MS Record: tc-2021-791:

Title: Advances in altimetric snow depth estimates using bi-frequency SARAL/CryoSat-2 Ka/Ku measurements.

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Referee#3 global comment

The presented manuscript by Garnier et al. shows promising results on the timely topic of snow thickness both in the Arctic and the Antarctic for use especially in sea-ice altimetry to derive sea-ice thickness and subsequent data products. It is therefore relevant and clearly in the scope of TC. However, I found the manuscript is overall lacking some clarity in writing and presenting and I therefore recommend major revisions. My comments/suggestions are detailed below and are also meant to be challenged.

Answers to the anonymous referee#3 comments

We would like to thank the reviewer for her/his careful reading of the manuscript and for the relevant and constructive remarks. In order to fit with your global comment, we have made an complete revision of the manuscript that should have considerably improved the quality of the writing and the readability of the document. We hope that the modifications we have made will meet your requirements. Please find below the details on how your general and specific comments have been taken into account. In this « author's response document », the referee's comments are in bold type, the answers are in italic type, and the corrections to the revised manuscript are in normal type.

General comments

1. In general, I find the manuscript lacks clarity and readability due to a lack of proper use of articles (e.g., the Arctic) and other frequent grammatical errors that need to be corrected.

We apologize for the editorial oversights in the manuscript. We have proofread the manuscript thoroughly to correct as many grammatical errors as possible.

2. Starting with the abstract, parts of the manuscript are hard to grasp for the reader as they are not well structured or flooded with acronyms and multiple line-long passages put into parenthesis.

In our revision of the manuscript, we have tried our best to increase the clarity of the document. For instance we have added 2 tables:
- Table A4 summarizes the time period of the different snow depth product used in the document.
- Table A5 list of acronyms table.

Table A5 allows to only explicit most important acronyms, which reduces multiple line-long passages put into parenthesis

Also, In order to increase the clarify and better define the objectives of the paper we have modified the end of the introduction as follows:

L132: A recent study of Zhou et al. (2020) presented an inter-comparison of available snow depth products from re-analyses, passive radiometry and altimetry (DuST). Similar, this paper reviews the state-of-the-art by comparing current main snow depth estimations. Yet, the main objective is to present and assess the upgraded version of the ASD product (see Sect. 2), covering the 2013-2019 period in both hemispheres. The article fits in with the upcoming HPCM CRISTAL mission (Kern et al., 2020) and aims to demonstrate the potential of such snow depth data to further specific studies on, for instance, improved sea ice volume representations, freshwater budgets, snow properties or data assimilation. Except from an analyse of the impact of the snow depth uncertainty on SIT retrieval, it doesn't explicitly address these questions.

The paper is organized as follows:

- First, we detail the methodology to process the ASD product and present all the datasets used in this study.
- Section 4 compare ASD with the main other existing snow depth satellite and model data in both hemispheres.
- The datasets are then assessed against OIB, CryoVEx and IMB validation data in the Arctic in section 5
- To circumvent the temporal limitation induced by SARAL, we propose in section 6 a preliminary snow depth climatology based on ASD.
- The last section 7 aims to quantify the SIT level of uncertainty due to the snow depth from an ensemble of SIT estimations calculated from the satellite and model snow depth datasets presented in the previous sections.
- We finally discuss and conclude, emphasizing current needs for snow depth data in sea ice studies.

3. Furthermore, while this might sound a bit picky, I found it quite irritating to read Antarctica throughout the manuscript as this would reference the continent, not the region (which would be the Antarctic). This goes in line with the usage of unfamiliar specific terms such as sea ice sinking in L32, which I think should be avoided and replaced by proper, i.e., commonly used terms.

All the grammatical issues raised in your specific comments have been corrected. We have carefully replaced "Antarctica" by "the Antarctic" and systematically used "the" in front of Arctic. Many phrasings have also been modified to improve the readability of the document.

4. Aside from these rather editorial remarks, I found the inclusion of the model data rather redundant and fail to have a clear take-home message from this aside from that model data appears to be very bad in general for snow depth. Could the authors elaborate a bit more on why they choose to include this in the presented way for the different datasets?

The synergy with models is crucial for instance to fill the observation gap. Of course we understand that we did not analyse in deep the sources of differences since it an entire article could have been dedicated to that topic. There are mainly two reasons why we wanted to include model data in our article

- *we wanted to show, in the form of the state of the art, that there are still very few representations of snow depth on sea ice and that they are still affected by significant uncertainties and inconsistencies.*
- *Synergy between observations and models will become crucial, either to improve the models or to complete the still incomplete observations.The first step towards this synergy is to observe the coherence and deviations of these different representations.*

5. The usage of different time periods for different comparison exercises for the ASD even with the same "reference" such as OIB (e.g., L14-16) comes along quite unintuitive and should be better justified/clarified by the authors!

We agree that the different time periods may affect the readability of the article. In our point of view, this is yet necessary to make consistent comparisons. To prevent the reader from misunderstandings we have specified this point in section 4.1 Methodology as indicated below. In addition Table A4 clarify the time periods of the snow depth different products.

L319-322: Since snow depth products and validation data are available over different time periods (see table x), the comparisons are also performed on different time periods. Our approach is to take, for each comparison, the time period common to all the compared data. The aim is to provide reliable statistics. For each comparison, a label specify the considered time period.

Specific comments

L1: Do not capitalize sea-ice thickness (also consider hyphenation); potentially add "retrieval" after sea-ice thickness for clarification!

This comment has been taken into account in all the revised document.

L2: Please include "the" in front of the term "Arctic" most likely throughout the whole manuscript – but I'll try to point most of them out.

We have included "the" in front of the term Arctic in the whole revised manuscript.

L2: Maybe it is just me, but shouldn't it be the "modified Warren climatology" and not the "Warren modified climatology"?

We now use the phrasing "modified Warren-99 climatology" in the whole revised manuscript

L3: Please consider using "the Antarctic" instead of "Antarctica" as this geographically references the continent where we would not expect much sea ice anyways.

We now use "the Antarctic" instead of "Antarctica" in the whole revised manuscript.

L9/11: add "the"; see L2

We have included "the" in front of the term Arctic in the whole revised manuscript.

L10: The official website from JAXA uses the acronym "AMSR2" without a hyphen.

We have removed the hyphen in the whole revised manuscript.

L11: "It's" refers to DuST?

"It's" refer to the ASD product. We have corrected the sentence as follows:

L11-12: The ASD product is further validated in the Arctic against the Ice Mass Balance (IMB) buoys, the CRYOsat Validation EXperiment (CryoVEx) and Operation Ice Bridge's (OIB) airborne measurements.

L14/16: Why are these time periods different?

The ASD product is available from 2013. Then, we compare with OIB campaign occuring after 2013, with respect to the other snow depth product availability. To assess the ASD climatology it is more consistent to compare with the OIB data prior to 2013. Since OIB campaign have strated in 2009 we then use the 2009-2012 time period.

L29: For the sake of completeness, a reference to the ESA CCI sea-ice thickness product covering both the Arctic and Antarctic should be included when detailing available sea-ice thickness products. This would be in line with the authors detailed introduction to available snow on sea ice products later on:
Paul, S., Hendricks, S., Ricker, R., Kern, S., and Rinne, E.: Empirical parametrization of Envisat freeboard retrieval of Arctic and Antarctic sea ice based on CryoSat-2: progress in the ESA Climate Change Initiative, The Cryosphere, 12, 2437–2460, https://doi.org/10.5194/tc-12-2437-2018, 2018.
Or the referenced data publications by Hendricks et al. (2018).

The articles Paul et al. (2018); Hendricks et al. (2018) have been added to the revised version of the document.

L28 : By integrating such sea ice freeboard estimations in the hydrostatic equilibrium equation, several SIT products have been computed (e.g., Laxon et al., 2013; Kwok and Cunningham, 2015; Guerreiro et al., 2017; Paul et al., 2018; Landy et al., 2019;

Laforge et al., 2020).

L462-463 : Note, that experimental SIT estimations (Hendricks et al., 2018) have already been done in the Antarctic in the framework of the Sea Ice Climate Change Initiative (SI-CCI).

L32: sea ice sinking a very unfamiliar terminology

We have modified the sentence as follows:

L32-33: For example, it is necessary to account for the snow loading (Laxon et al., 2013)

L37: "transfer of solar heat energy of the ice-ocean interface" reads kind of clunky and should be rephrased as energy from the ocean directed upwards probably does not fall under the term of "solar heat energy".

We have modified the sentence as follows:

L37-38: Because of its high albedo and a low thermal conductivity, the snow regulates the transfer of solar heat energy penetration accross the ice-ocean interface (e.g., Grenfell and Maykut, 1977; Sturm et al., 1997)

L42: "the" again

We have included "the" in front of the term Arctic in the whole revised manuscript.

L56: Insert a space before "Their"

We have inserted a space before their.

L68: If I am not mistaken, this should be "have" instead of "has" as we talk of the campaigns

We agree. the sentence have been corrected.

L69/70: "the Antarctic" again

We now use "the Antarctic" instead of "Antarctica" in the whole revised manuscript.

L71: There is also an English URL seaiceportal.de

We now provide the link (https://seaiceportal.de/en/) in the revised version of the manuscript.

L86: no " the" needed before radiometric data

We have removed "the" before radiometric data

L89 and 58: two different Names for the AMSR-E/2 missions and acronyms... please correct!

In the whole revised manuscript AMSR-E refers to the Advanced Microwave Scanning Radiometer for the Earth Observing System and AMSR2 to the Advanced Microwave Scanning Radiometer-2. To ensure clarity and consistency, the use of identical spellings have been verified.

L122: remove "over"

We have removed over.

L128 following: This part would profit from a numbered list format or bullet points

L134: In general discussion comes before the conclusion

L139/140: In Line 109 the authors referenced CryoSeaNICE as source of the development?

A preliminary version of the ASD product has been developped as part of the CryoSeaNICE project but the version presented in this article has been developped whithin the CSAO+ and Polar+ Snow on Ice projects. We agree that the phrasing in the introduction (L109-) might be confusing. For clarity we have modified these sentences as follows:

L123-127: Recently, Armitage and Ridout (2015) have demonstrated this possibility by considering the difference of penetration between the CS-2 Ku-band frequency radar (13.5 GHz), assuming it is reflected near the snow/ice interface, and the

SARAL/AltiKa Ka-band frequency radar (35.7 GHz), assuming it is reflected near the top of the snow pack, i.e the air/snow interface. Thereafter, a preliminary Altimetric Snow Depth (ASD) version covering the 2013-2016 winter period has been developed at the « Laboratoire d'Etudes en Géophysique et Océanographie Spatiales » (LEGOS) during the European Space Agency (ESA) CryoSat SciEnce-oriented data ANalysis over Sea-ICE areas (CryoSeaNICE) project (Guerreiro et al., 2016).

L144: 500x500 of what? Pixels?

500x500 is the number of pixel of 12.5km in the Arctic grid. To clarify this point, the sentence has been modified as follows:

L297: Model and satellite snow depth estimations are projected onto the same EASE2 grid with a pixel size of 12.5 km.

L147: Technically, these are still elevations that are compared from what we read before in the text and not yet freeboards.

We indicated freeboard because our methodology is based on the difference of freeboards. As you requested we have modified the sentence as follows:

L158: The main assumption is that the difference between these two surface elevations is only due to the penetration of the Ku radar in the snow pack, and that the Ku radar penetrates fully to the snow/ice interface.

L150 and 154: The authors reference the Baseline C handbook but use Baseline B data? Is that an error/typo and in case it is not, could the authors elaborate a bit more on their reasoning why they use a quite outdated baseline for their data? And what differences if any they would expect to more recent Baseline-based products?

We use the GOP CryoSat-2 Baseline B until 2017 and Baseline C from 2017 to 2019. The reason why we did not used the baseline C for all the time period is simply because the Baseline C was not available at the time we had processed the data. It is now available but it would need some times to reprocess all the data. Because the waveforms are exactly the same in the two Baselines (and then the computed snow depths), we have decided to keep this version for this article. Note that we are currently re-processing the data so that the ASD product will be computed over the 2013-2020 period in both hemisphere from the baseline C only . The only difference is then that it will also cover the SARIN mode zones. You are right that it is important to let the reader (and probable futur users be aware of this). For that purpose the sentences L151-155 of the article has been modified as follows:

L167-170: Since the Baseline-C PLRM GOP product was only available from 2017 at the time we have computed the ASD data, we have used the Baseline B for the period 2013-2016. It does not impact ASD since we use only the L1b product levels which have identical waveforms on both baselines. However, the baseline B does not include the SARin data. Then, the ASD data does not yet cover the SARin mode zones. The next version of the ASD product will include SARin mode zones.

L170: The abbreviation should be "TFMRA"

This has been corrected in the revised version.

L170/174: Could the authors elaborate a bit on their reasoning for a two-time smoothing? Is the data otherwise that noisy?

The 25km radius smoothing on leads is because we consider that the sea level anomaly should not significantly vary within this window. Variability should then be altimetric noise. Note that uncertainties are also computed using this assumption. For the 50km median smoothing applied to the retrieved freeboards, it is subject to discussions. Actually, we also compute freeboards with 25km smoothing. Other groups like AWI use a 25km smoothing on freeboards. This is more a matter of choice that only

very weakly affect the results. In our opinion the 50km smoothing reduce noises in marginal and coastal zones. It should be more adapted to reduce SARIN mode noises that will be included in the next versions .

L175/176: Would one expect comparable results between the two approaches of crossover calculations and monthly maps? Did the authors look into the differences and can provide a bit of insight?

The ASD product presented here is indeed an updated version of the product presented in Guerreiro et al. (2016). We do agree that first compare the two version and explain the differences would have been a consistent approach.

Of course we have first investigated the deviations between the 2 products. It appears that the results are quite different, with significantly higher gradients in the previous version but it is difficult to draw some conclusion from the differences. Is it mainly due to extrapolations (of croosover snow depths points) ? is it due to monthly mean freeboard smoothings ? along track better consistencies ? Note that, in addition, the previous ASD version hasn't been computed as a product for users but more as an experimental dataset for the work of a PhD. The data have not been computed after 2015 and only cover the central Arctic.

Since the article is already quite long and compare a larger amount of data we have chosen to avoid this comparison that, for our point of view, does not bring much information. Then apart from your imperative requirement for publication, we would prefer not to put more information concerning this previous product in this article.

Figure1: I would highly suggest to use "named" subpanels such as a), b), c), etc. as they can be more easily references in the text and the figure caption. This could improve the overall readability of the manuscript.

We do agree that it is a relevant advise. Unfortunately we haven't got the time before re-submission to modify this point. In case of a second review, we would do it.

L219: There is a "." missing before "Because".

This has been corrected in the revised version.

L221: Starting in which year ending in 2019?

To clarify this point we have modify the revised manuscript as follows:

L239-240: This product is available on a daily basis from November 2012 to April 2018 on a polar stereographic grid with a 25 km x 25 km resolution.

L247: The sentence reads incomplete after the URL, please change.

We have modified the sentence as follows in the revised version of the document.

L262-264: Data used in this paper are snow depth monthly mean maps provided on a 100 km $\times$ 100 km stereographic polar grid issued from the NESOSIM 1.0 configuration (Petty et al., 2018). It is freely available at https://earth.gsfc.nasa.gov/cryo/data/nasa-eulerian-snow-sea-ice-model-nesosim.

Figure2: "winter months" should be clarified in the figure caption

The caption has been modified as follows :

Times series of annual mean snow depth of the different products in both hemispheres. Annual means are calculated as the average of the spatial means of all monthly grid maps. Only the 6 winter months are considered in the calculation (November-April in the Arctic and May-October in the Antarctic). Note that the AMSR2 data are not represented in the Arctic since the

AMSR2-NSIDC product is only available over FYI and the AMSR2B product is only available at full spatial coverage (FYI and MYI) in March and April.

L277: how are they projected? Or rather resampled – using a NN approach? How are multiple assignments dealt with (mean,max,min)?

The gridded model and snow depth monthly data are projected onto the EASE2 grid of ASD using a simple two-dimensional multivariate interpolation (griddata function in python). We have added this specification in the revised manuscript:

L296: Model and satellite snow depth estimations are projected onto the 12.5km pixel size EASE2 grid similar of ASD using a linear two-dimensional multivariate interpolation.

L293: What do the authors mean by in-situ tracks? The OIB data?

We mean the gridded data (model and satellite products) are projected using a bilinear interpolation (linear is reductive) on the tracks of the in-situ and airborne data. It means that we compare the differents data in the space of the validation data instead of gridding the validation data in EASE2 grid as it is more commonly done. We think that this methodology is more appropriate (in data assimilation calculations are always performed in the observational space). We have modified the revised manuscript as follows :

L315: snow depth model and satellite gridded maps are projected along the aircraft trajectories using a bilinear interpolation.

L294: "monthly maps corresponding to that day" – does that mean, e.g. the the 12th of January gets monthly map of January? Please clarify.

It is exact. A snow depth airborne data of the 12th of January would be compared with, for instance, the ASD snow depth monthly mean data of January. To clarify this point we have modified the manuscript as follows :

L315-316: Airborne and in-situ are generally daily data, the comparisons are performed with mean maps of the month to which that day belongs.

L303: "lower than" – this means the snow is 3 cm thinner compared to AMSR2B? Please clarify!

Indeed, "lower than" means that the snow is, on average, 3 cm thinner compared to AMSR2B.

L307: "the" Appendix

This has been corrected in the revised version.

L309: This reads like we are comparing complete winter seasons but from what I read before I assumed DuST data is only available and used for the months of March and April? This should be clarified by the authors.

It not exactly true. The algorithm to compute DuST data use a re-calibration function based on the OIB data, which only exist in March and April. However the function is used to calculate snow depth data for the 6 months of winter. Note that considering

that snow depth is thicker in March and April, it is consistent to observe that positive bias for the DuST. To clarify this point we have modified the section 3.1.1 as follows

L221-222: The DuST (Lawrence et al., 2018) data are provided in the Arctic on a 1.5° longitude x 0.5° latitude grid for by the Centre for Polar Observation and Modelling, University College London (www.cpom.ucl.ac.uk/DuST). They are available for the 6 winter month (November to April) until 2018.

L314: only by the spatial availability or also by the temporal?

We have added this point in the revised version of the document:

L339: ....since DuST calibration is limited by the spatial and temporal availability of OIB.

Table A1 in general is referenced frequently in this section. Maybe the authors should consider to actually include it here and not the Appendix.

We agree that the table is frequently referenced in this section. Meanwhile this table is not needed to understand the section. Table A1 is only necessary for in-deep analysis. Then, for clarity, we would prefer to keep it in the Appendix.

Figures 3/4: see comment on Figure 2 [(a),b),c) + winter month)]

winter month has been explicated in the methodology section.

L343: "weaker" is quite judging… maybe rephrase to "lower"

This has been corrected in the revised version.

L359: I am not familiar with the DuST product in any detail but form what the authors provide as information it is specifically tuned/recalibrated using OIB data yet falls short in every comparison to OIB data? Could the authors elaborate on their opinion why that is the case and what they do specifically better?

It is not calibrated with the quicklook OIB version. We do not want to say that we do better but that the use of the pLRM data for CS-2 avoid a recalibration with OIB which is dependent to 1) the OIB version 2) the space and time resolution of OIB 3) not possible in the Antarctic at the moment.

L359: The authors should also stay consistent with their use of Ka/Ku or band/-band throughout the manuscript!

This point has been taken into account in the whole manuscript.

Figure 6: It is quite hard to separate in other figures as well but I found it especially hard in this one between the three different red colors!

The readability of the figure has been improved in the revised version of the article.

L404: "a more optimal" – maybe just say "better/improved"?

We have corrected this point using the word "better".

L446: Fig. 10 shows that the ASD climatology would be a better solution than W99m,

L420: Again, this lacks a proper reference to the ESA CCI product, see comment above.

We have added the reference to the work of Hendricks et al. (2018) :

L461-462: Note, that experimental SIT estimations (Hendricks et al., 2018) have already been done in the Antarctic in the framework of the Sea Ice Climate Change Initiative (SI-CCI).

L497: The double "mean" in this term is very confusing and should be clarified.

To simplify, we have modified the revision version as follows :

L536-537: Considering « obs snow products » and all winter months, we obtained a SIT mean standard deviation of ≈ 20 cm (14%).

Figure 12: The order and titles of the figures do not match the figure caption (min, mean, max). The last caption sentence

The snow products used to compute the maps are ASD, DuST, AMSR2B and W99m. These maps correspond to the case « obs snow products ».

L537: “based”

We have corrected this mistake in the revised document

References

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