We want to thank both of the reviewers for their comments and suggestion which helped to improve the manuscript. We hope that our explanations address the issues raised by the reviewers and will make the manuscript more clear.

We have thoroughly revised the manuscript to address the reviewers comments. In particular we have added a section discussing the uncertainties and sea ice concentration influence of the retrieval. Five more figures showing a) SIT bias and RMSD (daily variability and for bins of thickness) between daily averaged and 45 deg fit SMOS TBs - as a replacement for Fig. 3, b) Density plots with linear regression between SMOS 40 deg and SMAP data c) SIT sensitivity to change in horizontal and vertical brightness temperature ; d)SMOS 40 deg and SMAP SIT vs SIT uncertainty for a selected day 3) SIT retrieved as function of an assumed SIT under different sea ice concentration values. To Figure 5 we added a third map with SMOS at 40 deg SIT - SMOS+SMAP.

Answer to Anonymous Referee 1:

The paper entitled 'Combined SMAP/SMOS thin sea ice thickness retrieval' by Patilea et al. proposes a combined sea ice thickness (SIT) retrieval using SMOS and SMAP brightness temperature. First, authors present an algorithm to retrieve SIT from improved version of SMOS TB. Secondly, a SMAP calibration at 40 deg with SMOS is proposed. Finally, a combined SMOS+SMAP SIT retrieval is attempted. Although, the combined use of SMOS and SMAP circumvents several issues and has a lot of potential, more work needs to be done before the manuscript can be recommended for publication.

General comments:

Full validation, as mentioned by the authors on the last line of the paper, needs to be considered in this paper itself. Without validation, it is difficult to assess the performance of the proposed algorithm (s) – one from new version of SMOS TB, second from combined SMOS+SMAP.

The other major issue is the differentiation between contribution of TB from sea ice concentration (SIC) and thin sea ice. It is not clear from the paper, whether the authors assumed 100% SIC or above 80% or all 0-100%? If SIC less than about 80% is used, then thin ice retrieval is incorrect. A SIC map would be very useful. These point should be discussed in the paper.

As in Huntemann (2014), the same three areas (in the Kara and Barents Seas) over the same period were selected for the training of the SIT retrieval. The assumption is that SIC is 100%. For the training, SIC between 0 and 100 was allowed for the initial freeze-up to not miss the formation of very thin sea ice due to the SIC retrievals. Section 5.1 was included to discuss the SIT uncertainty that is introduced by SIC uncertainty.

Unfortunately, the paper does not show the validation part of this work, so it makes it very difficult to assess the retrieved SIT in the areas where SIC is below 80%. It is likely that the thin ice area shown in Figure 5 may be, in fact, marginal ice zone with SIC less than 80%.

I miss an error analysis, maybe you could cite the error budget from Huntemann.2014.

The retrieval error of 30% that we refer to in the manuscript is taken from the Huntemann et al., (2014). We have added it as a reference at the necessary location in the manuscript (P7L14). You are right that for the MIZ with SIC less than 80% the heterogeneity within the SMOS and SMAP footprints will cause larger uncertainties and the derived ice thickness will include the open water areas. This is a problem of all SMOS thin ice thickness retrieval available today. To resolve that problem is not the purpose of this paper. An estimate of the error introduced by SIC is presented in Section 5.1.

In Figure 1, it would be easier to read if you show sit of the same date as shown in Figure 5 SIT retrieval, i.e. 29 Oct. 2010 OR 11 Oct. 2015.

The 2010 date for Figure 1 was chosen because of two reasons:

1. it's in the freeze-up period of the 2010 which was used for the training of the SIT retrieval curve
2. it shows the difference in intensity for the same day between the two SMOS Level 1C data versions 5.05 and 6.20. The Huntemann paper has used SMOS 5.05 data for training the algorithm, data version that was discontinued after the release of 6.20. Thus the overlap available for comparison between the two datasets is pre-2015 freeze-up.

Since the new data version introduced some biases in the TBs as mentioned in P3L14-P3L16 and the Huntemann algorithm together with the new data version was used later as a reference as mentioned in P5L23-25, we compared the Huntemann algorithm using the two data versions as shown in Section 3.1
As a result Figure 1 can't be redone in the freeze-up period of 2015 due to the lack of 5.05 data, while Figure 6 (was Fig. 5) can't be moved to 2010 because it is before the launch of SMAP thus we cannot adapt the two figures to show the same date.

There are spelling errors throughout the paper.

We carefully reread the paper and corrected many spelling errors to the best of our knowledge.

Specific comments:

P1.L5: 'SMOS data covers a large incidence angle range whereas SMAP observes at a fixed 40° incidence angle which makes thin sea ice thickness retrieval more stable as incidence angle effects do not have to be taken into account'. I do not agree that the incidence angle variation of SMOS brings instability on the measurements. Explain it better to convince the reader or remove the sentence. SMAP is more stable because it is a real aperture antenna, better RFI control system, narrower swath, etc...

We considered mainly two factors for this affirmation:

1. depending on the position in the swath (closer to the center or to the edge) for a pixel, the distribution of the incidence angles recorded during one overpass will be different due to the nature of SMOS snapshot
2. the RFI filter used in Huntemann et al. removes the snapshots that contain even one data point >= 300 K. If I take as an example a source on land that is active during an overpass from land to ocean, this will result in the elimination of data points of higher incidence angle (if we consider an ocean pixel along the trackline) while after the source is cleared just the remaining incidence angle data points will be used for the mean.

Taking in account the previous two points if we consider the retrieval using the 40-50 deg mean brightness temperature, in some cases the resulting mean incidence angle for a pixel can be be at the ends of the this range. Due to the divergence of the horizontal and vertical brightness temperatures with increasing incidence angle, the resulting polarization difference can change significantly. Since the divergence is asynchronous (with horizontal Tbs decreasing faster than the increase of the vertical polarization Tbs) especially at lower brightness temperatures also the average intensity can change.
Since the retrieval doesn't take into account the actual average incidence angle it introduces additional uncertainty.
The sentence P1L3 will be change to: "SMOS data covers a large incidence angle range whereas SMAP observes at a fixed 40 deg incidence angle which makes thin sea ice thickness retrieval more consistent as incidence angle effects do not have to be taken into account".

P1.L20: The radar system of SMAP failed few months after launched. You should specify this, is you talk about the radar system.
This information will be added to the manuscript. Added at P2L5.

P2.L12: 'Within a snapshot just one or two of the Stokes parameters are measured at the same time'. Please explain this properly, this sentence has no sense. Explain when one or two are measured?
The explanation will be expanded to make it more clear P3L5-8 : "When just one of the Stokes parameters is measured, all three arms of the sensor record the same polarization. In the case of recording a cross-polarized snapshot, one arm of the sensor records a polarization while the remaining two arms the other. Measurements of single (XX or YY) and cross-polarization ((XX, XY) or (YY, XY)) are done alternatively."

P2. L23: 'SMAP started providing data starting in April 2015.' Re-phrase.
Sentence will be rephrased. Rephrased and moved to the end of the paragraph P3L25.

P.2.L8. It is not clear to me which is the RFI filtering method used in this paper, the one in Huntemann et al 2014, or 2015?

Neither of the two methods are employed for the retrieval that is using the fitted brightness temperatures. The method from Huntemann et al. (2014) was used just for the 40-50 deg retrieval (both 5.05 and 6.20) in Section 3.1. Huntemann et al. (2015) is referenced to show an alternative to the previous filter. It preserves more data improving the overall coverage.

For this paper the RFI filtering for SMOS is done in two steps:

1. using the flags included in the Level 1C SMOS data product as mentioned in P6L6-8
2. afterwards by the iterative process which eliminates the data with the highest absolute difference from the fitting curve

For SMAP data we use the quality flags for filtering.
The third paragraph of Section 3.2 (P6L8-21) will be modified to make it clear that the iterative process is the second step used for RFI filtering.

p3.L25: You should explain that a resolution of 12.5km is a subsampling grid, this is not the real SMOS resolution. In fact, in my opinion, it has not sense to go to 12.5Km, only with SMOS data, you should use the grid of 25km. In case you use other data with thinner resolution combined with SMOS then you could go to 12.5km, if not this resolution is completely false. You should explain this clearly in the paper.

A sentence will be added explaining the fact that the SMOS and SMAP spatial resolution is approximately 40 km not 12.5 km (P5L5). Also the resolutions of the two satellites will be added in the Section 2 (P2L29,P3L23).
The two reasons for choosing this grid is consistency with the older SIT product which is provided in this resolution and the fact that SMOS L1C product from which we start is already oversampled to 15 km.

Eq. 2: It is very dangerous to use in the equation of Q the exponential of a number which is raised to d (Q=(a-b).exp(-x/c)^d)+d), it makes the model inestable. But I imagine this comes from Huntemman 2014 method...

Yes, the two functions I and Q that were fitted to the training data come from the Huntemann et al., (2014). The parameter d is determined only once, during training. As presented in that paper, the function for Q was chosen empirically to represent well the polarization difference from the training data as dependence on the sea ice thickness.

P3.L28. Please explain – spillover effects. Or Re-word.
Explanation will be added (P5L8-9). - The spillover produces an erroneous increase or decrease in brightness temperature of 1 to 1.5~K in the high contrast areas (land/ocean, sea ice edge). The value of the TB change is taken from the SMOS Calibration Team reference.

P4.L9-10. 'Also…version.' Please re-write the sentence. It's unclear.
Will be changed. (Whole paragraph rewritten P5L15-20)

P4.L22: 'Moreover,…' , here you are talking about your method to remove RFI and averaging the TB, not on the SMOS acquisition method. This should be specifed, if not, it seems this is a problem of SMOS, since the previous sentence you talk about the SMOS acquisition method. This sentence starting with 'Moreover,' I understand is the basis to explore the new method of ftting a curve, so please explain this clearly.

In this section we tried to explain why using a fit function for TBs of SMOS should improve the results compared with the old algorithm. We considered that:

1. due to the geometry of the snapshot, different incidence angles distributions are available to one pixel along the trackline during an overpass
2. the 300 K threshold RFI filter that will remove whole snapshots.

These two issues alone or together can generate biases in the resulting averaged incidence angle distribution for a pixel. This issues are eliminated by using a retrieval at a fixed incidence angle which is achieved by using all the data points available for one pixel and fitting them with a curve. See also our answer to your comment regarding P1L5 above. The paragraph will be update (P5L27-P6L2) with a more clear explanation based on this and the above P1L5 answer.

P5.Eq 3: Are the values of a, b, c, d the ones in table 1? This is not cited here. And are bh and bv from the equation different? I don't see the values of H and V pol in table 1. Moreover, bh and bv, they should be equal, to permit to have Tbh=TBV at Theta=0 (nadir).

Equation 3 represents the brightness temperature fit functions while Table 1 represents the parameters for the Sea Ice Thickness retrieval used in Equation 2. Regarding the two parameters at nadir sin^2 will be 0, eliminating bh and bv parameters while the cosines will be 1 therefor the only remaining value in both equations is C/2 representing the intensity at nadir.

P5.L23. Figure 4 is mentioned in the text before Figure 3. Please correct it.
The change will be done. Figure 4 became 3, while Fig. 3 was replaced with a new figure and move on position 4.

P6. L1: You talk about 'estimated retrieval error of 30% of SIT'. This is not commented before, from where do you have this value? Please add reference. Which method has this retrieval error? The daily of the 45º? Please discus better the error budgets as well.

Reference for the 30% retrieval error will be added. The error estimate was computed for Huntemann et al. (2014), it is done for the 40-50 deg daily mean retrieval. Since we consider that the retrieval itself wasn't changed, just the parameters of the retrieval curve (due to the new fitted TBs at a fixed incidence angle that went into the retrieval) the error budget should still be consistent with the retrieval. In addition a new Section discussing the uncertainties in the retrieval, including SIC will be added. (Section 5 added)

Figures:

Figure 1 and 4: Increase font size.
Font size will be increased.

Figure 5: Please also show the SIT map derived using SMAP only, and SMOS only for the same date alongside SMOS+SMAP SIT map. This will make it easier for visual comparison.

The differences between the SMOS and the SMAP maps are very small and noisy and will not add much information. We will add a difference map between the mixed and the 40 deg

SMOS retrieval which will indirectly show the distinctions between the two sensors without cluttering the figure.

References:

-Please add webpage from where to fnd the documents used in the references (Indra Systems and SMOS Calibration…). I am sure they are public.
Links will be added.
SMOS Calibration Team:
https://earth.esa.int/documents/10174/1854503/SMOS_L1OPv620_release_note

The link to the Indra Systems is down for the version cited, an older version which still includes the referenced part is found here (pag. 305):
https://earth.esa.int/documents/10174/1854583/SMOS_L1_Aux_Data_Product_Specification

If the original link will not be restored, the reference will be changed to this one.

-I think the references should order it for name of frist author and year. So reference 3 and 4 should be switch.

The ordering is done automatically by the bibtex style file. My understanding is that multi author papers come after dual author ones regardless of the year of publications thus even if the third reference is from a latter date it will still come before the fourth one. Anyway, we assume that the bibtex style file will produce a correct order as needed by the journal.

Answers to Anonymous Referee 2:

The paper by Pațilea et al. deals with retrieving thin sea ice thickness (SIT) from L-band radiometry using brightness temperatures (TB) from two different satellite missions: SMOS and SMAP. The study mainly deals with three things: 1) An existing SIT retrieval is applied to a newer data version of SMOS. 2) A slightly different approach to fit TBs in the SMOS retrieval is applied (using a TB fit to a specific incidence angle, e.g. 45°, instead of using the average TB from measurements between 40 and 50°). 3) SMAP TBs are "converted" to be used in the SIT retrieval, which was originally set up for SMOS, and combined SMOS and SMAP SIT maps are produced. The produced maps are compared with each other but not compared with independent SIT data.

Unfortunately, the used methods are not described precisely enough (see, for example, comments 6), 10), 11), 12) below). Furthermore, the Level 1B SMAP data is claimed to be "top of the atmosphere" TBs, i.e. atmospheric effects are not taken into account. However, according to the Algorithm Theoretical Basis Document (ATBD): "SMAP Calibrated, Time-Ordered Brightness Temperatures L1B_TB Data Product" [1] and De Lannoy et al. (2015) [2], for example, SMAP Level 1B TB data are "corrected for atmospheric effects". As far as I know, this is also one of the reasons why SMOS (Level 1C) TBs (which are not corrected for atmospheric effects) and SMAP (Level 1B) TBs differ. Thus, it is not clear how the authors dealt with this. In general, I think the differences between SMOS and SMAP should be discussed and presented in more detail.

Regarding TOA TBs of SMOS and SMAP: Yes, SMOS L1C data that is used here do not contain atmospheric correction. While SMAP L1B data files contain both both surface TBs and TBs before correction (including the TB correction it self). This allowed us to choose TOA TBs for SMAP since they are contained in the data files.

Link for data fields in the SMAP L1B: https://nsidc.org/data/smap/spl1btb/data-fields#toa_v

Section 4.1 dealing with the SMOS/SMAP intercalibration will be overhauled and should explain more clear the differences between the sensors (the possible SMOS bias mentioned in SMOS Calibration Team reference and TOA SMAP TBs are corrected for extraterrestrial noise) in the data from to sensors. (P8L15-P9L15 added/modified for explanations)

Another issue is that there is a study by Huntemann et al. (2016) [3] that deals with using SMOS and SMAP for ice thickness retrieval and shows a resulting map (it is mainly with the same authors). The paper ([3]) gives the difference between SMAP and SMOS retrieved SIT for Oct to Dec 2015 and contains a SMAP SIT map and the SIT difference between SMAP and SMOS for 7 Oct 2015, while the paper presented here compares the combined SMOS and SMAP SIT with SMOS SIT and shows a combined SMOS and SMAP SIT map and how it differs from SMOS SIT for 11 Oct 2015 (Fig. 5). As these two studies seem to deal with very similar things, I think it is very important to clearly state the difference and the "added value" of the study presented here. My main concern is that there is already a paper ([3]) that shows how SIT retrieved from SMAP compares with SIT retrieved from SMOS (for the TB polarization difference and intensity approach) for Oct to Dec 2015. The new thing in the study presented here seems to be that SMOS and SMAP SIT are not compared but instead averaged to form combined SIT maps, and these have been compared to SMOS-only maps for Oct to Dec 2015 (I think this is the period, see comment 19)). However, as it is not clear how the SMAP SIT or the combined SMOS and SMAP SIT compare with independent SIT data, just combining the two data sets, as done here, does not necessarily bring new information.

The Huntemann et al. (2016) used the L1C SMAP data, which means gridded and corrected data. In the current paper we used L1B SMAP data which is not gridded and also gives the possibility of choosing Top of the Atmosphere (TOA) TBs which should be closer to the SMOS L1C data which is TOA.

The most important new thing in this paper is the introduction of the fitting function for the SMOS brightness temperatures. This is used for the following things:

1. the iterative process used to determine the fit function parameters in which we removed the highest 20% of data with absolute difference from the fit is replacing the 300 K threshold RFI filter used before. This is additionally to the RFI flags that were included in the new SMOS 6.20 data version and now are used for a preliminary filtering
2. the fit function allows for computing SMOS TBs at a fixed incidence angle. As it is mentioned in Section 3.2 and 3.3 this removes possible incidence angle biases that would have appeared in the 40-50 deg incidence angle averaging, making the retrieval more self consistent and allows computation of a new retrieval curve based on the fixed incidence angle data.
3. regarding SMAP/SMOS calibration and retrieval: in Huntemann et al. (2016) the retrieval curve is it was done using two linear regressions between, first the SMAP TBs were compared 40-50 deg to 38-42 SMOS TBs, to bring SMOS data to an approximate incidence angle of 40 deg.

Section 4.1 will be changed to try to make it more clear what are the differences relative to the Huntemann et al. (2016) paper and improvements that the current paper. Main differences are: here we use TOA TBs, the SMAP data is used for a retrieval trained for 40 deg L-band data (SMAP incidence angle), while in Huntemann et al. (2016) the retrieval was done using the 40-50 deg trained retrieval. The adjustment of SMAP TBs had to take in account also this difference while now, this is not necessary.

P9L1-15 goes into detail regarding the differences between the two papers.

The manuscript contains several spelling errors that could have been avoided by simply using a spell checker (thus I will not point them out). Furthermore, the style of writing could be improved and the usage of commas should be revised. Not all statements are supported by references (or a reference is given that I cannot find/access), see specific comments below.

Specific comments:

1) Introduction:

- I think the introduction should be improved in that the work presented here is put more into a scientific context. Is this the first time SMOS and SMAP are merged? What are the "challenges"? Why not elaborate more on the differences between SMOS and SMAP? This is not mentioned at all in the introduction (only shortly in the abstract but that should be independent). In general, I think that the introduction (especially starting from p. 1, l. 22) may be hard to understand for those who are not very familiar with the SMOS SIT retrieval and the SMAP mission.

The differences between SMOS and SMAP will be made clear: fixed vs variable incidence angle range (resulting in different swath size), synthetic vs real aperture, SMAP containing correction for ~~extraterrestrial noise~~ (we decided against adding extraterrestrial noise to the introduction to not clutter it since this is related more to the data products used) and onboard RFI corrections mechanisms. This issues will be addressed. References to previous attempts for SMAP SMOS TB comparison will be added in introduction. (P1L10-P2L14)

- No references given for statements made in the first lines of the introduction (p. 1, l. 10-13) and for "The atmosphere has little influence on the radiation at L-band as both absorption and scattering are small." (p. 1, l. 16-17).

Proper references will be added:

"Sea ice as an important climate parameter" (P1L10)

- Moritz et al., (2002), Dynamics of recent climate change in the Arctic, Science, 297, 1497–1502
- Holland et al., (2010), The sea ice mass budget of the Arctic and its future change as simulated by coupled climate models, Clim. Dyn., 34, 185–200,
- Stroeve et al., (2007), Arctic sea ice decline: Faster than forecast, Geophys. Res. Lett., 34, L09501,

"Sea ice inhibits evaporation, reduces heat and gas exchange between ocean and atmosphere and increases the albedo" (P1L14)

- Maykut, G. A.: Energy exchange over young sea-ice in the central Arctic, J. Geophys. Res., 83, 3646–3658, 1978
- Perovich et al., (2012), Albedo evolution of seasonal Arctic sea ice, Geophys. Res. Lett., 39, L08501

"... resistance against the deforming forces … " (P1L12)

- Häkkinen, S.: A constitutive law for sea ice and some applications, Mathematical Modelling, 9, 81–90, 1987
- Yu, Y., Rothrock, D. A., and Zhang, J.: Thin ice impacts on surface salt flux and ice strength: Inferences from advanced very high resolution
- radiometer, Journal of Geophysical Research: Oceans, 106, 13 975–13 988, 2001

"The atmosphere has little influence" (P1L25)

- N. Skou and Dorthe Hoffman-Bang, "L-band radiometers measuring salinity from space: atmospheric propagation effects," in *IEEE Transactions on Geoscience and Remote Sensing*, vol. 43, no. 10, pp. 2210-2217, Oct. 2005

2) Several sentences start with "It" or "This", which can make reading hard because it is not always clear what "it" or "this" refers to (especially if referring to something mentioned in the last sentence or even earlier...).
Example 1 (four sentences in a row): "and it will be used... This is combined ... It is used for... This is also..." (p. 1, l. 24 - p. 2, l. 1)
Example 2: "It adds better ... At the same time it ..." (p. 2, l. 17-18)

The sentences where “it” and “this” add confusion will be changed to clear the confusion.

3) p. 2, l. 9-15, including eq. (1): Maybe this section is not needed because this is not the focus of the study and seems to be the same approach as in Huntemann et al., 2014?

We consider that since for this article all the SMOS data processing on our side starts from the antenna frame of reference. Also for the first step in removal of contaminated RFI observations (Section 3.2 - will add extra sentence for clarity (P6L6-7)) is done using the flags contained in the data files: the flagging and removal is done before the antenna to earth reference frame change.

4) Statements on p. 2, l. 17 ("It adds better RFI flagging...") and l. 20-21 ("The new data version also reduces... ") are not supported by references. Is "SMOS Calibration team and Expert Support Laboratory Level 1, 2015" the reference for these? I cannot find or access this. Please provide a web link or other hints how to find this. Also the "Indra Sistemas S.A.: SMOS Level 1 and Auxiliary Data Products Specifications, Product Document, Madrid, 2015" reference may contain more information to make it more easy to find. References for statements in p. 2, l. 29 - p. 3, l. 3?

Will add relevant links for the SMOS Calibration Team and Indra Sistemas documentation. The better RFI flagging is mentioned in the SMOS Calibration Team document at P2-Section 2 and P7-Paragraph g). For the differences between ascending and descending overpasses see Figure 2 from the same document.

SMOS Calibration Team:
https://earth.esa.int/documents/10174/1854503/SMOS_L1OPv620_release_note

The link to the Indra Systems is down for the version cited, an older version which still includes the referenced part is found here (pag. 305):
https://earth.esa.int/documents/10174/1854583/SMOS_L1_Aux_Data_Product_Specification

5) p. 2, l. 18-19: "... it introduces a warm bias in the brightness temperatures of aproximately 1.4 K relative to the previous version 5.05 over ocean..." -> Is 1.4 K warmer brightness temperatures over the ocean more/less realistic? Or just a trade off to get the SMOS brightness temperatures over land (and Antarctica) closer to modeled and measured values? But for this study this is not important anyways because no changes were observed for the high latitudes? This is somewhat confusing…

The information is taken from the SMOS Calibration Team document P4-Section 4-paragraph a). It is suggested that the 6.20 ocean TBs might be approximately 1 K too warm respective to modeled values and 1.4 K warmer relative to the old version. The difference is also seen in Figure 1 (now Figure 2) from the our article, with the intensity for the 6.20 data being higher compared to the 5.05 version, same as in the manuscript. The sentence mentioning the high latitudes is referring just to the ascending/descending differences as they can be seen in Figure 2 of the SMOS Calibration Team document. We will rephrase this paragraph to make it less confusing (P3L14-19).

6) p. 2, l. 29 - p. 3, l. 5 two RFI filters are described. However, it is not mentioned which RFI filter approach is used in the study presented here. Later (p. 4, l. 28-30) you describe a third RFI filter method. Were different RFI filters used for different parts of this study?

A third method is used for removing RFI. Section 3.2 will be updated to make it more clear that RFI removal is done in two steps: first by eliminating L1C data that is already flagged with RFI as was already mentioned in (P6L4-7) and second, the data removal in the iterative process is used for eliminating possible remaining RFI influences (P6L19-21). (answered more detailed for Referee 1 P2L8 comment)

7) p. 3, l. 12-14: "retrieval based on a fitting function ... through the full incidence angle range. This will provide more stable brightness temperatures and is necessary for a consistently combined SMOS and SMAP ice thickness retrieval." -> What is the "full incidence angle range"? Why is this "more stable"? More stable than method by Huntemann et al., 2014? Is that a result of the work presented here? Or has that been shown somewhere else (where?)? Please clarify. Why is fitting through the full incidence angle range "necessary for a consistently combined SMOS and SMAP" retrieval if SMAP measures only at one incidence angle?

By full incidence angle range we mean that for each grid cell we use the observations from all available incidence angles instead of restricting them to the 40 to 50 deg only as was done in Huntemann et al., 2014.

By using the fit function now we can compute the TB for a grid cell at an exact incidence angle removing the variation of the incidence angle that could appear in the daily averaged observations. Because of the dependence of brightness temperature on incidence angle, a difference in TB between two grid cells can come just due to a difference in the resulted averaged incidence angle. We consider the TBs resulted from fitting more stable due to the removal of the incidence angle effects. This is problem is discussed in the first paragraph of Section 3.2 and 3.3. We removed the sentence in P3L13 because it was adding confusion to Section 3 which doesn't deal with SMAP.

The fitting process allows obtaining SMOS TBs at a fixed incidence angle. This means that we can compute SMOS TBs at 40 deg, the incidence angle of SMAP, removing possible incidence angle biases either for the retrieval itself or during the training of the retrieval curve. Having both TB sets at the same incidence angle makes the combination of them consistent.

8) p. 4, l. 6: "From a total of 5.1 million data points,..." -> Where does this number come from? All Arctic data points from a certain time period?

It represents the cumulated data points from all the 87 days (1 October - 26 December 2010) where we select just grid cells that contain retrieved ice between 1 and 50 cm for at least one of the two algorithms. Sentence will be updated to make it more clear (P5L13).

9) p. 4, l. 19-22: Maybe a reference to a paper that describes the SMOS snapshot geometry would be useful here.
Reference added - Font et al., - SMOS: The Challenging Sea Surface Salinity Measurement From Space, Proceedings of the IEEE, 98, 649–665, 2010. (P5L28)

10) Where do the equations in eq. (3) come from? How is C "determined by averaging the sum of the polarizations for each observation" (p. 4, l. 33-34)? After all fit parameters ah,av,bh,bv,dv have been determined first (are they determined for each observation? for each incidence angle range? as generally valid values?) ?

Equation 3 comes from the Zhao paper. We will change (P6L3) the sentence where the paper is mentioned to refer to the equations (Section 3.2, paragraph 2).

Regarding C: 1. we will correct the manuscript. The correct procedure is not averaging but taking the median (P6L10) 2. for each grid cell we have a large number of observations per day. For each observation we have the TB at two polarization. These two values are summed up for each observations and then we take the median of the result. This represents C. An extra sentence will be added to explain why the median is used and not the mean (P6L10). As was mentioned in the paper at P5L30 we consider C/2 to be the intensity at nadir.

At each step first C is computed and afterwards the other five parameters are determined through a least squares procedure. This is done separately for the two polarizations with ah, bh for horizontal and av,bv and dv for vertical. One set of six parameters is valid for one individual grid cell for one day. As was mentioned in the paper at P6L8, we don't consider the fit to be optimal for extrapolation that the incidence angle range valid is just in between the minimum and maximum incidence angle contained by the observations.

The paragraph that starts at P6L8 is modified to better explain the fitting process.

11) p. 5, l. 9-10: "only grid cells with the incidence angle range of observations that covers the wanted angle, e.g. 45◦, are used for the retrieval" -> What is the exact criterion here? (e.g. "only grid cells that contain at least N observations with incidence angles θ±Δθ around the considered incidence angle θ")

One grid cell contains data points at various incidence angles. We will consider for retrieval just the grid cells that have observations with incidence angles both below and above the required angle for retrieval. If the desired angle is either higher than the observation with the maximum incidence angle or lower than the one with the minimum angle, the grid cell will not be considered for retrieval. There is no minimum incidence angle range around the required angle nor minimum number of observations. The sentence will be modified to make it more clear (P6L23).

12) p. 5, l. 27-30:
-"On the other hand for many ocean areas which formerly were excluded by the RFI filtering (grey in Fig. 4 left) now data is available, e.g. around Iceland, Eastern Greenland and Vladivostok." -> I don't know which TB measurements are used for the "fitted 45° brightness temperature" method… The text says that you need "at least one observation under 40°" and that you use "only grid cells with the incidence angle range of observations that covers ... 45°" (see also comment above). If the latter means, for example, that you use incidence angles between 40 and 50° PLUS at least one measurement with incidence angle <40° (which adds at least one more possibility to encounter an RFI-contaminated observation), how can this method be less influenced by RFI than the algorithm that uses the daily mean from measurements between 40 and 50°? Is it because of different RFI filters? (see also comment 6)) Is there a minimum number of measurements that has to be available in order to perform the SIT retrieval?
-"At the same time in the area of the Hudson Bay there is a 30% decrease in the area covered due to the high uncertainty of the fit." -> How does the "high uncertainty of the fit" influence the number of grid cells the retrieval is performed on? Is there a criterion for cases in which the retrieval is terminated / not performed? Is that given anywhere in the manuscript?
- Is the same number of SMOS measurements used for both retrieval approaches here? SMOS data can be quite "scattered", the number of data points used/averaged in the retrieval can have an impact on the results…

Most of Section 3.3 will be rewritten making it more clear what is calculated.

- “I don't know which TB measurements are used for the "fitted 45° brightness temperature" method…”. For each grid cell we use all the data points at all incidence angle available and we used this data to compute two fit curves which represent the dependence of the TB on the incidence angle (this is done for each polarization separately). After we obtain the parameters of the fits we used them to compute the TB at the 45 deg incidence angle. This brightness temperature is then used to compute the SIT.

- “The text says that you need "at least one observation under 40°" and that you use "only grid cells with the incidence angle range of observations that covers ... 45°" (see also comment above)”. 1. Since we assume that the two polarizations vary synchronous with the incidence angle (TBv increasing and TBh decreasing from nadir) until approximately 40 deg ; this is considered together with 2. the C parameter in the fit function is computed using just under 40 deg incidence angle data (Tian-Kunze et al. (2014) - Fig. 3 TB vs TBh/2+TBv/2). If the we would have just higher incidence angle data, even if the data might not contain any RFI influences the asynchronous variation of the two polarizations would bias C/2 which we consider to be the intensity at nadir.

- In our current case the SIT will be computed for one grid cell just if we have at least one data point below 40 deg and at least one data point at 45 deg or higher (due to the necessity not to extrapolate the fit)

- “The text says that you need "at least one observation under 40°" and that you use "only grid cells with the incidence angle range of observations that covers ... 45°" (see also comment above)" - we consider that RFI sources although can propagate through a snapshot don't need to contaminate all of it. The simple threshold of 300 K used as a filter was removing possibly a lot of unaffected data. In the Huntemann et al. (2015) a threshold for the standard deviation for incidence angle binned data eliminated RFI while preserving more data. We consider that by removing data points with high difference from the fit function in the iterative process we can remove RFI without removing too much of the unaffected data.

- "How does the "high uncertainty of the fit" influence the number of grid cells the retrieval is performed on?" Sentence corrected. The grid cells in Hudson Bay don't fulfill at least one of the two thresholds mentioned (at least one data point below 40 deg and and one above or equal to 45) and also the least square routine can fail to converge on a solution for the fit parameters hence we cannot compute the TBs at the desired incidence angle. The 40 deg data requirement also means the overall the swath will be narrower resulting in larger areas not covered at low latitudes.

- "Is the same number of SMOS measurements used for both retrieval approaches here? SMOS data can be quite "scattered", the number of data points used/averaged in the retrieval can have an impact on the results…" - that is one of the benefits of using the full incidence angle range. A fit procedure will use all the data available from all incidence angles and at the and using the resulted parameters of the fit to compute the TB at a fixed angle that is used for the retrieval. Meanwhile the daily average due to the strict incidence angle range for TBs can end up having a biased average incidence angle and as a result TBs and SIT. For a fit we can have many data points below 40 and a few close to 50. We expect that in a case like this the fit will return TBs closer to the real value at 45 deg than the daily mean approach that will end up with an incidence angle average close to the high end of the range.

13) In the manuscript text, Fig. 4 is mentioned before Fig. 3.

Will be changed. Figure 4 became 3, while Fig. 3 was replaced with a new figure and move on position 4.

14) p. 6, l. 1: "estimated retrieval error of 30% of SIT." -> Where does this number come from?

Huntemann et al. (2014), Reference will be added. (P7L14)

15) p. 6, l. 5: "within the error margin of the retrieval" -> Which error margin? From where? (the 30% given in l. 1?)

Yes, the 30% from Huntemann et al. (2014). Sentence will be changed. (P7L17)

16) Do the RMSD and bias given on p. 6, l. 2-5 refer to the comparison of the two retrieval approaches for just the one day (29 Oct 2010) shown in Fig. 3 and 4? I wouldn't consider this representative…

Yes, this was done. We will keep Fig. 4 as an example of one day (became Fig. 3), and will calculate the statistics for the ~3 months of the 2010 freeze-up. A double figure (Figure 4) will be added with SIT bias and RMSD for each individual day and, for the whole period for 1 cm thickness bins. Results are explained in P7L19-35.

17) p. 6, l. 16-17: You mention that Lannoy et al. (2015) take into account atmospheric contributions for SMOS "to convert between SMOS and SMAP TBs". You didn't, did you? (earlier (p. 2, l. 26) you claimed that SMAP TBs are "top of atmosphere"). Please write clearly what YOU have done to bring SMOS and SMAP TBs together and how and why your approach differs from other approaches etc.

No, we have not corrected for atmospheric contributions. We only mention Lannoy et al. (2015) as another attempt to convert between SMOS and SMAP TBs before ours.
SMAP L1B datafiles contain both surface and TOA brightness temperatures.
The Section 4.1 (P8L15-P9L15) where we explain the calibration has been extended to make it more clear how we actually bring the SMAP TBs to SMOS TBs and how is it different from the previous approach (see also answer to last General comment).

18) p. 7, l. 1-2: "For 11 October 2015 (not shown) the differences ... between SMOS fitted TBs retrieval and SMAP retrieval are small." Why do you pick one day to state this, and then not even show it? What about the other days? What is "SMOS fitted TBs retrieval" here? The one fitted to 40° incidence angle?

The SIT is calculated using TBs from SMOS at 40 deg. For SMOS vs SMAP, statistics will be calculated for the whole 3 months period. The Section will be updated with the appropriate statistics. Figure 5 moved to Fig. 6 and includes also a SMOS@40 deg - SMOS+SMAP subfigure as an example from which we can infer the contributions of SMOS and SMAP to the merged product.

19) p. 7, l. 13-14: "The RMSD between the original 40◦ to 50◦ incidence angle daily mean retrieval from Sect. 3.1 and the new mixed sensor one is 2.14 cm for the three months period investigated, while the bias is -0.63 cm..."
-What is the "three months period investigated" here? The same as was used for calibration earlier (Oct to Dec 2015)?
-It would be interesting to know the difference between SIT from SMOS fitted to 40° and SMOS+SMAP; otherwise we cannot distinguish whether the difference comes mainly from the different approaches for the SMOS retrieval (fitted to 40° or mean between 40 and 50°) or the different sensors (SMOS or SMOS+SMAP). Indeed, the values from the comparison in 3.3 are very similar (bias 0.69cm and RMSD 2.2cm), although a) I am not sure in which direction the negative sign in "-0.63 cm" points here, and b) the results in 3.3 seemed to be for a comparison of one day only.

Yes, the three months period is the same period that was used for calibration. The bias and RMSD for SMOS vs Merged dataset (Fig. 6 right, P10L5-7)will be included in this section to differentiate better between the contributions of the two sensors. b) the comparison in 3.3 will be extended to a three months period to make it more relevant (P9L19-22).

20) In the conclusions, there seems to be a "new" result: "Using SMAP data and the SMOS data fitted to the same incidence angle to calibrate the SMAP TBs to those of SMOS has improved the TB RMSD between the two datasets for both polarizations with 2.7 K and 2.81 K for TBh and TBv, respectively." (p.7, l. 22-24) -> This was not mentioned before. Do you mean improved to or by 2.7K? The sentence is hard to understand, also because the reference to the "improvement" comes only in the next sentence. It says "This is an improvement from previous attempts (Huntemann et al., 2016) where the the RMSD for both polarizations was over 4 K showing that using fixed incidence angles for SMOS data increases the accuracy." The phrasing could be clearer (who concludes this?). And I don't agree... 1) This shows only that SMOS and SMAP TBs as compared here and in Huntemann et al. 2016 agree better if a fixed incidence angle is used. And as I don't know how you dealt with the atmospheric corrections for SMOS, I cannot say whether it is a good thing that the SMOS TBs you used here (not corrected for atmosphere? corrected differently than SMAP?) and the SMAP TBs (atmosphere corrected) are closer to each other or not... 2) Averaging SMOS TBs differently does not "increase the accuracy" of SMOS data, but these SMOS data might be more suitable for comparison with SMAP.
The two values (2.7 and 2.81 K) are the RMSD of the linear regression between SMOS at 40 deg and SMAP TBs. This values are improved relative to the Huntemann et al. (2016) paper where they were around 4 K. We will add the relevant sentences to the calibration section (P8L32,P9L14) and a new Figure 5 with the density plots and regression line.

"This shows only that SMOS and SMAP TBs as compared here and in Huntemann et al. 2016 agree better if a fixed incidence angle is used." - Since during the calibration the SMAP TBs are adjusted to the SMOS ones, we consider that a better agreement between the two datasets will reduce the uncertainty introduced by the adjustment.

As mentioned in previous comments the SMAP L1B data we use contains also TOA brightness temperatures which were used here.

"2) Averaging SMOS TBs differently does not "increase the accuracy" of SMOS data, but these SMOS data might be more suitable for comparison with SMAP." It's not just averaging the data differently, we average a much larger amount of observations due to using the full incidence angle range 0-65 deg and by using a fit we consider that we eliminate the incidence angle bias which should also increase consistency between grid cells. Additionally, the fitted brightness temperatures were also used to create the new retrieval curves, eliminating the incidence angle bias from their generation. Returning to the sentence in question, we consider that by intercalibrating data directly at a fixed incidence angle, instead of the Huntemann et al. (2016) where the intercalibration was done through a two-step regression which required correlating averaged 40-50 deg to 38-42 SMOS TBs. The second averaging will contain just a few observations per grid cell thus having a high uncertainty. Since this step is avoided we consider that the SMOS fitted brightness temperatures used in the intercalibration will have a higher accuracy. Nonetheless "increased accuracy" was removed from the sentence.

21) What about ice concentration? Has big impact on L-band TBs but is not mentioned at all
.
Section 5 will be added for discussing uncertainties estimates, including SIC. The change of SIT with SIC will be discussed, and some estimates of the error introduced by SIC will be provided. Also few sentences are added in Section 3.1 (P4L17-20) regarding the usage of SIC in the training of the retrieval. The training using SIC follows the Huntemann et al. (2014) algorithm.

22) The numbers given in Tab. 2 for the "original 5.05 data version" (SMOS) do not correspond to the numbers given in the literature for this SIT retrieval with SMOS (Huntemann et al., 2014 & Huntemann et al., 2016). (a and b interchanged for I_abc; different a, c, d for Q_abc).
Thank you for catching this discrepancy. The values have been corrected for I. The parameters used in the manuscript are the ones currently used for the operational SMOS ice thickness retrieval at University of Bremen for SMOS data version 5.05. They are different from the ones in Huntemann et al. (2014) because a different SMOS data version was used there. This information was added to the text under Section 3.1 P4L26-27.

23) Fig. 1 in the current print version is quite small, especially the label font size.
Will be changed (also changed to Figure 2).

Further comments:

p. 1, l. 4-5: "... SMAP observes at a fixed 40◦ incidence angle which makes thin sea ice thickness retrieval more stable as incidence angle effects do not have to be taken into account." -> Why would this be "more stable"? Isn't it mainly a restriction to not have any measurements at incidence angles other than 40°? For example, wouldn't a retrieval using only SMOS measurements at 40° be as stable?
We have changed “stable” to “consistent”. (P1L4)
Yes, as we used “stable” in this context, we meant exactly that: a fixed incidence angle retrieval is stable compared to averaged observations where the mean incidence angle might vary. Thus a 40 deg SMOS retrieval is as stable as a SMAP one in this context.

p. 1, l. 20: Very abrupt and sudden transition from describing SMOS to introducing SMAP.
The SMAP introduction was rephrased and moved to the next paragraph. (P2L3-9)

p. 1, l. 22-23: "... by calibrating the SMAP brightness temperatures (TBs) to those of SMOS" -> Why do SMAP measurements have to be calibrated to SMOS measurements? Here you could mention whether/how they differ. I guess this has also to do with SMOS brightness temperatures having been compared (or "validated") with other sources (in Huntemann et al., 2014, for example).

The algorithm was developed for SMOS data and the results were compared with other sources. Since the algorithm is empirical, we consider that the retrieval curve obtained is valid in a direct manner just for SMOS observations. In Section 3.1 we presented that even for

SMOS data only we can have biases (Fig. 2) that appear with a new data version, we consider that we can not apply the algorithm directly to SMAP data.

Although measurements for both satellites are provided at the top of the atmosphere, SMAP L1B TOA data contains galactic noise and sun specular reflection corrections while SMOS does not (was mentioned in the calibration section P6L28-29 (also introduced at P2L17). Also, a possible 1 K warm bias of the ocean is mention in the 6.20 data release notes (value will added to P3L15).

Sentence will be added in introduction (P2L17-19) : "As a first step, an inter-calibration of the brightness temperatures ...". Furthermore, Section 4.1 dealing with the intercalibration will be expanded (P8L15-P9L15) to explain the differences between SMOS and SMAP TBs.

p. 2, l. 12: "the the"
p. 2, l. 16: "... version 6.20 has been available since 5 May 2015 operationally..." -> version 6.20 has been operationally available since 5 May 2015
p. 2, l. 24: "a equator" -> an equator
p. 2, l. 24: "...data is used, which contain..." -> "...data is used, which containS..." or "...data ARE used, which contain..." (but then "data" has to be used as a plural word throughout the paper)
p. 2, l. 27: "36x47 km" -> 36 km x 47 km
p. 3, l. 20: "retrieval curve" singular vs. two equations
All comments were implemented.

p. 4, l. 7: "it increases" -> they increase?

Rephrased to "The bias and standard deviation are under ±1 cm and 2 cm, respectively, for ice thicknesses below 25 cm. For 50 cm thickness the bias increases to +4 cm while the standard deviation reaches 11~cm." (P5L13-14)

p. 4, l.10: "This allows to estimate" -> I think this is grammatically incorrect (while "This allows us to estimate..." should be ok I guess)
p. 4, l. 13-14: Remove "given above"?
p. 4, l. 29: "observation" -> observations
p. 7, l. 17-18: I recommend to combine these two lines to one because they are very repetitive.
p. 7, l. 19: "rage" -> range
p. 7, l. 25: "the the"
The modifications will be included in the manuscript.

References:

[1] Algorithm Theoretical Basis Document (ATBD): "SMAP Calibrated, Time-Ordered Brightness Temperatures L1B_TB Data Product", J. Piepmeier, P. Mohammed, G. De Amici, E. Kim, J. Peng, and C. Ruf (2014), e.g. Tab. 1, p. 11, file accessed at https://www.google.de/url?sa=t&rct=j&q=&esrc=s&source=web&cd=3&ved=0ahUKEwiF2sqb3MDYAhVBa1AKHbJKAfIQ

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[2] De Lannoy, G. J., Reichle, R. H., Peng, J., Kerr, Y., Castro, R., Kim, E. J., & Liu, Q. (2015).
Converting between SMOS and SMAP level-1 brightness temperature observations over nonfrozen land. IEEE Geoscience and Remote Sensing Letters, 12(9), 1908-1912.

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Combined SMAP/SMOS Thin Sea Ice Thickness Retrieval

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Abstract. The spaceborne passive microwave sensors Soil Moisture Ocean Salinity (SMOS) and Soil Moisture Active Passive (SMAP) provide brightness temperature data at L-band (1.4 GHz). At this low frequency the atmosphere is close to transparent and in polar regions the thickness of thin sea ice can be derived. SMOS data covers a large incidence angle range whereas SMAP observes at a fixed 40° incidence angle which makes thin sea ice thickness retrieval more ~~stable~~ consistent as incidence angle effects do not have to be taken into account. Here we transfer a retrieval algorithm for thickness of thin sea ice (up to 50 cm) from SMOS data at 40° to 50° incidence angle to the fixed incidence angle of SMAP. Now the SMOS brightness temperatures (TBs) at a given incidence angle are estimated using empirical fit functions. SMAP TBs are calibrated to SMOS for providing a merged SMOS/SMAP Sea Ice Thickness product.

1 Introduction

Sea ice is an important climate parameter (Moritz et al., 2002; Stroeve et al., 2007; Holland et al., 2010) and accurate knowledge of sea ice properties ~~are needed for improved~~ is needed for weather and climate modeling and prediction and for ship routing. The thickness of the ice is one of the parameters that determines resistance against the deforming forces of wind and ocean currents (Häkkinen, 1987; Yu et al., 2001). Even a thin layer of sea ice inhibits evaporation, reduces heat and gas exchange between ocean and atmosphere and increases the albedo (Maykut, 1978; Perovich et al., 2012). It provides a solid surface for snow to deposit, which further reduces heat exchange and increases albedo.

The Soil Moisture Ocean Salinity (SMOS) satellite was launched by ESA in November 2009. It is a synthetic aperture passive microwave radiometer working at L-band (1.4 GHz). The aperture synthesis requires an array of small antennas reducing the total weight and size of the satellite. The instrument works in a full polarimetric mode, recording all four Stokes parameters. Its large field of view allows for multi angular observations organized in an approximately 1200 km × 1200 km snapshots.

SMOS has been developed for retrieving soil moisture (Kerr et al., 2012), by inferring the surface emissivity which is correlated with the moisture content, and sea surface salinity (Zine et al., 2008; Font et al., 2010) where the measured brightness temperatures (TB) are linked with the sea salinity through the dielectric constant of the water in the first few centimeters. Modeling and observations showed that at this frequency ~~radiation varies with~~ the radiation is sensitive to ice thickness up to 0.5 meters (Kaleschke et al., 2010, 2012). The atmosphere has little influence on the radiation at L-band as both absorption and scattering are small ~~. These aspects~~ (Skou and Hoffman-Bang, 2005). The correlation of ice thickness with emitted radiation together with a small atmospheric contribution make SMOS a candidate for thickness retrieval of thin sea ice. ~~Two~~ To date, two retrieval algorithms have been developed for SMOS, one using the intensity at averaged over incidence angles between 0° and 40° (Tian-Kunze et al., 2014) and one using intensity and polarization difference at averaged over incidence angles between 40° and 50° (Huntemann et al., 2014).

In 2015 the Soil Moisture Active Passive (SMAP) satellite was launched by NASA . It has (Entekhabi et al., 2010, 2014). It carries two sensors onboard, an a L-band radiometer, and a radar which share a rotating 6 m real aperture antenna reflector. The radar was recording high resolution (1 to 3 km) data used for soil moisture sensing, until it failed after three months. In contrast to the synthetic aperture observations of SMOS, the real aperture antenna observations of SMAP cover an area of 36 km × 47 km at a fixed incidence angle of 40° and results in a swath with an approximate width of 1000 km. SMAP also includes on board detection and filtering of Radio Frequency Interference (RFI) while SMOS does not.

Here After the launch of SMAP, different approaches were taken to convert data products between the two sensors. A previous approach to convert SMOS to SMAP TBs for usage in soil moisture retrieval and assimilation systems is presented in Lannoy et al. (2015) and involves a quadratic fitting of the SMOS TBs at the SMAP incidence angle and employing auxiliary data and an empirical atmospheric model to correct for the atmospheric and extraterrestrial contributions, respectively. In contrast, Huntemann et al. (2016) convert SMAP 40° surface TBs to SMOS top of the atmosphere equivalent 40 to 50° averaged TBs through two linear regressions.

In this article, we present a mixed Sea Ice Thickness (SIT) dataset combining data of the two sensors by calibrating the SMAP brightness temperatures (TBs) to those of SMOS (Sect. 4). As a first step, an inter-calibration of the brightness temperatures of the two sensors is required due to a possible warm bias in SMOS data (Sect. 2) and due to corrections for galactic noise and sun specular reflection contained in the SMAP but not in the SMOS data. In addition, the SIT retrieval from Huntemann et al. (2014) is adapted to the new version 6.20 of the SMOS Level 1C data and it will be used as a reference for all other comparisons (Sect. 3.1). This new retrieval is combined with the introduction of a fit function for the dependence of horizontal and vertical brightness temperatures (from now on refered referred as TB_h and TB_v, respectively) on the incidence angle (Sect. 3.2). It The fit function is used for Radio Frequency Interference (RFI) RFI filtering and for SIT retrieval at a fixed incidence angle. This The fit is also a required step step required for the SMOS and SMAP merged product to combine the observations of the two sensors at a common incidence angle.

2 SMOS and SMAP data sources

The

The MIRAS radiometer onboard the SMOS satellite has 69 receivers on three arms measuring radiances at 1.4 GHz (Kerr et al., 2001). One complete set of data from the aperture synthesis process done each 1.2 seconds is called a snapshot. For this investigation the SMOS Level 1C sea data gridded on the icosahedron Snyder equal area (ISEA) 4H9 grid (Sahr et al., 2003) is used. Its resolution is 15 km while the SMOS footprint size varies with incidence angle from aproximately approximately 30 km×30 km at nadir to 90 km×30 km at 65° (Castro, 2008). Over the whole field of view the average resolution is approximately 43 km. The Level 1C data is provided within 24 h of aquisitionacquisition.

In full polarization mode, all four Stokes parameters are measured. Data is recorded in the reference plane of the antenna as T_X, T_Y, T_3 and T_4, and ~~are~~ is converted to TB_h, TB_v, TB_3 and TB_4 in the Earth surface plane (Zine et al., 2008) using

$$\begin{bmatrix} T_X \\ T_Y \\ T_3 \\ T_4 \end{bmatrix} = \begin{bmatrix} \cos^2(\alpha) & \sin^2(\alpha) & -\cos(\alpha)\sin(\alpha) & 0 \\ \sin^2(\alpha) & \cos^2(\alpha) & \cos(\alpha)\sin(\alpha) & 0 \\ \sin(2\alpha) & -\sin(2\alpha) & \cos(2\alpha) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} TB_h \\ TB_v \\ TB_3 \\ TB_4 \end{bmatrix}, \quad (1)$$

where $\alpha = \alpha_{gr} + \omega_{F_r}$, α_{gr} is the ~~the~~ georotation angle and ω_{F_r} is the Faraday rotation angle. Within a snapshot just one or two of the Stokes parameters are measured at the same time. When only one of the Stokes parameters is measured, all three arms of the sensor record the same polarization. In the case of recording a cross-polarized snapshot, one arm of the sensor records one polarization while the other two record the other polarization. Measurements of single (XX or YY) and cross-polarization ((XX,XY) or (YY,XY)) are done alternatively. In order to obtain the values for TB_h and TB_v from the matrix, depending if the current measurement is single or cross-polarization, we will have to use one or two adjacent snapshots. The missing values required for the conversion are interpolated from neighboring snapshots within a 2.5 s range and with a maximum incidence angle difference between the measurements of 0.5°.

The SMOS L1C data version 6.20 has been operationally available since 5 May 2015 ~~operationally and older aquisitions~~ and also older acquisitions were reprocessed. ~~It~~ This version adds better RFI flagging and it improves the long-term and seasonal stability of the measurements. At the same time it introduces a warm bias in the brightness temperatures of ~~aproximately~~ approximately 1.4 K relative to the previous version 5.05 over ocean~~while~~ . The bias over the ocean can be 1 K too warm with respect to the true values (SMOS Calibration team and Expert Support Laboratory Level 1, 2015). Over Antarctica and land~~have a bias~~ , the bias is above 2 K, which is closer to modeled and ground based measurements~~(SMOS Calibration team and Expert Sup~~ The new data version also reduces the difference in brightness temperature between ascending and descending overflights over ocean at low latitudes. ~~Changes at high latitudes~~ At high latitudes such changes were not documented. Before, the difference varied considerably with time and latitude due to thermal variations in the instrument.

~~SMAP started providing data starting in April 2015. It is positionied~~ The SMAP satellite is positioned on a quasi-polar sun-synchronous orbit with ascending equator crossing time ~~at~~ 6 pm, while SMOS has ~~a~~ an equator crossing time at 6 am. SMAP carries a conically scanning radiometer with a fixed incidence angle of 40° which leads to a narrower swath and decreases the area covered at the pole compared to SMOS. The footprint of a SMAP observatoin is approximately 36 km × 47 km, resulting in an approximate resolution of 40 km.In this study, the SMAP Level 1B data is used which ~~contain~~ contains time ordered ungridded ~~top of the atmosphere~~ Top Of the Atmosphere (TOA) brightness temperatures. The data is available from 31 March 2015 and is provided with a latency of about 12 h. ~~The SMAP footprint is aproximately 36×47 km.~~

~~The frequency bands of both~~ SMOS and SMAP ~~are located~~ observe in a restricted band (1.400-1.427 GHz) reserved for passive radioastronomical use. Nevertheless, there are surfaced based artificial sources causing RFI (Mecklenburg et al., 2012). The image reconstruction process required to obtain the SMOS TBs includes an inverse Fourier transform (Corbella et al., 2004). Therefore, not only the grid cells that contain the RFI source are affected, but the whole snapshot can be contaminated, resulting in high or even negative brightness temperatures (Oliva et al., 2012). Since in nature brightness temperature will not exceed 300 K over the polar ocean (Kaleschke et al., 2010; Mills and Heygster, 2011; Tian-Kunze et al., 2014), a simple ~~filter for the RFI~~ RFI filter is to eliminate the whole snapshot which contains at least one TB exceeding this threshold. This filter is used in sea ice thickness retrieval algorithm presented in Huntemann et al. (2014). An alternative approach for filtering RFI has been shown in Huntemann and Heygster (2015) where incidence angle binning is used, resulting in a higher preservation of data and fewer gaps on the grid. Since SMAP contains onboard hardware for detection and filtering of RFI and ~~neighbouring~~ neighboring pixels are unaffected by a RFI source, no additional filtering is required for the SMAP Level 1B data.

3 Sea ice thickness retrieval using a fit function

Due to the new SMOS data version 6.20 used here compared to version 5.05 used in Huntemann et al. (2014), a retraining of the SMOS thin ice thickness retrieval is necessary. First, in Sect. 3.1 we use the method presented in Huntemann et al. (2014) just using the newer data version 6.20. This involves averaging the brightness temperatures between 40 and 50° incidence angle. ~~In Section 3.3 we present an improved ice thickness retrieval based on~~ Secondly, we employ a fitting function ~~(Sect.~~using the dependence of brightness temperature on incidence angle (Section 3.2) ~~through the full incidence angle range. This will provide more stable brightness temperatures and is necessary for a consistently combined SMOS and SMAP ice thickness retrieval~~as input for the retrieval (Section 3.3). The fitting function is used to obtain SMOS brightness temperatures at a fixed incidence angle.

3.1 SMOS retrieval retraining

Three SMOS grid cells in the Kara and Barents Sea were used for training over a period of three months (1 October - 26 December 2010) with sea ice thickness data obtained using the relation with the Cumulated Freezing Degree Days (CFDD) based on NCEP temperature data (Huntemann et al., 2014). CFDD is the daily average temperature below -1.8° (freezing point of sea water), integrated over the time with sub freezing temperatures (Bilello, 1961). The relation beween the CFDD and the thickness as presented in Bilello (1961) is $SIT[cm] = 1.33 \cdot (\mathrm{CFDD}[°C])^{0.58}$. The ASI (Spreen et al., 2008) Sea Ice Concentration (SIC) was used to filter low SIC data during the training period. Only during the early part of the freeze-up when ice is really thin, the SIC was allowed to have a value between 0-100% (Huntemann et al., 2014) otherwise 100% SIC was required. The brightness temperatures are averaged daily over the incidence angle range between 40° to 50°. The ~~resulting sea ice thickness retrieval curve is:~~ functions

$$\begin{aligned} I_{abc}(x) &= a - (a-b)\cdot \exp\left(-x/c\right), \\ Q_{abcd}(x) &= (a-b)\cdot \exp\left(-(x/c)^d\right) + b, \end{aligned} \tag{2}$$

are fitted to the I and Q data measured over the training areas and the SIT resulting from the CFDD method, where a, b, c and d represent the ~~curve~~ curves parameters (Table 1), x is the sea ice thickness while I and Q are the brightness temperature intensity and polarization difference, respectively. The sea ice thickness retrieval curve is the result of using the two fitted functions from Equation 2 in the (Q, I) space. For each pair of Q and I the minimum Euclidean distance to the retrieval curve is used to determine the SIT. The retrieval curve parameters for data version 5.05 presented in Table 1 are updated values of the Huntemann et al. (2014) that are currently used for daily processing at the University of Bremen (www.seaice.uni-bremen.de).

Figure 1 shows the retrieval curves in the (Q, I) space. The dots on the curves represent the SIT increasing with intensity and decreasing with polarization difference in steps of 10 cm from 0 cm to 50 cm. Over 50 cm the retrieval is too sensitive to small changes in intensity and polarization difference and it will be cut off. The sea ice thickness retrieval curve for data version 5.05 and the retrained curve using the 6.20 data version are shown in black and blue, respectively. The new curve has about 1.7 K higher value at zero SIT for intensity and polarization difference. The difference increases up to 3 K at 50 cm SIT.

Figure 2 shows the intensity (left) for 29 October 2010 using daily mean TBs for each grid cell. The data has been regridded to the NSIDC polar stereographic ~~projection~~ grid with a resolution of 12.5 km. This resolution is a oversampling of the true resolution of the SMOS data which is 43 km on average. The original validated retrieval (Huntemann et al., 2014) was trained with the old data version ~~hence it~~ and is used as a reference here. The warm bias of the new data is seen in the difference plot (Fig. ~~1~~ 2 right) both over ocean area and sea ice. In regions of high contrast like the ice edge or coastlines, ~~the old data version 5.05 tended~~ both data versions tend to produce spillover effects ~~. They are reduced in the new data version 6.20 with improved image reconstruction techniques (SMOS Calibration team and Expert Support Laboratory Level 1, 2015).~~

~~Figure 2 shows the initial sea ice thickness retrieval curve for data version 5.05 (black) and the retrained curve using the 6.20 data version (blue). The new curve has about 1.7 K higher value at zero SIT for intensity and polarization difference. The difference increases up to 3 K at 50 cm SIT~~(SMOS Calibration team and Expert Support Laboratory Level 1, 2015). The spillover produces an erroneous increase or decrease in brightness temperature of 1 to 1.5 K in the areas mentioned (not visible in the plot).

The algorithm trained with SMOS data version 5.05 has been compared with ~~that~~ the one trained with version 6.20 for the period 1 October to 26 December 2010, considering sea ice ~~thickness starting~~ thicknesses from 1 cm to 50 cm. The bias of the new retrieval is -0.22 cm while the RMSD is 1.35 cm. From a total of 5.1 million ~~data points~~cumulated data points over the 87 days period and 50 cm sea ice thickness range, 97% have at most 3 cm difference. The bias and standard deviation are ~~under~~ below ±1 cm and 2 cm, respectively, for ice thicknesses below 25 cm~~and it~~. For 50 cm thickness the bias increases to +4 cm ~~and~~ while the standard deviation reaches 11 cm~~, respectively for 50 cm thickness~~.

~~Also the two algorithms have been compared as above with the difference that both of them have as input just the new data version. This allows~~ A test is done to estimate the error introduced by the usage of the original retrieval (Huntemann et al., 2014) with the ~~new data .~~6.20 data version. The two algorithms trained with the different data versions have taken as input the 6.20 data only. The data covers the freeze-up period from 1 October to 26 December 2010. The bias between the retrained retrieval and the original one is 0.33 cm with 99% of the data having a difference of 3 cm or less, while the RMSD is 0.91 cm. This means, although it is recommended to use the algorithm adapted for the new data version, the error is below 1 cm thickness on average for ~~under~~ SIT below 51 cm ~~SIT data~~ if processed with the old algorithm~~given above~~.

3.2 SMOS TBs fit characteristics

In the previous section~~we showed~~, we have shown that the SIT retrievals with the new data version and new retrieval is consistent with the ~~validated algorithm while using the new data version~~ old data version and retrieval. In all of the next sections the SMOS Level 1C 6.20 data version will be used, and when making reference to the original daily mean sea ice thickness retrieval, the retrained 6.20 data version algorithm from Sect. 3.1 will be utilized. In each grid cell, the number of data points and the covered incidence angle range are highly variable due to the orbit characteristics, the large incidence angle range of 0° to 65°, and the complex distribution of incidence angle within a SMOS snapshot. Grid cells located ~~near~~ closer to the center of the swath will cover a large incidence angle range. ~~Closer to~~ Near the swath edges, the range is reduced ~~due to lack of coverage of the~~ and low incidence angles ~~. Moreover, the RFI filtering removes data and~~ are not covered (Font et al., 2010). The snapshots removed using the over 300 K RFI filter can create a local bias in the average incidence angle. ~~Within one~~ The existence of an RFI source before an observed grid cell, ~~this~~ relative to the trackline, will result in the elimination of snapshots with high incidence angle data points for that cell. As opposite, a RFI source located after the grid cell of interest will result in elimination of the low incidence angle data points. The varying angle distribution depending on the position in the swath and the data removal due to the RFI filtering for one grid cell may shift the average incidence angle of the ensemble of observations between 40° and 50° away from the assumed average of 45°~~, and the~~. The average brightness temperatures and SIT values retrieved from ~~them will be corrupted by the corresponding shifts~~the affected grid cells will be shifted accordingly. This error can be avoided by fitting a curve to the angular dependent brightness temperatures, allowing to estimate brightness temperature for a fixed incidence angle to be used for the retrieval.

Here we propose as a solution a modified version of the fit functions (Eq. 3) described in Zhao et al. (2015). The fit is applied ~~separatly~~ separately to each polarization, horizontal and vertical, for each grid cell using daily observations. An initial filtering of RFI is done by removing ~~observation which were~~ observations which are flagged in Level 1C data for either being affected by tails of point source RFI or for indicating RFI by the system temperature standard deviation exceeding the expected trend (Indra Sistemas S.A., 2014). The flagged data is removed before the brightness temperatures are transformed from the antenna to the earth reference frame.

The fit is done iteratively with a maximum of five steps. ~~At each step, the 20% of the observations with the highest absolute difference from the fit are removed if the RMSD of the fit is higher than 5 K or if the RMSD fit difference between sucessive iterations exceeds 1 K.~~ For each step the parameter C (Eq. 3) is determined ~~by averaging the sum of the polarizations for each observation~~for a given grid cell by first summing up the brightness temperatures of horizontal and vertical polarization for each individual observation and then taking the median of the result. Median is used so that any RFI influenced outliers will not influence C. Due to ~~asymetric~~ asymmetric change in TB between horizontal and vertical polarization at higher incidence angles, only grid cells with at least one observation under 40° are considered. This increases the stability of the fit since $C/2$ represents the intensity at nadir. The 40° threshold ~~was~~ is selected due to increased ~~asymetry~~ asymmetry between vertical and horizontal brightness temperatures at higher incidence angles which will generate a bias in the computation of the ~~C parameter~~

parameter C. The other five fit parameters a_h, b_h, a_v, b_v and d_v in the fit functions

$$
\begin{aligned}
TB_h(\theta) &= a_h \cdot \theta^2 + \frac{C}{2} \cdot [b_h \cdot \sin^2(\theta) + \cos^2(\theta)] \\
TB_v(\theta) &= a_v \cdot \theta^2 + \frac{C}{2} \cdot [b_v \cdot \sin^2(d_v \cdot \theta) + \cos^2(d_v \cdot \theta)].
\end{aligned} \qquad (3)
$$

are determined by a least squares procedure. The Brewster angle effect on ~~influencing~~ the vertically polarized TBs is represented by the additional parameter d_v.

At each iteration of the fitting procedure 20% of the observations with the highest absolute difference from the fit are removed if the RMSD of the fit is higher than 5 K or if the RMSD fit difference between successive iterations exceeds 1 K. The data removal in the iterative process is the second step used to discard possible RFI influences.

The fit function is not ~~optimised~~ optimized for extrapolation of the covered incidence angle range. Incidence angles not covered by the observations will have high uncertainty. To avoid extrapolation, only grid cells ~~with the incidence angle range of observations that covers the wanted~~ which contain observations with incidence angle both below and above the desired angle, e.g. 45°, are used for the retrieval.

3.3 Sea ice thickness retrieval training using fitted data

The retrieval algorithm has been retrained as described in Sect. 3.1 but ~~now using as input brightness temperatures obtained through~~ instead of using TBs averaged over 40-50° incidence angle, now we use brightness temperatures from the fit process ~~presented in~~ (Sect. 3.2~~using~~) at a nominal incidence angle of 45°. The resulting retrieval curve (Fig. 2 green) has 1.3 K higher polarization difference at 0 cm ice thickness than the algorithm trained with the daily mean data (blue). The difference decreases to 0.1 K at 20 cm thickness and increases to ~~aproximately~~ approximately 0.5 K at 50 cm. This ~~comes~~ can come from variability in mean incidence angle. The daily averaged observations have an incidence angle bias of -0.5° (with single differences as high as -2.5°) relative to the assumed 45° one. The smaller incidence angle will result in a smaller polarization difference since this decreases when ~~approching~~ approaching nadir. The ocean and thin sea ice have low intensities and high polarization difference. As the sea ice gets thicker, the intensity increases and the polarization difference decreases. For the same incidence angle bias at higher thicknesses the polarization difference error will be smaller. The intensity values for the two curves at the same sea ice thickness are nearly the same. The difference between these two curves is small compared to the difference to the retrieval curve for the SMOS 5.05 data version (Fig. 2 black).

Figure ~~4~~ 3 shows the retrieved sea ice thickness using the daily mean method (left) presented in Sect. 3.1 and the retrained retrieval curve at nominal 45° incidence angle (~~centre~~center) based on the fitted ~~brigthness~~ brightness temperatures for 29 October 2010. Due to the requirement for the fit computation to have observation below 40° (Sect. 3.2), ~~many~~ some grid cells in the central Arctic are not covered anymore. The decrease is around 1° in latitude, ~~coresponding to aproximately~~ corresponding to approximately 1000 grid cells. This area is mostly covered by ~~multiyear~~ ice with thickness higher than 50 cm thus not being the focus of the retrieval. On the other hand for many ocean areas which formerly were excluded by the RFI filtering (grey in Fig. ~~4~~ 3 left) now data is available, e.g. around Iceland, Eastern Greenland and Vladivostok. At the same time in the area of the Hudson Bay there is a 30% decrease in the area covered due to ~~the high uncertainty of the fit.~~

Figure 3, for 29 October 2010, shows the difference between the daily mean and the fitted brightness temperatures retrievals for pixels with SIT smaller or equal to 50 cm and at least one of the retrievals returning a non-zero valuenot fulfilling the incidence angle criteria required for SIT retrieval or the failure of the least square procedure to converge to a solution. For 90% of the grid points the difference is less than 3 cm which is below the estimated retrieval error of 30% of SIT computed in Huntemann et al. (2014). The daily mean retrieval has a positive bias of 0.690.41 cm. The highest differences appear north of Alaska with values up to 10 cm (Fig. 4 right). This is a result of a biased distribution of the incidence angles, resulting in a large number of grid points having under 45° mean incidence angle. This decreases the polarization difference dragging the resulting SIT to higher values. Overall the RMSD is 2.2for this day is 1.9 cm which is within the expected 30% error margin of the retrieval.

Figure 4 (top) represents the bias (blue) and RMSD (red) of the SIT based on the 45° incidence angle fitted TBs relative to the 40-50° daily mean SIT calculated for the period 1 October to 26 December 2010. This is computed by dividing the SIT into bins of 1 cm thickness, from 0 to 50 cm, selecting all grid cells with that thickness from the daily averaged SIT and subtracting them from the fitted TBs SIT. Only grid cells that contain at most 50 cm and non-zero in at least one of the two algorithms are used. Overall the SIT from the fitted TB is smaller than the SIT from the 40-50° incidence angle mean TB. Until 40 cm of thickness the bias varies between 0 and -1 cm and then increases gradually up to -5 cm at 50 cm SIT. The green curve shows the cumulative histogram for daily mean TB at each sea ice thickness. Approximately 52% of the data is below or equal to 3 cm in the daily averaged TB SIT. This can be explained by the coarse resolution of about 43 km of SMOS, always generating thin sea ice at the ice edge due to brightness temperature contamination from either the ocean or the ice pack. In addition also coastal areas will generate thin sea ice due to spillover effects. Overall we can see that 95% of all data is below 40 cm while thickness corresponding to just 40 and 50 cm are contained in 5% of the data so that the region of high bias is small. Figure 4 bottom shows the daily bias (blue) and RMSD (red) of the 45° fitted brightness temperatures SIT relative to the daily average TB SIT. Over the whole period the bias stays between 0 and -0.6 cm while the RMSD increases from 1.3 K to 2.5 K. The increase in RMSD can be explained by the freeze-up period which contains larger areas with intermediate thicknesses compared to the start and peak freeze-up periods which contain either ocean or over 50 cm SIT grid cells. The overall bias of the 45° fitted brightness temperatures SIT for the whole period for all thicknesses is -0.3 cm with a RMSD of 2.02 cm. The absolute bias for over 3 cm thicknesses is 1.6 cm.

4 Sea ice thickness retrieval using SMAP data

This section adapts the SMOS SIT algorithm to observations of SMAP. Because SMOS observations have a variable incidence angle, they have to be computed at the fixed incidence angle of SMAP using the fitting function method described in Section 3.2. In order to apply the SIT retrieval calibrated with SMOS data also to those of SMAP, first the brightness temperatures of both sensors have to be inter-calibrated (Sec. 4.1). In Section 4.2 the resulting inter-calibrated brightness temperatures are mixed and used for generating a combined SMOS/SMAP sea ice thickness dataset.

4.1 SMAP~~TBs calibration using 40°~~ /SMOS ~~fit data~~inter-calibration

The first step is to retrain the SMOS retrieval as in Sect. 3.3 using the nominal incidence angle of 40°, which is the fixed incidence angle of SMAP. The resulting SIT retrieval curve is shown in red in Fig. ~~2~~1. As expected, the lower incidence angle results in a lower polarization difference ~~especialy~~ especially for thin ice and reduces the usable polarization difference range for the retrieval from 22-54 K to 17-43 K.

A procedure to convert between SMOS and SMAP TBs over land was previously suggested in Lannoy et al. (2015). It uses a radiative transfer model and auxiliary data for taking in account atmospheric and galactic contributions for SMOS. For interpolation of SMOS TBs to 40° incidence angle it fits a quadratic function to the angular dependent SMOS TBs.

~~For this study , in order to use SMAP data for SIT retrieval, we perform a linear regression of~~ In this study the procedure to convert from SMAP brightness temperatures to ~~bring them to an equivalent 40° SMOS incidence angle~~SMOS equivalent TBs is done through simple linear regression. For the ~~calibration we use the period~~ procedure we use SMOS 40° measurements data and SMAP L1B TOA observations for the period between 1 October to 31 December 2015, which covers the first freeze-up in the Arctic observed by both sensors. ~~A similar calibration of SMAP to SMOS TBs was presented previously in Huntemann et al. (2016). This used gridded SMAP Level 1C TB product and a two steplinear regression for the calibration of SMAP TBs to daily mean SMOS TBs.~~

~~The SMAP TBh and TBv~~ In the first step, the SMAP data is gridded daily on the SMOS ~~used~~ ISEA 4H9 grid (the native SMOS Level 1C data grid) using a Gaussian resampling with a cutoff distance from the grid cell center of 20 km and Full Width Half Maximum (FWHM) range of 40 km. Only grid cells located more than 100 km away from the coast are considered to ~~minimise~~ minimize the land contamination~~effect.~~

. In the second step we determine the fit function parameters for the SMOS data on a daily basis and compute the 40° SMOS TBs for each grid cell for each day. Figure 5 shows the scatter plots between the TBs of SMAP and SMOS 40° for horizontal (left) and vertical (right) polarization. For each polarization the magenta line shows the linear regression. We can distinguish two areas of high data point density at the two ends of the clouds open water and for thick sea ice, respectively. Over open water at a brightness temperature of 80 K and 120 K for TB_h and TB_v, respectively, SMOS has a warm bias of approximately 3.3 K and 5.2 K. At the high brightness temperatures representing the solid ice cover, the bias for SMOS decreases to 2.7 K and 3.3 K for TB_h and TB_v, respectively. The bias of SMOS TBs in the 6.20 data version that is presented in Section 2 can be one of the sources for the difference between SMOS and SMAP TBs. The asymmetry between low TBs and high TBs can come from the high and low reflectivities of ocean and sea ice, respectively at L-band. Unlike SMAP, SMOS data does not include correction for galactic noise which can have a higher influence over water due to its high reflectivity. The reflectivity decreases over sea ice, resulting in galactic noise having a smaller impact on recorded values thus lower differences between corrected and uncorrected TBs. The overall RMSD of the two linear regressions is 2.7 K and 2.81 K for TB_h and TB_v, respectively. The resulting linear regression parameters are presented in Table 2. ~~One source for the difference between the brigthness temperatures of the two sensors is that~~

For this study, in order to use SMAP data for SIT retrieval, we adjust the SMAP TBs by a linear regression to 40° SMOS incidence angle data. A similar calibration of SMAP to SMOS TBs was presented previously in Huntemann et al. (2016). For that calibration, however, the SMAP Level 1C TB product was used which contains surface brightness temperatures on a 36 km EASE grid. They contain an atmospheric correction unlike the TOA Level 1B ~~includes corrections for galactic contamination and sun specular reflection which is not the case in the~~ data that is used in the current paper. Also, the calibration is done through two separate linear regressions. The SMAP and SMOS 38-42° incidence angle data is daily averaged and compared for the period 1 October to 31 December 2015 (Sect. 4.1). In the second step, since the SMOS SIT retrieval algorithm used in Huntemann et al. (2016) was developed for 40-50° daily averaged data another calibration is required. Using SMOS L1C data for the same period, a linear regression is done between SMOS 40-50° and SMOS 38-42° daily averaged data. The main differences between the Huntemann et al. (2016) and the current paper is that here the SIT retrieval has been retrained to the fixed incidence angle of 40° and is not necessary anymore to correlate SMAP TBs with the 40-50° SMOS averaged TBs. Instead we retrain the retrieval to work directly with 40° TBs. Since the incidence angle difference between the SMAP data and the SMOS 40-50° does not need to be corrected anymore, the calibration that is done in the current paper is necessary to compensate for extraterrestrial contributions that are corrected in SMAP data and for the warm bias of the SMOS data. The RMSD for the linear relation between SMAP and SMOS data in Huntemann et al. (2016) is over 4 K for both polarizations, with at least 1.3 K higher than the one presented in this paper.

For a daily sea ice thickness retrieval, based on SMAP brightness temperatures only, both horizontal and vertical, are first adjusted to the SMOS brightness temperature using the linear regression parameters. Then they are gridded into a 12.5 km resolution NSIDC polar stereographic grid using a Gaussian weighting for the distance with a cutoff from the grid cell center of 15 km and FWHM range of 40 km. For ~~11 October~~ the period from 1 October to 31 December 2015~~(not shown) the differences~~, the difference in sea ice thickness between SMOS 40° incidence angle fitted TBs retrieval and SMAP retrieval are small~~. The RMSD of the SIT between the two retrievals for thicknesses below 51 cm is 2.0 cm with 0.4 cm positive bias~~, 2.39 cm RMSD and -0.2 cm average difference for the SMOS SIT relative to the SMAP retrieval taking into account only grid cells containing at most 50 cm SIT and at least one of the two retrievals having over 0 cm.

4.2 SMOS/SMAP combined sea ice thickness retrieval

Because of the small differences of the retrievals from the two sensors, combined maps are produced using both of them. The daily mean horizontal and vertical brightness temperatures are computed separately for both sensors~~for each grid cell~~. For each grid point of the SMOS ISEA 4H9 grid we compute the daily SMOS TBs using the 40° fit. Then the brightness temperatures are regridded to the NSIDC 12.5 km grid commonly used for sea ice maps. SMAP brightness temperature data ~~are~~ is gridded directly to the NSIDC grid using a Gaussian resampling as was done in Sect. 4.1. The two resulting TB datasets are averaged. Finally the sea ice thickness retrieval for 40° incidence angle is applied. The result is a SIT map that has the benefit of using data from both sensors (e.g. Fig. ~~5~~ 6 (left)) ~~:~~ it has a larger coverage, and is less affected by RFI sources. ~~Also~~ For the area north of 55.7°N the coverage in the mixed dataset increases over 6% compared to the 40-50° daily mean TB retrieval. Also the combined brightness temperatures are more representative for a daily mean due to the 12 hours difference in the equator crossing time between the two sensors, the combined brightness temperatures are more representative for a daily mean. The RMSD between the original 40° to 50° incidence angle daily mean retrieval from Sect. 3.1 and the new mixed sensor one is 2.142.05 cm for the three months 1 October to 31 December 2015 period investigated, while the bias is -0.63 cm (see also Fig. 5 for an example of the spatial distribution of differences on -0.58 cm. The result means that the mixed sensor SIT is on averaged slightly smaller than the SMOS daily averaged brightness temeratures SIT. Figure 6 center shows the difference between SMOS 40-50° incidence angle averaged TBs sea ice thickness and the mixed data for 24 October 2015. The highest differences appear mostly in the transition area of 40 cm to over 50. Taking in account just data points with maximum value of 50 cm and for at least one of the two datasets a value over 0 cm, the 93% of the data has an absolute difference of at most 2 cm for the three months period compared. Figure 6 right compares the retrieval done just with the SMOS 40° fitted brightness temperatures to the mixed data one. For this comparison, the averaged difference is below -0.1 cm and the RMSD is 1.37 cm for the complete three months period.

5 Assessment of uncertainties

5.1 Sea ice thickness uncertainties

In the SIT retrieval using 40° incidence angle TBs of the two sensors several factors contribute to the uncertainty: the radiometric accuracy of the observations, RFI contamination in the TB data, the uncertainty in the auxiliary data used for the training of the retrieval, the influence of the SIC on the TBs and the sub-daily variability of the TBs themselves.

Here we propose a method to quantify the uncertainty of the retrieval. We first compute the SIT in the (TB_h, TB_v) space using the 40° TBs trained retrieval (Fig. 7 (left)). The TBs that will be used in a retrieval will more likely be found above the one-to-one line (black line) where the vertical brightness temperature is higher than the horizontal one. The color in the diagram indicates the retrieved SIT according to the retrieval curve for 40° incidence angle (red curve in Fig. 1). The TB space covered by the 40 to 50 cm thickness is small compared with the rest of the thickness range.

As second step we compute the derivative of SIT as a function of TB_h and TB_v seen in Fig. 7 center and right, respectively. Almost all of the data points will be found above the one-to-one line where the polarization difference is positive. For most of TB_hs below 200 K the rate of change of the SIT is below 0.5 cm per K and is increasing sharply with increased TB_h at over 230 K TB_v. In contrast, the derivative for TB_v (Fig. 7 right) at values above 230 K is positive for TB_h below 213 K, and becomes negative above it. The sensitivity of SIT relative to TB_h and TB_v will be used to compute the uncertainty of the retrieval. For a given pair (TB_h, TB_v) and their associated uncertainties we compute the SIT and corresponding SIT uncertainties:

$$sigma_{SIT} = \sqrt{\left(\frac{\partial SIT}{\partial TB_h}\right)^2 \cdot \sigma^2_{TB_h} + \left(\frac{\partial SIT}{\partial TB_v}\right)^2 \cdot \sigma^2_{TB_v} + 2 \cdot \left(\frac{\partial SIT}{\partial TB_h}\right) \cdot \left(\frac{\partial SIT}{\partial TB_v}\right) \cdot \sigma_{TB_h} \cdot \sigma_{TB_v} \cdot \rho_{TB_h TB_v}} \quad (4)$$

where σ_{TB_h} and σ_{TB_v} represent the TB uncertainties, $\rho_{TB_h TB_v}$ is the correlation between the two polarizations. The values of the SIT derivatives are taken from the second step of the method for each pair of (TB_h, TB_v).

For this study we do not take into account the radiometric accuracy of either sensor because they are small compared to the other errors, especially the brightness temperature variation during one day. For each SMOS observation at 40°incidence angle, the TB uncertainty is assumed to be the RMSD resulting from the fitting process presented in Sect. 3.2. During the fitting routine the RMSD is computed for each iteration and a 5 K threshold is used for eliminating outliers. Although this process is used to eliminate potential RFI influences in the data, it will also reduce the variability that comes from observations of the same grid cell at different times of the day. For SMAP brightness temperatures a weighted standard deviation for each grid cell using all observations from one day is used as uncertainty. The correlation between the TB_h and TB_v is 0.81 and 0.97 for SMOS and SMAP, respectively. The correlation was calculated for a period of seven days. It was computed per day over the whole Arctic using daily averaged TB for each grid cell and is consistent during the whole period.

Figure 8 shows as an example the scatter plot and moving average (red lines) of the SIT uncertainty (Eq. 4) for 11~~October~~ October 2015 for SMOS (top) and SMAP (bottom). The restrictions imposed on the RMSD of the SMOS data have a clear impact on results. The TB uncertainties for SMOS in majority over 2 K lead at higher thicknesses to high uncertainty. Because the SMAP data is still containing the full variability of observations of one day, there will be grid cells with over 5 K uncertainty, but overall the median is around 1.2 K, in comparison with SMOS where the uncertainties are clustered around 4 K. Again, the smaller uncertainty of the SMOS data is only due to the TB fitting procedure, which removes outliers. Without that, for the raw data, the SMOS uncertainty would be similar or even larger than for SMAP. For both sensors we can observe a rapid increase of the uncertainties beyond 35 cm SIT (Fig. 8).

~~The original validated SMOS thin~~

5.2 Sea Ice Concentration impact

The SIT retrieval used in this paper assumes 100% ice concentration. As a result, the retrieved sea ice thickness decrease if this condition is not fulfilled. We assume that brightness temperature over sea ice varies linearly with the change in sea ice concentration:

$$TBp(SIT, IC) = TBp_i(SIT) \cdot IC + TBp_w \cdot (1 - IC) \tag{5}$$

where p represents the polarization, TBp_i and TBp_w are the brightness temperatures of ice and water, respectively and IC is the sea ice concentration.

For this study we first use 40° SMOS brightness temperatures from 11 October 2015 for retrieval. The resulting SIT will be considered the assumed sea ice thickness~~algorithm from Huntemann et al. (2014) has been adapted to SMAP data .~~. In the second step we take the same TBs as input for TBp_i, use fixed tie points for TBp_w with 85 K and 125 K as values for the horizontal and vertical TBs, respectively. For each pair of SMOS and water brightness temperatures we consider a range of sea ice concentrations for which we compute SIT using Eq. 5. The assumed SIT is grouped in bins of 1 cm thickness. Its corresponding thicknesses from the second step are averaged for each SIC separately. Figure 9 shows how the retrieved SIT varies relative to the assumed SIT depending on the SIC. For a SIC of 90% at 10 cm the retrieved SIT is 8.5 cm, while at 50 cm is just 28 cm.

Current retrievals for SIC are influenced by thin sea ice. In Heygster et al. (2014), SIC algorithms have been tested for 100% sea ice concentration with thicknesses below 50 cm. All algorithms show less than 100% SIC for thicknesses below 30 cm. In another study done by Ivanova et al. (2015) all SIC algorithms registered a decrease in SIC, up to 60% at 5 cm, and an overall bias of 5% for over 30 cm. As we have observations at two polarizations at each grid cell available, it should in principle be possible to retrieve SIT and ice concentration simultaneously. However, an attempt has shown a strong noise increase in SIT (Kaleschke et al., 2013).

During the winter most of the Arctic is covered by SIC of 90% and higher (Andersen et al., 2007). For an assumed uncertainty of the sea ice concentration data of 4% (Ivanova et al., 2015) the error that could be introduced by a correction of sea ice thickness for high SIC is higher than that of the error introduced by the assumption of 100% sea ice concentration (Tian-Kunze et al., 2014). The uncertainty of SIC algorithms at high concentration and their covariation at thin thicknesses will cause high errors if a correction to SIT is applied using current SIC datasets. As a result full ice cover is assumed for the SIT retrieval.

6 Conclusions

The existing retrieval for thickness of thin sea ice (Huntemann et al., 2014) from the L-band sensor SMOS (launched 2009) has been adapted to SMAP (launched 2015) by (i) modifying the SMOS retrieval to use 40° incidence angle instead of the average in the ~~rage~~ range 40° to 50°, (ii) establishing a linear regression between the SMOS and SMAP brightness temperatures at 40° incidence angle.

To derive the SMOS brightness temperature at 40° incidence angle required for the first step, an analytical function is fitted to the incidence angle dependent brightness temperatures. ~~Using SMAP~~ SMAP top of the atmosphere data and the SMOS data fitted to the same incidence angle ~~to calibrate the SMAP TBs to those of SMOS has improved the~~ yield a small TB RMSD between the two datasets for both polarizations ~~with~~ of 2.7 K and 2.81 K for ~~TB$_h$ and TB$_v$~~ TB_h and TB_v, respectively. This is an improvement ~~from~~ compared to previous attempts (Huntemann et al., 2016) where the ~~the~~ RMSD for both polarizations was over 4 K~~showing that using fixed incidence angles for SMOS data increases the accuracy~~. Moreover the SMOS based ice thickness retrieval has been adjusted ~~for~~ to the new SMOS data version 6.20. The new ~~algoritm~~ algorithm contains a new RFI filtering routine exploiting the dependence of the brightness temperatures on the incidence angle. This ~~results in improved coverage for~~ method improved coverage of previously RFI affected areas. Although the TB datasets of the two sensors are processed differently, the overall resulting thicknesses are similar, with SMOS TBs having smaller variability at lower thicknesses due to the iterative observations removal operation, .

Concluding, the benefit of SMAP for retrieval of thickness of thin sea ice is twofold: first, the combined product has ~~the advantage of~~ a better spatial and temporal coverage that in future studies can allow insights even on a sub-daily scale. The overall increase in spatial coverage is 6%. Second, SIT can be retrieved from ~~SMAP data alone ,~~ any of the two sensors alone with similar accuracy~~as with SMOS~~, making the production chain more stable in the case of malfunction of one of the two sensors. The small differences in retrieved SIT between the presented method and the method from Huntemann et al. (2014) allows us to refer to their comparisons for the assessment of the quality of this product. A full validation of the current retrieval requires a comparison with independent in-situ sea ice thickness data currently not available at the scales of thickness (below 50 cm) and horizontal extent of the sensor footprint (~43 km diameter).

Data availability. https://seaice.uni-bremen.de

Competing interests. No competing interests are present

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~~SMOS intensity for 6.20 data (left) for 29 October 2010 ; Intensity difference (right) between the 6.20 and the 5.05 data versions.~~

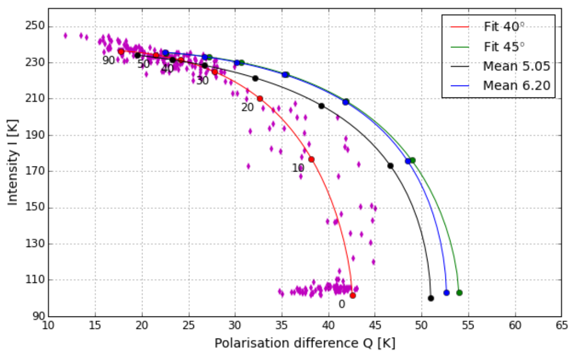

Figure 1. Sea Ice Thickness retrieval curves derived from SMOS data representing original algorithm (black), new data version (blue), 45° (green) and 40° (red) incidence angle fitted brightness temperatures. Dots represent data from the three training areas used for obtaining the 40° fit curve. Numbers under the curve represent the SIT in centimeters.

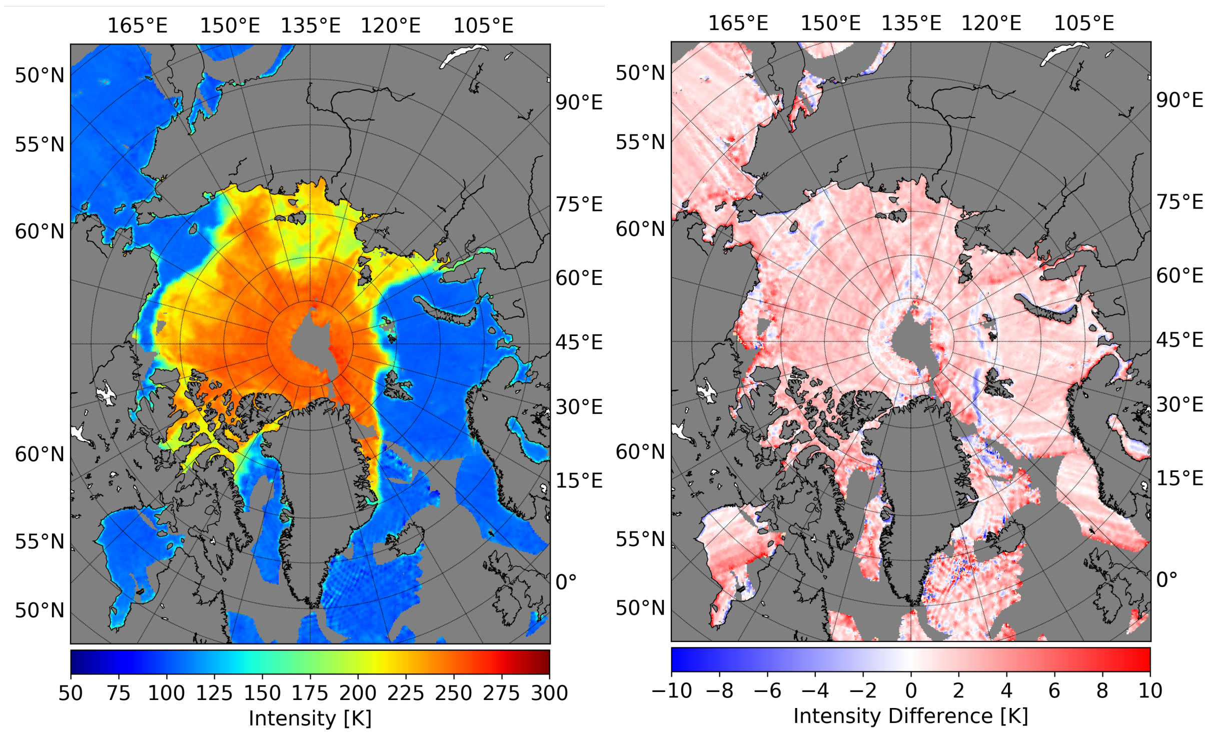

Figure 2. ~~Histogram of~~ SMOS ~~sea ice thickness~~ intensity for data version 6.20 data (left) for 29 October 2010 ; intensity difference (right) between ~~daily mean retrieval~~ the 6.20 and ~~45° incidence angle fitted brightness temperatures retrieval on 29 October 2010.~~ the 5.05 data versions.

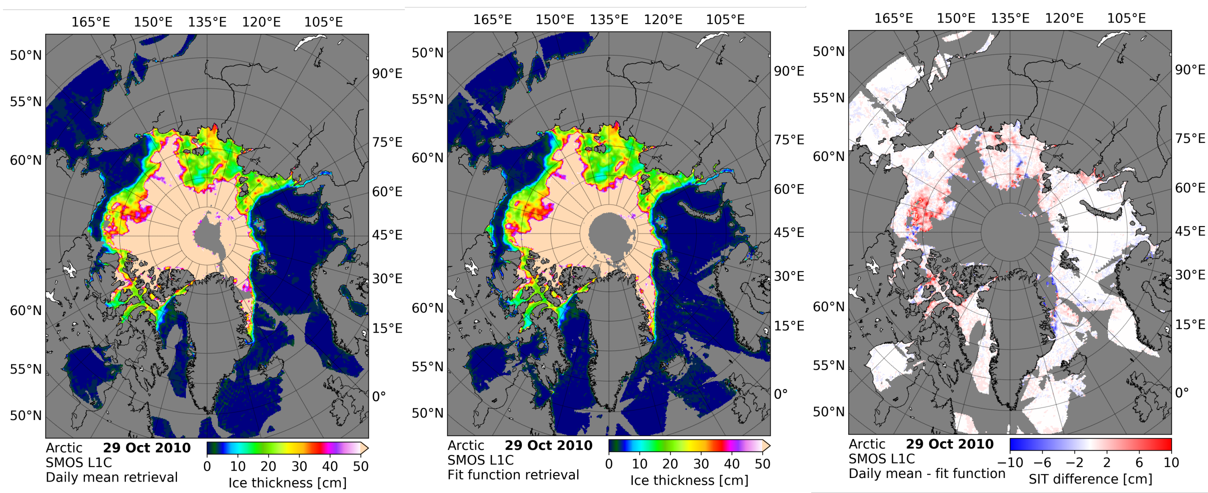

Figure 3. SMOS sea ice thickness retrieved on 29 October 2010 using 6.20 retrieval (left), retrieval using 45° incidence angle fitted brightness temperatures (central), and the difference between the two (right) with areas over 50 cm SIT not shown.

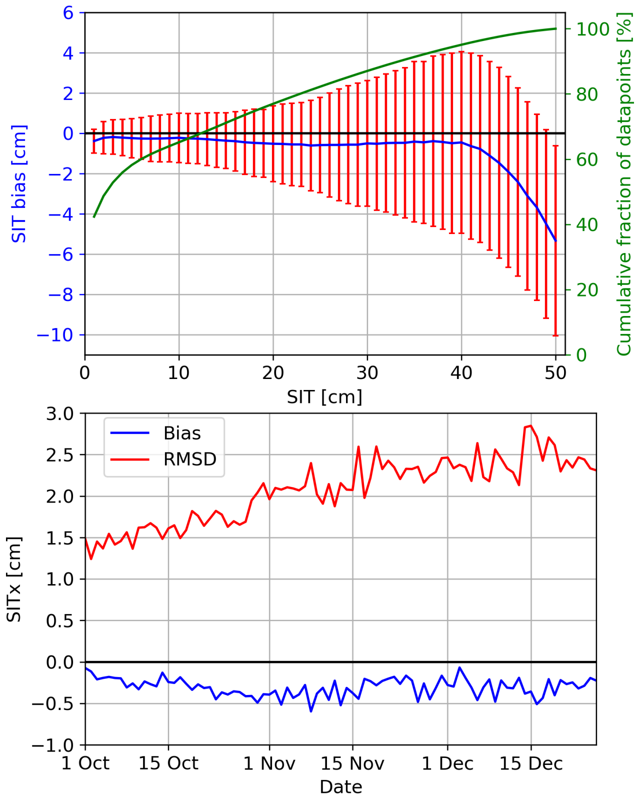

Figure 4. (Top) SIT bias (blue) calculated by substracting the SIT computed using 40-50° daily average from SIT using TBs fitted at 45° for the 1 Oct. to 26 Dec. 2010 period. Bias is computed relative to the daily average SIT in bins of 1 cm and its coresponding RMSD (red). Green curve represents the fraction from the total amount of data points for each thickness bin. Bottom figure shows the bias (blue) and RMSD (red) for each day separately.

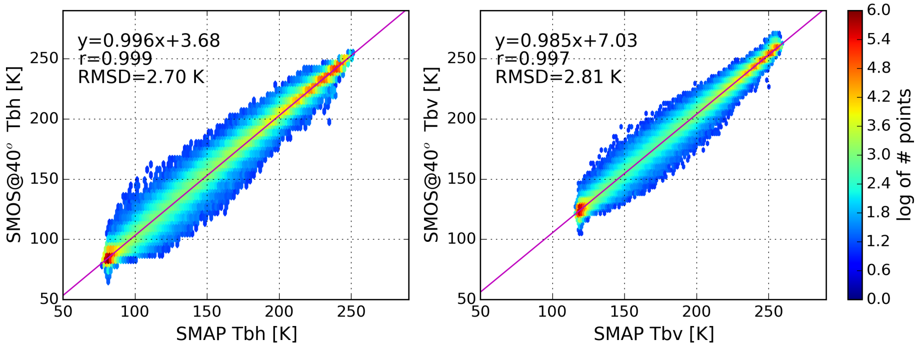

Figure 5. Logarithmic density plot of TB_h (left) and TB_v (right) data from SMAP and SMOS for the period 1 October to 31 December 2015. Magenta lines represent the linear regression between the two datasets.

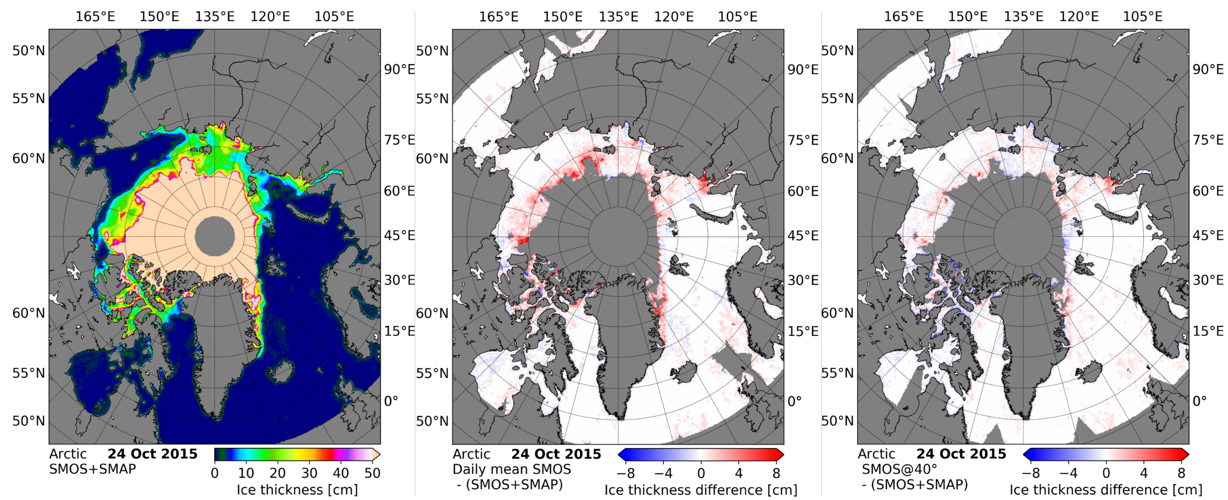

Figure 6. Sea Ice Thickness retrieved on ~~11~~ 24 October 2015 for the joint SMOS+SMAP product (left)~~and~~, the SIT difference between the SMOS daily mean retrieval and the joint ~~product~~ retrieval (center), and the SIT difference between SMOS fitted TBs at 40° incidence angle and the joint retrieval (right).

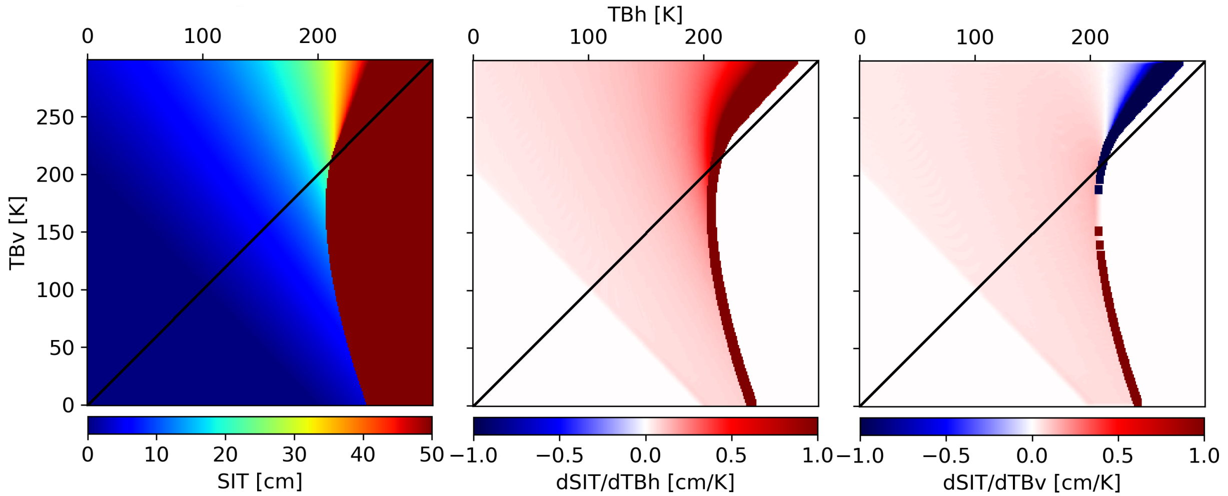

Figure 7. SIT (left) computed with the 40° TB algorithm (Fig. 1 red curve) represented in the space of TB_h and TB_v. Derivative of SIT as a function of TB_h (center) and TB_v (right). Black line represents the location of equal TB_h and TB_v, with the area above the line (TB_v higher than TB_h) representing values found in observations.

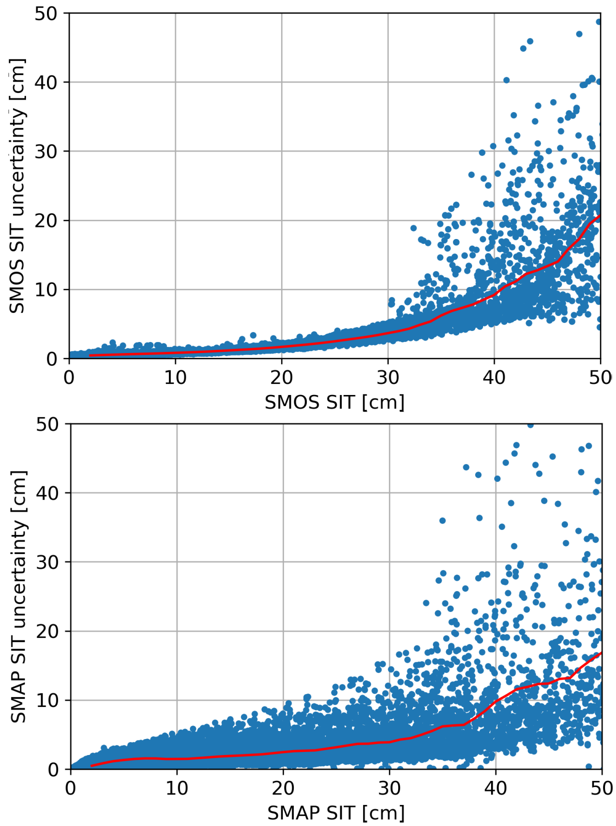

Figure 8. Scatter of SMOS (top) and SMAP (bottom) retrievals at 40° incidence angle for 11 Oct. 2015 in the Arctic and their respective uncertainties. Red line represent the rolling average of the uncertainty.

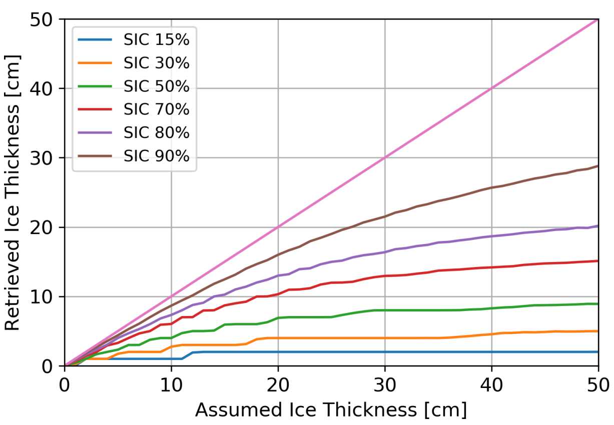

Figure 9. SIT retrieved as function of the assumed SIT under different SIC values.

Table 1. Sea ice thickness retrieval curve parameters for the original 5.05 data version training, 6.20 training, and the two fit curve parameters for 40° and 45° incidence angle

Retrieval	Parameter	a [K]	b [K]	c [cm]	d
5.05	I_{abc}	~~100.2~~ 234.1	100.2	12.7	-
	Q_{abcd}	51.0	19.4	31.8	1.65
6.20	I_{abc}	~~103.0~~ 235.7	103.0	12.7	-
	Q_{abcd}	52.7	22.3	33.2	1.60
fit 40°	I_{abc}	~~101.5~~ 236.4	101.5	12.2	-
	Q_{abcd}	42.6	17.3	32.9	1.39
fit 45°	I_{abc}	~~103.3~~ 235.4	103.3	12.5	-
	Q_{abcd}	54.0	22.2	33.0	1.47

Table 2. Parameters for linear regression between SMOS and SMAP brightness temperatures

Polarization	Slope	Intercept [K]	RMSD [K]	r
H	0.996	3.68	2.70	0.999
V	0.985	7.03	2.81	0.997