Satellite-based sea ice thickness changes in the Laptev Sea from 2002 to 2017: Comparison to mooring observations

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General comments

ESA CCI-2 project has produced SIT CDR over the Arctic based on ENVISAT and CryoSat-2 (CS2) radar altimeter data. The SIT CDR covers the period from 2002 to 2017 and winter months from Oct to Apr, and includes both monthly gridded data (25 km) and SIT data along orbit tracks. The authors of this paper have compared this SIT CDR to in-situ sea ice draft measurements (VAL data) by ULS and ADCP sensors in the Laptev Sea. The SIT CDR data was converted for the draft data for this comparison. In addition, also SIT data from merged SMOS-CS2 product converted to draft was compared to the VAL data, but this study has a minor part in the paper (which is ok). The draft data from ADCPs (accuracy ±0.1 m) cover years 2003-2016 and more accurate (accuracy ±0.05 m) ULS draft data is for 2013-2015. The main result of the study is very interesting: in the Laptev Sea, where first-year ice mainly occurs, the SIT CDR data agrees better with the modal sea ice draft measured by ULS and ADCP, and it overestimates drafts below 0.7 m and underestimates drafts over 1.3 m with this underestimation increasing with increasing draft. The modal draft (and SIT) is related to sea ice thermodynamic growth, i.e., SIT/draft of level ice. This seriously hampers (if I understood correctly) investigating temporal SIT trends in the Laptev Sea based on the CCI-2 SIT CDR (or any other SIT record based on the radar altimeter data). A comparison between the validation data (VAL) and SIT CDR (SAT-VAL difference) showed linear trends in the SAT-VAL difference in different VAL draft ranges (0-1 m, 1-2 m, 2-3 m), but these trends could be robustly attributed to intermission bias between ENVISAT and CS2. Therefore, the accuracy of the CCI-2 SIT CDR was found to be stable over time, but its uncertainty is different from ENVISAT and CS2 periods. The SIT CDR were used to briefly investigate SIT anomaly trends (Figure 2). Trends were found, but the only trend during the CS2 period is statistically significant. It was emphasized that these trends need to be investigated further due to short periods and high uncertainties of the SIT products.

In general, the study set up with data acquisitions and data processing is sound, as are methods for the data analyses. The conclusions in the paper are well justified by the results from the data analyses. This paper should be of interest for the scientists producing or analyzing SIT records from RA data, and it fits nicely to the scope of TC. However, I have following general comments which could improve the paper:

The authors should discuss whether their main results are also applied to other Arctic areas dominated by FYI, like Kara Sea, and point out clearly whether the current CCI-2 CDR can be used to investigate SIT trends over FYI dominated oceans; in Figure 2 only SIT anomaly trend from the CS2 period was statistically significant.

In Introduction Section you could review what is current understanding on the accuracy/quality of the CCI-2 SIT CDR: it seems this has been investigated at least by Kern et al. 2018. Are there any other studies, especially in peer-reviewed journals? You could also review similar other studies: comparisons between RA SIT records and sonar draft data. What is the typical relationship(s) between sonar and RA drafts over MYI?

A short section describing typical sea ice conditions and typical progress of sea ice season in the Laptev Sea would be good addition to the paper. How much there can be MYI in the Laptev Sea?

Can there be large areas of grounded landfast ice for which the used freeboard to SIT conversion is not valid, and thus, could have an effect on your results?

Sections 2-4 should have short introductions about their content and focus.

The processing of ADCP data to the sea ice draft is based on reference (Belter et al., 2019b), but this is paper under review; so it is possible that it may not ever get published, or at least at time of possible publication of this paper this reference is not available. Is it possible to include this ADCP processing method (summary) as Appendix here? Are there any conference papers, web-pages, etc., you could also have as references?

In Section 2 you could have a sub-Section which describes how different datasets are processed to match each other. Now this information is scattered in sub-Sections describing the datasets. Also include a Table which summarizes datasets: spatial and temporal resolutions, accuracies, etc.

How many pixels there are in the gridded datasets over the Laptev Sea? This is relevant to Figure 2. The gridded (25 km) SIT data were selected from and an area of 25 km radius around a sonar mooring, thus at maximum four pixels were selected? You should give these kind details on the dataset matching Section.

The uncertainty of the sea ice draft calculated from the CCI-2 CDR SIT data is estimated with (1)

$d_{unc}=d/SIT*SIT_{unc}$

But d = SIT – freeboard, so d_{unc} could be sqrt(SIT_{unc}^2+fb_{unc}^2)? Well SIT and fb are correlated…How about if you estimate d_{unc} with typical uncertainties of all parameters in the equation d = SIT – fb; e.g. snow thickness, would you end up a same figure as with (1)?

Section 3.3.2 Merged CS2SMOS sea ice draft contains also a summary of all results; this should be in its own sub-Section.

Section 4.4, Taymyr 2013/2014 case, is under ‘Discussion’, but it includes data processing and analyses, these could be under ‘Results’, also the data processing methods would fit better to Section 2. Why this very important case study which reveals that the CDR SIT correspond modal sea ice draft, and not the mean draft, was not repeated with any ADCP dataset? This would be very important so that we would see consistency of this conclusion. This case study could be also described with more details in Introduction, now only one sentence.

Tables 1-3 show averages of statistical parameters from different mooring locations. I am not sure this is meaningful, what an average correlation coefficient really tells us here? I think better would be here to combine all datasets together and then calculate RMSD, mean difference and r.

Specific comments

1 Introduction

line 21: “While knowledge about SIC is widely available it provides limited insight into overall sea ice changes.”

You could include reference(s) to SIC records, like OSI SAF ones.

l. 26: “Satellite remote sensing of SIC started in the 1970s with passive microwave sensors (Parkinson et al., 1999) and was further developed, updated and improved by multiple follow-on missions (Comiso and Nishio, 2008; Cavalieri and l. Parkinson, 2012) until today.”

Some newer references would be nice, like:

Lavergne et al., Version 2 of the EUMETSAT OSI SAF and ESA CCI sea-ice concentration climate data records, The Cryosphere, 13, 49–78, 2019

l. 36: “the impact of snow radar backscatter”

the impact of snow on radar backscatter?

Explain that both gridded and orbit track SIT CDRs are used in your study.

l. 64: ‘Taymyr mooring’

at this point a reader does not know what this Taymyr mooring is

2 Data and methods

Can you explain why ADCPs where not moored at some locations in different years?

Figure 1: you could mask land out; add color scale for the water depth; show boundaries of the Laptev Sea.

It would be interesting to see what is the typical variation of the sonar draft during a day, week and month. A figure about a time series of sea ice draft from some ADCP location would be nice.

How sonar draft data was processed to a monthly scale, just averaging all datapoints?

Are there any peer-reviewed journal papers that could be put as reference to CCI-2 SIT CDR in Section 2.2.1? A figure about monthly gridded SIT over the Laptev Sea would be interesting see; also what it typical SIT spatial variation over the Laptev Sea in this monthly product? How many pixels there are over the Laptev Sea?

l. 118: “Although Paul et al. (2018) minimized the inter-mission sea ice freeboard biases for the basin average, ENVISAT freeboards in multi-year ice (MYI) regions are still thinner than CS2 freeboards, while ENVISAT provides thicker freeboards than CS2 in regions that are dominated by FYI.”

Give some figures; how much thinner and thicker.

l. 127: “a weighted mean sea ice draft value.”

What is this weighting?

Section 2.2.2

Give typical uncertainty in a single SIT orbit value. How many SIT points are typically averaged within 25 km radius and in a daily scale? What is the uncertainty of this average?

3. Results

Comment correlations shown in Figure 2 in Section 3.1.

Did you investigate SIT anomalies in different part of the Laptev Sea? I think AARI uses Eastern and Western Laptev Sea regions. Is it possible to compare the SIT anomaly trends to any other study/data source? E.g. based on AARI ice charts? Are the trends related to polynya activity (extent, ice production) in the Laptev Sea?

Figure 3(b) is not commented/discussed in the text; e.g. symmetry/normality of the pdf?

Section 3.2 title could be “Gridded monthly sea ice draft”.

Section 3.3 title “Higher temporal resolution satellite products” is not good, what is this ‘higher’?

“Daily and weekly sea ice draft products”?

In Figure 4 it is difficult to see grey crosses. Maybe these single datapoints can be removed and instead describe in the text how many RA draft datapoints were typically in each VAL draft interval.

l. 214: “It also confirms the intermission biases between ENVISAT and CS2 that were published by Paul et al. (2018).”

Please give out these biases here.

l. 227: “Consequently the underestimation of sea ice draft with increasing thickness is largest for CS2SMOS because of the larger uncertainties of SMOS over thicker sea ice.”

But for thicker ice CS2MOS SIT comes only from CS2 data? If so then SMOS uncertainty should have no effect here.

4 Discussion

Figure 6(b) is not discussed in the text.

What data is ICETrack using? SAR imagery? Describe in the text.

l. 346: “That means that, for investigations into the sea ice cover in the Laptev Sea it is important to be aware that sea ice can persist some time after the presented satellites stop providing SIT data.”

How about before the winter in late summer? Phrasing here: satellites do not provide SIT data, but your data processing methods do, i.e. SIT estimation is not possible (at least currently) for summer/melting season.

5 Conclusions

l. 350: “The ESAs CCI-2 gridded SIT CDR covers a period from 2002 to 2017 and has been validated for multiple regions around the Polar regions of the Earth.”

A short summary about the results of these validation activities would be good here. Later in Conclusions you could summarize what new insight in the accuracy of the CCI-2 SIT CDR your study resulted.

l. 378: “Therefore, improvements in the processing of radar altimetry data are required for the estimation of surface roughness but also for the parametrizations of snow depth and densities of snow and ice.”

How surface roughness would be utilized in the freeboard tracking? How about different freeboard trackers for different ice types, like FYI and MYI?

l. 383: “Furthermore would continuous long-term SIT measurements in the Laptev Sea provide much needed information on deformation processes.”

Is this supposed to be an interrogative clause? Or “Furthermore, continuous long-term SIT measurements in the Laptev Sea would provide…”?