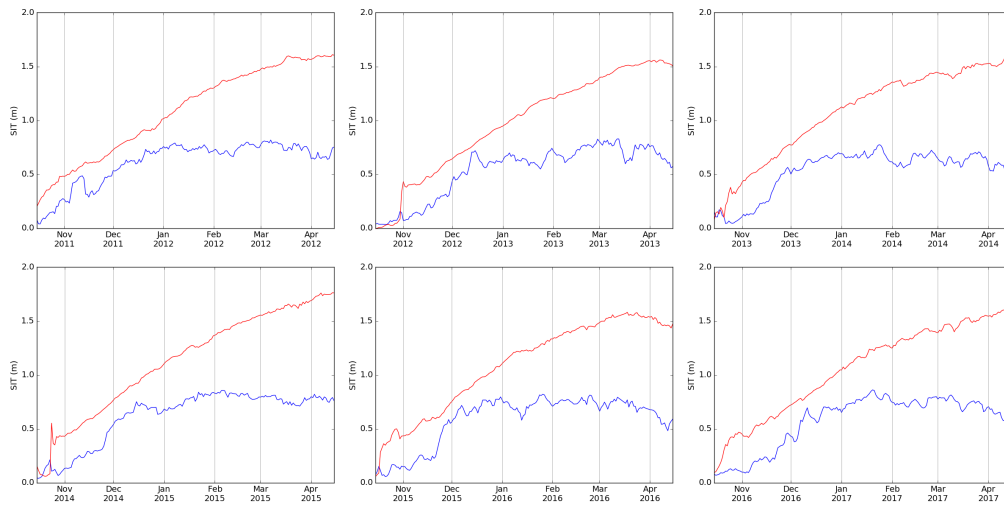


Figure 2: Time series of ice thickness in SMOS-SIT (blue line) and ORAS5 (red line) for the winters 2011/12 to 2016/17. Thickness is calculated from all data points within the box 80W–64W, 67N–75N, which corresponds to the Wester Baffin Bay area as defined in Landy et al. (2017).

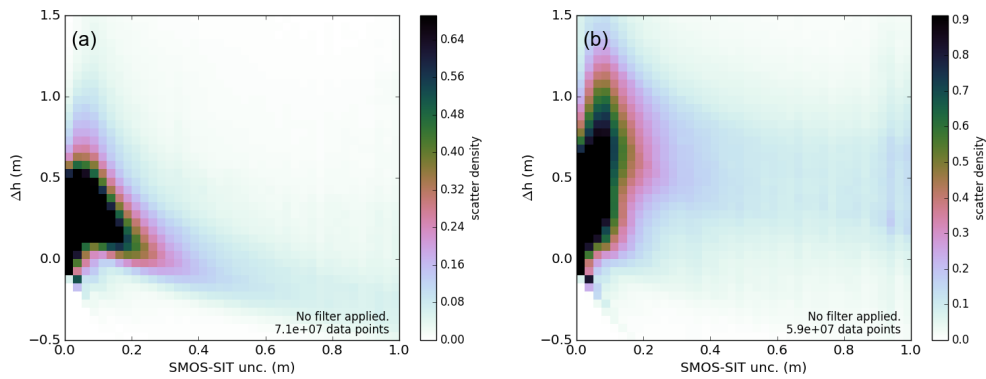


Figure 3: Normalized joint frequency distribution (scatter density) of pairs of SMOS-SIT retrieval uncertainty and SMOS-SIT-ORAS5 departures; (a) October to December 2011–2017, (b) February to April 2012–2017. All data points with a valid SMOS-SIT value have been considered, no filter was applied.

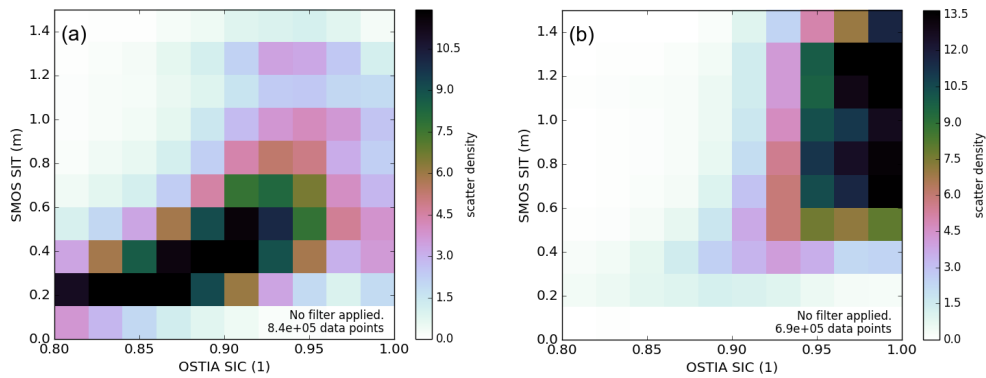


Figure 4: Normalized joint frequency distribution (scatter density) of pairs of OSTIA SIC and SMOS-SIT SIT within the box 80W–64W, 67N–75N (roughly corresponding to the Western Baffin Bay as defined by Landy et al. (2017)); (a) October to December 2011–2017, (b) February to April 2012–2017. All data points with a valid SMOS-SIT value have been considered, no filter was applied.