

Reviewer 1

Monitoring Arctic thin ice: A comparison between Cryosat-2 SAR altimetry data and MODIS thermal-infrared imagery, R1

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The authors have presented detailed, proper answers to most of my comments to the first version of the paper, and made corresponding changes and additions to the paper. I think that the paper has improved considerably. Below I have some minor comments for your consideration for further possible paper improvements.

We thank the reviewer for the constructive support. All remaining technical comments were accepted and added to the manuscript. Individual responses to comments can be found in the following section.

“It is true that the SMOS dataset is not mentioned in the datasets. We would like to focus intentionally on Cryosat-2, MODIS and Sentinel-1, since these data were mainly used. In the case of SMOS, a readymade data product was used. The dataset was taken unchanged as a basis for comparison and is therefore well documented and referenced, whereas in the case of Cryosat-2, MODIS and Sentinel-1 observations had to go through various pre-processing steps.”

I have to strongly disagree here, you should describe the SMOS dataset under Section 2.

With respect to the Editor comment and our initial focus on a MODIS/CS2 comparison, we decided to remove the SMOS comparison from the main manuscript body (as well as Figure 7) and therefore also eliminate the need for a more detailed description in Section 2 of the data. However, we added an additional Figure from our letter to the Editor into the manuscript's Appendix as an exemplary basis for our decision to not further investigate SMOS as a potential candidate for this type of comparisons. All occurrences in the manuscript were adjusted accordingly to reflect this decision.

line 38: “Numerous studies exist on the automatic detection of leads. These use altimeter data (e.g., Lee et al., 2018; Dettmering et al.; Wernecke and Kaleschke, 2015) or SAR images (e.g., Park et al., 2020; Boulze et al., 2020).” Please include also Murashkin et al., 2018 here.

Done

“This algorithm was developed at UB and AWI, so maybe the authors have access to it?”

You could discuss in the paper why did you not use automatic methods to detect leads/thin ice in SAR images.

We added Murashkin et al. as a reference for SAR lead detection in the Introduction and an explanation for not including automatic SAR image processing in Section 2.3

“An automatic thin-ice detection from SAR images is not applied in this study because this falls outside the main focus of the work.”

Reference details missing:

Dettmering, D., Wynne, A., Müller, F. L., Passaro, M., and Seitz, F.: Lead Detection in Polar Oceans—A Comparison of Different Classification Methods for Cryosat-2 SAR Data, Remote Sensing.

Done

“However, none of the existing studies has yet attempted to detect thin-ice using satellite altimetry data.”

I guess I have to trust you here; I don't have time to do a survey on altimeter literature, and I have not worked much with altimeter data.

“Only manual visual screening was conducted as the MODIS cloud mask tends to eliminate especially very thin ice areas”

“Is snow on thin ice neglected in the TIT calculation?”

“Yes. This is one assumption in general for the retrieval of thin-ice thickness from MODIS in our and also other approaches and also outlined in, e.g., Paul et al (2015).” Please give this information (snow and cloud screening) in Section 3.2.

Done

“From ERA5 2m air temperature data, the average temperatures for the study period and region is always well below freezing point as one would expect in winter (about 253K depending on the exact location; a). However, there are rare occasions of above freezing-point temperatures (about 1.6%; b) especially over land, but also near the coast over sea-ice/fast-ice areas. While certainly the surface conditions change under these conditions and impact the received returns for CryoSat-2, we consider the overall impact on the UWC negligible.”

Please give this discussion on weather conditions in the paper.

Done. Please see Section 3.

“[...] the basic ESA Climate Change Initiative's (CCI) CryoSat-2 surface-type classification with classes 'sea ice', 'lead', and 'unknown' [...]”

In the track changes doc 'sea ice', 'lead', and 'unknown' are missing.

This was a technical LaTeX problem. We thank for that hint and can confirm that everything is included in the non-track change document.

“[...] there is currently only a single operational Arctic-wide thin-ice data product available [...]”

This is not exactly the case: there are two SMOS SIT products, one by UHAM (now AWI?) and one by UB, using same SMOS input data, but different algorithms. You should also give references to UB product.

We refer here to the official operational ESA SMOS product. However, we added a reference to the UB product as well.

“We follow the reviewer's suggestion and provided numerical (Pearson) correlations. Please find a table in the Appendix.”

Yes, good to have these correlations, but you should also include some discussion on them to the text.

We have included correlations in the text to support the discussion.

“We have added the sea ice concentration source products to the manuscript.” Also references or web-links should be given.

We added a reference.

l. 24: “Leads and polynyas are openings of varying size and shape between drift...” Between 'drift ice'? Leads and polynyas can also occur within landfast ice.

Per definition the ice would not be land-fast anymore with an active polynya/lead within it but at least partly mobile. We assume the reviewer refers to flaw leads/polynyas which occur at the fast-ice edge. However, there was an ‘ice’ missing after ‘drift’ and we corrected the sentence in the manuscript accordingly.

1. 69: “resolution to enable future monitoring of thin ice with a high spatial-temporal resolution”

You could define what mean by ‘high spatial-temporal resolution’, in context of which applications. We rephrased this sentence to read: “[...] NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) to allow for a better understanding of the received CryoSat-2 waveform returns over thin sea-ice areas and, subsequently, an improved surface-type classification.”

Start of Section 2.3 needs editing – two first sentences on Sentinel-1.

We rephrased the two sentences and added information about the status of Sentinel-1B.

Finally,

“It would be interesting to also see how CS2 thin ice classification works as a function of MODIS TIT, a similar investigation is now conducted for CS2 waveform features. “

“This comment leads in the direction of the table shown in the comment above.”

This table is interesting and you could consider to include it to the paper with some discussion. I understand that coarse MODIS resolution causes some errors here (explain this in the paper).

We prefer to leave this table in the rebuttal of Review 1, which is public and can be viewed at any time. There are various notes and discussions in the paper regarding the different resolutions of MODIS and CS-2.

Reviewer 2

Suggestions for revision or reasons for rejection (will be published if the paper is accepted for final publication)

The authors have made substantial improvements to the paper by thoroughly addressing several of the reviewer comments. In cases where the authors did not act on a reviewer comment, they provided a justification for their decision. The authors should be commended for their attention to detail in making the revised version of the manuscript a worthwhile contribution to The Cryosphere pending some additional minor comments and corrections.

We thank the reviewer for the constructive support. All remaining technical comments were accepted and added to the manuscript. Individual responses to comments can be found in the following section.

By line number.

L7: thin-ice thickness (singular not plural since it is a variable) : done

L9: change “or to directly adjust” to “or direct adjustments to” : done

L9: “... specifically to” should be “.... for” : done

L11: delete “mere” : done

L12: delete “basic” : done

L13: delete “between” : done

L20: delete “sea-ice” before leads and polynyas : done

L27: delete “the” : done

L38: change “allows measure” to “enables direct measurements of” : done

L52: This doesn't need to be a new paragraph. : done

L57: Since this is mentioning the current situation, it would be appropriate to update this to the combined SMAP-SMOS thickness product.

We refer here primarily to ESA's official operational product which is based on SMOS only but are also including now the University of Bremen's similar data product due to a strong request by Reviewer 1. The combined product, however, is not considered on par and also not used due to its very limited availability.

L64: delete “the capabilities of” : done

L79: should be “highlights” : done

L83-84: It would be better to be consistent with ESA stated primary Cryosat-2 objectives of measuring diminishing land and sea ice in polar regions, for understanding the role of climate in diminishing polar ice.

We thank for this comment and changed the sentence.

CryoSat-2 was launched in April 2010 aiming to monitor the Earth's cryosphere and, in particular, to measure the decline of land and sea ice in the polar regions in order to understand the role of climate in the retreat of polar ice.

L85: delete “the cryosphere”: done

L97: change waveform returns to “waveforms” : done

L102: Clarify the wavelengths associated with these band numbers. : done

L111: Since Sentinel 1B is no longer operative, it would be appropriate to update this sentence to better reflect the situation. Or change it to past tense to reflect the situation relevant to the study.

We added a sentence.

Unfortunately, Sentinel-1B became non-operational after an instrument failure in December 2021.

L115: provides: **done**

L116: delete “in the ice covered ocean”: **done**

L121: “a” shows up twice: **done**

L128: map projection (no “s”): **done**

L129: It is unclear what is meant by theoretical size. If this is an estimate it should be indicated as such.: **We mean the potentially usable image dataset size. We changed that in the manuscript.**

L142: Please clarify what is meant by observations here. It is relatively straightforward but someone outside of altimetry might find it difficult to follow whether an observation is a track or a waveform (or other). : **done**

L157: Delete "see". Also "Fig." or "Figure" be consistent: **done**

L191: It would be more appropriate to define this when first used as TIT and use TIT throughout.: : **done**

L202: Confusing sentence. Do you mean “... NCEP2 reanalysis by Kalnay et al. ... “?: **yes – this was a LaTeX typo and we changed it to show the reference in parenthesis**

L204: TIT: **done**

L209: Since comparisons are also made to SMOS, it would be better to mention that here too. Currently it is on L217.

The SMOS comparison was removed from the manuscript to focus on the initial CS2/MODIS comparison and replaced by an additional Figure taken from our Letter to the Editor in the previous round of revisions.

L225: Where it is mention that reasons are two-fold, some consideration of the geometric i.e. positional accuracy of the different sensing systems should also be considered here. At least nominally, how well is everything co-located?

We are not quite sure if we understand the comment correctly or what the reviewer is aiming at. The orbit accuracy of both missions is in the lower centimeter range. We consider these smaller uncertainties to be negligible in comparison to other influences such as co-occurring sea ice drift or the size of the SAR pixels as well as footprint coverage of the altimeter.

L228: add a space after small: **done**

L243: Unclear what is meant by “fall up”. Contain?: **We changed to “contain”.**

L255: “... change in roughness ...”: **done**

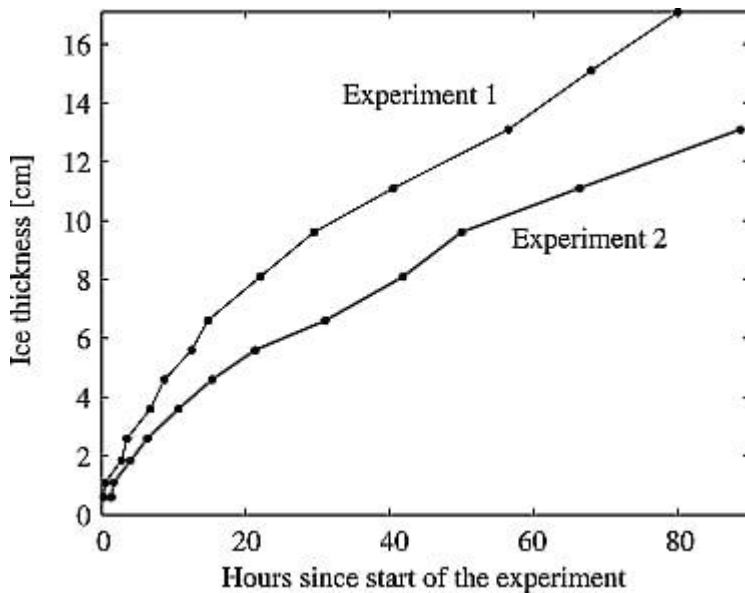
L257: Change “But is” to “It” : **done**

L262: Delete “really” : **done**

L275: change “but also” to “and: **we totally rephrased this part**

L279: It would be helpful to have some context on expected growth rates of sea ice, or at least how long it takes for a lead to freeze over, with reason given that it will be dependent on e.g. air temp, water temp, etc. (minutes, hours, days, etc.)?

While the mentioned paragraph was removed in the context of eliminating the SMOS comparison in this study, a simple answer as mentioned also by the reviewer is difficult to provide. The growth rate depends on several parameters (air temp, ocean heat flux/water temp, salinity, etc.). However, as outlined in Notz and Worster (2008; Figure 7, included below), within about 24 hours the ice grows up to between 5-8 cm, which is slightly above the MODIS uncertainty provided for this study for a maximum time difference between CryoSat-2 and MODIS acquisitions.



Notz, D., and Worster, M. G. (2008), *In situ measurements of the evolution of young sea ice*, *J. Geophys. Res.*, 113, C03001, doi:[10.1029/2007JC004333](https://doi.org/10.1029/2007JC004333).

Figure 8 caption: the average feature values are blue circles not “blue dotted line”: done¹

L382: Is it noise, or just a more variable signal (less peakiness)?:

Both signal characteristics are included. The noise increases with a simultaneous decrease in peakiness. We have added “higher variability” and “less peakiness”.

L391: For the reason stated in the sentence beginning “Moreover ...” the summary is better and stronger without this in it

This was removed in the process of eliminating the SMOS comparison from the current version of the manuscript.

¹ Please note: Now it is Figure 7