Point-by-point response to editor and reviewer concerns by
corresponding author: H. Jakob Belter
March 16, 2020

tc-2019-307:
Satellite-based sea ice thickness changes in the Laptev Sea from 2002 to 2017: Comparison to mooring observations
https://doi.org/10.5194/tc-2019-307:
Belter, H. Jakob, Thomas Krumpen, Stefan Hendricks, Jens A. Hoelemann, Markus A. Janout, Robert Ricker, Christian Haas

Dear anonymous Reviewer #2,

on behalf of all authors, I would like to thank you for this extremely helpful review. Below, we provide you with a point-by-point response to your comments. We hope that we were able to answer all your comments sufficiently. We would also like to refer you to the responses to the other reviewers for more improvements and changes to the manuscript.

General comments:

- *(1) The 'Data and method' section lacks important details. The data section only briefly introduces different data sets. It is not clear how many measurements were compared and how the mean Laptev Sea sea ice thickness from gridded data was calculated. Section 4.1. and 4.2 describing data limitations can be moved to the 'Data and methods' to provide the reader with valuable information before introducing the results.*
  -Response:
  We added more information, especially on the processing of ADCP sea ice draft to the respective subsection in the 'Data and methods' section. We also added an additional paragraph to the 'Sonar-based ice draft measurements' subsection to clarify how weekly and monthly VAL draft values have been calculated. Further changes have been made to the 'ESA CCI-2 orbit data' subsection to indicate how many data points are used for the comparison to VAL data (also in response to Reviewer #3). Also in response to the other reviewers we combined the averaging of the satellite SIT values into a single paragraph at the end of the 'Satellite data' subsection. The explanation of how ESA CCI-2 Laptev Sea SIT anomaly was calculated is provided in the first paragraph of the 'Results' section. Thanks to your great suggestion to move the 'Data limitations' subsection to the 'Data and methods' section we also provide additional information before presenting the results, which we agree provides the reader with more information to better follow the rest of this study. We hope you agree that the 'Data and methods' section is more comprehensive now.
  -Changes:
  Changes to the 'Sonar-based ice draft measurements' subsection (**LINES 121-124**). Additional changes to the 'ESA CCI-2 orbit data' subsection (**LINES 146-150**). New paragraph to combine satellite sea ice draft averaging at the end of 'Satellite data' subsection (**LINES 162-171**). 'Data limitations' subsection was moved to the end of 'Data and methods' section (**LINES 172-200**).

- *(2) The discussion can be elaborated. - The Anabar, Khatana and Lena stations a located in the area of polynya formation. Are polynya events taken into account in SAT and VAL data? Do the polynya events affect your comparison between SAT and VAL monthly mean? - One of the main finding shows that SAT data represents modal sea ice thickness rather than mean. What is a possible explanation? - The SAT-VAL difference depend on sea ice thickness. It there a seasonal change in this difference? I suggest that a scatter plot with seasonal cycle might be informative. - Section 4.4 introduces new data, method and results. Would it make more sense to restructure it*

and add a subsection to methods and results? Why other data from ADCP and ULS is not shown? Does it confirm you findings?

-Response:

Since you are asking a whole bunch of questions here we will divide this response into subtopics:

Polynya influence:

First of all, you are right that Anabar, Khatanga and Lena stations are in the area of possible polynya formation, however, the impact of polynya events on the VAL data is rather limited. In cases of open water (in the polynya) both ADCP and ULS are able to identify the lack of ice. In cases where thin ice is present in the polynya the instruments recognise the ice as well. Daily, weekly and monthly averages of sea ice draft are calculated after open water was exclude from the draft time series and therefore do not impact the final daily, weekly or monthly values. However, daily, weekly and monthly averages of sea ice draft are only calculated in cases where 'enough' data points are available. If for example 20 out of 30 days in October show open water (or no data for that matter), no October mean value is calculated for the respective mooring. The threshold for calculating any of the averages is 50% of the maximum number of data points that are available for that period. If more than 50% of the data is missing or attributed as open water no average is calculated. As for the SAT data, open water is also not included into the SIT values. Thin ice is a little more complicated as it is an issue of ongoing research. The problem here is whether the satellite detects thin ice as ice or as water. Is it detected as water, it does not influence the final SIT value. Thin ice on the other hand is very much overestimated just because of the fact that the algorithm predefines the same amount of snow it would add to thicker ice. For the presented comparison these difficulties from the SAT data side should not be an issue since our VAL data defines whether data points are compared or not. If the sonar detects a long period of polynya induced open water, no daily, weekly or monthly value is calculated. Accordingly there is no VAL data point that could be compared to the SAT data.

Explanation for better agreement with modal sea ice draft:

This issue is also actively discussed right now. The first step to identify reasons for this result would be to figure out whether the initial freeboard measurements already show this tendency. However, the available VAL data is based on draft measurements and no additional information on freeboard is available for comparison here. Possible reasons for this bias are mentioned in this study and include: errors in the retracking, surface type classifications, snow depth, ice density. It is very likely that a combination of all these factors contribute to the overall bias. In order to quantify them future comparisons with ICESat-2 data are planned.

Seasonal changes:
Considering that SIT has a seasonal cycle and SAT-VAL difference is dependent on thickness the SAT-VAL difference will definitely have a seasonal cycle as well. Thick winter ice is underestimated by the satellites (most negative SAT-VAL difference of the respective time series), while thin ice is overestimated (most positive SAT-VAL difference of the respective time series). It would definitely be interesting to look at seasonal changes especially for long-term data sets from one location, however, our data is limited to one year time series from all over the Laptev Sea and this is not possible here. Furthermore do we feel that this is not relevant for the study as it is. The agreement is thickness dependent, independent of when thick or thin ice is observed. The aim, especially of the 'Stability' subsection is to investigate the performance of the satellite data. Answering questions like: Is the SAT-VAL difference the same when 1 m thick ice is measured in 2003 compared to when 1 m thick ice is measured in 2015?
Taymyr 2013/2014 case study:
We thoroughly discussed whether the case study should be part of 'Data and methods' and 'Results', however, we came to the conclusion that it is more of an addition that highlights the results presented before. The introduction of the new method (using ICETrack to calculate accumulated convergence) is an add on here in order to give a first explanation about what possible reasons for the underestimation of thicker ice by the satellites could be. Something similar was commented by Reviewer #1. The analysis on whether the agreement between modal or mean VAL draft is better with satellite draft data was done only for ULS-based draft time series. The temporal resolution of the ADCP-derived drafts was simply not appropriate to calculate meaningful modal ADCP draft values. The result that satellite sea ice drafts agree better with modal VAL drafts was confirmed for all four ULS data sets. We only chose the Taymyr example here since it was the only one of the four ULS data sets that showed a gradual increase in mean sea ice draft (Taymyr 2013/2014 Jan to March). Accordingly the difference between mean and modal VAL draft is larger and our finding could be visualized best.
-Changes:
Polynya influence:
We added the information that open water values were excluded prior to averaging of VAL draft data (**LINES 121-124**).
Taymyr 2013/2014 case study:
We added a sentence on why the comparison to modal values was only done with ULS data (**LINE 364-366**).

Specific comments:

- *(1) Line 160: 'The ESA CCI-2 SIT CDR shows an overall thinning of sea ice in the Laptev Sea between 2002 and 2017.' The sentence about is too strong. The error of the overall trend is as large as trend. Also the significance of the trend is quite low. The black line rather shows that there is no changes in sea ice thickness.*
  -Response:
  Thank you for pointing that out. You are right these first few sentences concerning the overall trend are too strong.
  -Changes:
  We toned down the sentences in question to make sure the reader realizes that although the trend line is slightly negative it is highly uncertain and should rather be interpreted as no significant trend over the period from 2002 to 2017 (**LINES 203**).

- *(2) Lines 161-162: How is the Laptev Sea defined? Please show the region used for SIT anomaly calculation in Figure 1.*
  -Response:
  -Changes:
  The region used to calculate ESA CCI-2 SIT anomaly was added to Fig. 1. Fig. 1 and Fig. 2 captions were updated.

- *(3) Line 210: 'ENVISATorbit data shows a higher average RMSD, stronger average underestimation of VAL sea ice draft and much lower average correlation with VAL sea ice drafts compared to the gridded ENVISAT data' Is there an explanation? Why does the orbit data which supposed to be closer to the VAL measurement shows worse statistical characteristics?*
  -Response:
  This is very likely related to the uncertainty of the individual orbit values and the larger number of data points that go into the weighted mean and the corresponding larger noise compared to the gridded data sets.
  -Changes:
  Also in response to a comment from Reviewer #1 the uncertainties of ENVISAT and CS2 orbit SIT values were added to the respective 'Data and methods' subsection (**LINE 146**).

- *(4) Lines 282-283: 'The seasonal biases between ENVISAT and CS2 need to be considered for the temporal development of the Laptev Sea SAT-VAL differences between the two periods'. Please elaborate. Are those biases considered in this study?*
  -Response:

What that means is that simultaneously measured SIT values from ENVISAT and CS2 are different from one another. This seasonal bias is strongly connected to the different ice thicknesses that can be observed over the course of a 'season' (which is basically late-autumn, winter and early-spring, since CCI-2 SIT data is only available from October through April). These differences are introduced in the 'Data and methods' section (2.2.1). This sentence here serves as a reminder that these inter-mission biases exist and that they are not constant throughout a single season. We consider these biases here, as we compare monthly mean values of sea ice draft from ENVISAT and CS2 rather than annual averages. The offsets between ENVISAT and CS2 to VAL data are shown in Fig. 3, 4 and 5. However they are not declared or displayed as seasonal but thickness dependent offsets. Biases between ENVISAT and CS2 can be specifically seen in Fig. 3 where ENVISAT-VAL and CS2-VAL differences are plotted for the Outer Shelf stations (2010/2011 and 2011/2012). As the focus of this study is on whether satellite products are stable over time we are concerned with thickness rather than seasonal values. We do not want to show whether ENVISAT and CS2 show the same agreement or offset every March but whether they show constant biases for, for example, 1 m thick ice independent of when 1 m thick ice occurs.
-Changes:
No changes.

- *(5) Lines 343-348: It is worth mentioning that ULS provide sea ice draft measurements after the onset of melt. However it is not a real finding that there is sea ice in the Laptev Sea in June-July. Please consider reformulating.*
-Response:
We apologize if it seemed like we presented this fact as a new finding. We were merely trying to remind the reader that the temporal limitations of the radar altimeter satellite products should not be mistaken for complete loss of sea ice after April.
-Changes:
We reformulated the above-mentioned paragraph (**LINES 367-372**).

- *(5) Line 359: 'The presented satellite products represent similar sea ice drafts differently.' I am not sure the meaning is clear. Do you mean identical sea ice draft or sea ice draft of similar thickness, e.g. within presented bins?*
-Response:
Thank you for bringing this up. We are referring to Fig. 5 where it is indicated that the same VAL sea ice draft values are represented very differently by the five investigated SAT data products.
-Changes:
We clarified that in the 'Results' section (**LINES 280-281**).

Technical comments:

- *(1) Page 1 line 24: sea ice system - sea ice state?*
  -Response:
  -Changes:
  Changed.

- *(2) Page 2 Line 43: a space after '(ULS)' is missing.*
  -Response:
  -Changes:
  Corrected.

- *(3) Line 132: a space after 'ENVISAT' is missing.*
  -Response:
  In this case we are using the abbreviation ENVISATorbit that was introduced in the line above.
  -Changes:
  No changes required

- *(4) Figure 2: It seems that colors of the legend in the upper left corner are mixed up. The negative trend should be the ENVISAT one.*
  -Response:
  -Changes:
  Corrected.

- *(5) Figure 7: The scale on the sea ice draft axis is missing.*
  -Response:
  We are not sure what you meant with the missing scale. The sea ice draft axis (left) shows sea ice draft values from -1 to 5 m and is labelled with the corresponding unit (m). It is the reference axis for mean, modal, CS2 and CS2SMOS sea ice draft, while the axis to the right corresponds to accumulated convergence from the NSIDC (both the axis and the acc. convergence graph are given in blue).
  -Changes:
  No changes.

Additional changes from the authors

- *(1) Due to changes in the review process of the ADCP sea ice draft derivation method paper (previously Belter et al., 2019b, now Belter et al., 2020b, in review at the Journal of Atmospheric and Oceanic Technology) the estimated uncertainty values provided for the daily mean sea ice draft time series have been changed. See changes in* ***LINE 116-117 and LINE 179-181****.*
- *(2) Daily mean sea ice draft time series from the Laptev Sea ADCPs have been published and a reference was added to the 'Data availability' section (****LINE 415****).*

Finally, we would like to thank you again for your comments and great suggestions. We hope you agree that the changes made improve the manuscript.
Kind regards,
H. Jakob Belter