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

Felix L. Müller, Stephan Paul, Stefan Hendricks, and Denise Dettmering

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General comments

The authors have conducted a study which is related to on-going development of sea ice thickness (SIT) retrieval algorithms for CryoSat-2 (CS2) radar altimeter. They modified an existing unsupervised CS2 waveform classification (UWC) method by Müller et al. (2017) to include thin ice class as an additional output (previous sea ice class in now divided into sea ice and thin ice classes). The new UWC was applied to the CS2 data over the Laptev Sea region (as shown in Figure 1) for the winter months Jan-Mar in 2011-2020. The C2 classification results were compared to MODIS thin ice thickness (TIT; max 25 cm) swath charts (in total 161), few Sentinel-1 (S-1) SAR images. SMOS SIT charts, and to ESA CCI CS2 surface classification product which does not have thin ice class. The comparisons are conducted by visual and quantitative analyses. The results suggest (as summarized in Abstract) that there is possibility to either develop simple correction terms for CS2 ranges over thin ice or to directly adjust current retracker algorithms specifically to very thin sea ice. Further, the new UWC can rather reliably discriminate between sea ice, open-water leads, and thin ice within recently refrozen leads or mere areas of thin sea ice. The new UWC surface type classification should be better for freeboard and SIT retrieval than the current ESA CCI CS2 product, e.g. the new UWC gives much less unknown surface type classifications. It may be possible, after further developments, to estimate SIT of thin ice based on the CS2 waveform data (freeboard methods lacks sensitivity to very small freeeboards of thin ice).

I think the study set up with data acquisitions and data processing is sound, as are methods for the data analyses. However, I think there are some room for improvements, and in the following I have some general questions and comments, followed by miscellaneous specific ones.

First, the you should clearly define in the Abstract and Introduction what you mean by ‘thin ice’, what is the maximum assumed thickness for it? I think it is not good to use term ‘young ice’ in this context, as in the WMO sea ice nomenclature it is a sea ice class with 10-30 cm thickness.

All the used datasets should be presented under Dataset Section, this is not the case now for SMOS SIT data and the ESA CCI product, e.g. the ESA CCI product is now described in Section 4.3.

The discussion on thin ice remote sensing methods in Introduction is quite brief and should be expanded. This can focus on altimeter data based studies and methods, but it is good to discuss also other ones, e.g. discussion on high frequency radiometer data based thin ice detection is very brief, there have be many studies on recent years, see e.g.:

K. I. Ohshima, S. Nihashi, and K. Iwamoto, “Global view of sea-ice production in polynyas and its linkage to dense/bottom water formation,” Geosci. Lett., vol. 3, no. 1, p. 13, 2016.

K. Nakata, K. I. Ohshima, and S. Nihashi, “Estimation of thin-ice thickness and discrimination of ice type from AMSR-E passive microwave data,” IEEE Trans. Geosci. Remote Sens., vol. 57, no. 1, pp. 263–276, Aug. 2019.

K. Nakata, K. I. Ohshima, and S. Nihashi, “Mapping of active frazil for Antarctic coastal polynyas, with an estimation of sea-ice production,” Geophys. Res. Lett., vol. 48, no. 6, Mar. 2021, Art. no. e2020GL091353.

First study about frazil ice monitoring.

It is nice that the authors are also using S-1 SAR imagery as reference data, but only with visual analysis. Currently, there are many automatic S-1 SAR sea ice classification algorithms available, e.g. this one especially for lead detection:

Murashkin et al., Method for detection of leads from Sentinel-1 SAR images, Annals of Glaciology (2018), doi: 10.1017/aog.2018.6

This algorithm was developed at UB and AWI, so maybe the authors have access to it? At least lead detection by SAR should be briefly discussed. See also S-1 SAR sea ice classification studies, e.g.:

Park, J.-W., Korosov, A. A., Babiker, M., Won, J.-S., Hansen, M. W., and Kim, H.-C.: Classification of sea ice types in Sentinel-1 synthetic aperture radar images, The Cryosphere, 14, 2629–2645, https://doi.org/10.5194/tc-14-2629-2020, 2020.

Boulze, H.; Korosov, A.; Brajard, J. Classification of Sea Ice Types in Sentinel-1 SAR Data Using Convolutional Neural Networks. Remote Sens. 2020, 12, 2165. https://doi.org/10.3390/rs12132165

Previous altimeter lead/thin ice detection studies should also be discussed in more detail, their methods and results summarized, and later to compare the methods/results of this study to the previous ones, maybe it would be good to add Discussion Section. Some previous related studies:

Lee et al., Arctic lead detection using a waveform mixture algorithm from CryoSat-2 data, The Cryosphere, 12, 1665–1679, 2018, https://doi.org/10.5194/tc-12-1665-2018

N. Longépé et al., "Comparative Evaluation of Sea Ice Lead Detection Based on SAR Imagery and Altimeter Data," in IEEE Transactions on Geoscience and Remote Sensing, vol. 57, no. 6, pp. 4050-4061, June 2019, doi: 10.1109/TGRS.2018.2889519.

Wernecke, A. and Kaleschke, L.: Lead detection in Arctic sea ice from CryoSat-2: quality assessment, lead area fraction and width distribution, The Cryosphere, 9, 1955–1968, https://doi.org/10.5194/tc-9-1955-2015, 2015

I guess their relevance to the study depends how ‘leads’ are defined in them, are they only open water covered or also may have thin ice cover? In your CS2 UWC classification how you do define differences between classes ‘lead’ and ‘thin ice’? Your ‘lead’ has only open water surface, or could it also have few cm of thin ice coverage?

You could shortly summarize in Introduction the comparison results from:

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, 10, https://doi.org/10.3390/rs10081190, 2018.

It is understandable to you have a limited study region, and the Laptev Sea with recurring polynyas is good for it, but it would have been nice to see how your new UWC performs over some MIZ, like Barents Sea where large areas of thin ice may occur at the ice edge.

AWI conducts HEM flights over the western Arctic, would it be possible to include also HEM data to your study? It would give accurate data on the leads and thin ice, although temporal and spatial matching with CS2 tracks is likely a problem. You could discuss about this in Introduction, even in case the HEM data are not added.

Did you investigate also using Sentinel-2 imagery as lead/thin ice reference data? It has been used in some sea ice studies, e.g.

Muchow, M., Schmitt, A. U., and Kaleschke, L.: A lead-width distribution for Antarctic sea ice: a case study for the Weddell Sea with high-resolution Sentinel-2 images, The Cryosphere, 15, 4527–4537, https://doi.org/10.5194/tc-15-4527-2021, 2021.

Petty, et al. (2021). Assessment of ICESat-2 sea ice surface classification with Sentinel-2 imagery: Implications for freeboard and new estimates of lead and floe geometry. Earth and Space Science, 8, e2020EA001491. https://doi. org/10.1029/2020EA001491

Why did you not use the latest CS2 L1B baseline-E data? https://earth.esa.int/eogateway/news/new-ice-baseline-e-and-near-real-time-processors

I have following questions on the MODIS data in Section 2.2 and MODIS TIT calculation in Section 3.2:

How cloud masking is conducted?

Are both daytime and nighttime MODIS images used?

Why did you not use the MOD29 product which has cloud masked IST?

What ERA5 fields were used, hourly? If so then reference for this is:

H. Hersbach et al. (2018). ERA5 Hourly Data on Single Levels From 1979 to Present. Copernicus Climate Change Service (C3S) Climate Data Store (CDS). Accessed: X. [Online]. Available: https://doi.org/10.24381/cds.adbb2d47

Why did you not use ERA5 mean surface downward long-wave radiation flux? How it was now obtained?

Is snow on thin ice neglected in the TIT calculation?

MODIS TIT accuracy is given according to Adams et al. (2012), but is your TIT calculated exactly as in this paper? If not then their accuracy figure may not be valid for your TIT.

Your description of new UWC in Section 3.1 does not include any information on the weather conditions. Your study was conducted in winter conditions, but still is there any dependence on resulting clusters on the air temperature? Thin ice surface condition: slushy, dry, frost flowers etc., depend on the weather conditions. What was the air temp range in your study? Any above zero cases?

You should summarize in Section 3.1 rules how the 25 clusters are classified to different surface classes, e.g. with table or flowchart. You could also show statistics and pdf's of some features for different classes. In general, your description how clusters are classified is now very rough.

On backscattering mechanism discussion in lines 230-231 and 281-283: you should include discussion on the coherent vs. non-coherent scattering for radar altimeter. The coherent scattering is very high, increasing roughness decreases it quickly and non-coherent scattering due to roughness increases.

In Section 4.2 Quantitative analysis the CS2 vs. MODIS comparison results should be presented also in a table/matrix format. Give also the accuracies for CS2 thin ice and thick ice classes against the MODIS TIT charts, and e.g. commission error or False Alarm Rate: percentage of MODIS thin ice pixels falsely classified as thick ice out of all MODIS thin ice pixels.

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.

In Summary and outlook Section: "This fact brings the future task to check further waveform clusters regarding possible thin-ice detections."

What this exactly means, that you are not sure yet what surface classes all your 25 clusters really represent? If not then you should conduct further studies already in this paper.

Spesific comments

Abstract

"the ESA Climate Change Initiative's (CCI) surface-type classification"

You should mention that this is also based on the CS2 data, and that it does not have thin ice class.

1. Introduction

page 1, line 21: “However, the resulting data sets are generally bound to an upper sea-ice thickness limit in their retrieval capabilities as well as methodological limitations (e.g. cloud cover presence when using thermal-infrared data”

It would be good to mention here also the effect of snow cover.

l. 27: “However, studies suggest a higher uncertainty towards thinner sea-ice (Ricker et al., 2017).”

Please give the current ‘accurate’ SIT retrieval range of CS2.

In the CS2 SIT retrieval discussion you could also mention the effect of snow salinity, decreases penetration depth:

Nandan, V., et al. (2017). Effect of snow salinity on CryoSat-2 Arctic first-year sea ice freeboard measurements. Geophysical Research Letters, 44. https://doi.org/10.1002/2017GL074506

l. 48: “While information on the presence of thin-ice areas is important for our understanding on sea-ice mass balance changes, there is currently only a single operational thin-ice data product available due to the above-mentioned short-comings and limitations.”

JAXA has AMSR2 based operational research product “Detection of thin sea ice”, see https://suzaku.eorc.jaxa.jp/GCOM_W/data/data_w_product-3.html

l. 52: “This method is limited for thicker sea ice and thus data fusion of SMOS and CryoSat-2 using Optimal Interpolation”

Give the maximum SIT for an ‘accurate’ SMOS SIT estimation, in papers by Kaleschke and Tian-Kunze et al.

l. 56: “In this study, the authors utilize Delay-Doppler radar altimeter echoes from ESA’s Earth Explorer mission CryoSat-2 in combination with the capabilities of NASA’s Moderate Resolution Imaging Spectroradiometer (MODIS) to monitor thin ice with a high spatial-temporal resolution.”

To my understanding MODIS TIT data is used for comparison, and not in combination with CS2 for thin ice monitoring.

l. 62: “flaw and coastal polynyas”

Describe shortly what these are; good general info for readers.

2. Dataset

Or Datasets and their processing?

l. 87: “ESA Cryosat-2 Product Handbook (https://earth.esa.int/eogateway/documents/20142/37627/CryoSat-Baseline-D-Product-Handbook.pdf/c76df710-2a5c-c8b8-00c1-13c8db0e9f51,”

Make this as reference.

l. 97: “2009). Subsequently, the sea-ice-surface temperature (IST) was computed following Riggs and Hall (2015).”

Original reference for MODIS IST is:

Hall, D.; Key, J.; Casey, K.; Riggs, G.; Cavalieri, D. Sea ice surface temperature product from MODIS. IEEE Trans. Geosci. Remote Sens. 2004, 42, 1076–1087.

In your discussion of S-1 SAR backscatter signatures for leads a good reference is:

Murashkin et al., Method for detection of leads from Sentinel-1 SAR images, Annals of Glaciology (2018), doi: 10.1017/aog.2018.6

which discusses about dark and bright leads. This paper could also be as your basis for visual lead identification in the SAR imagery (if you keep doing so, and not applying some automatic method). Give the total number of S-1 SAR images used in your study.

l. 117: “The images are ground-range detected and show a pixel resolution of 40m and a swath width of 400km.”

The pixel size is 40 by 40 m, and spatial resolution is close 100 m depending on range.

l. 118: “The images are processed using the SNAP - ESA Sentinel Application Platform v8.0, (http://step.esa.int) following the processing steps described in Müller et al. (2017) and Passaro et al. (2018b), but with an additional speckle filtering.”

Please summarize these processing steps.

3. Methods

l. 129: “The MODIS comparison database used includes 161 scenes, which corresponds to an altimetry dataset of about 21300 Cryosat-2 observations (MODIS scenes and their time difference from the Cryosat-2 observations are given out in a list upon request).”

What is the spatial resolution of these CS-2 observations? Just the area for one CS2 waveform? And there can be several waveforms within one 1 km MODIS IST pixel?

l. 137: spell out LRM acronym.

l. 139: “However, none of these studies has classified thin-ice, since altimeter waveforms generated by this surface type are quite similar to open water returns.”

Can you at this point summarize the difference between the open water and thin ice backscatter/waveforms based on earlier studies?

l. 142: “After clustering next classification steps consist of an assignment of the clustered waveforms as well as remaining waveforms to certain surface types (e.g. ocean, lead/polynya or sea-ice conditions).”

How this is conducted? I would assume some automatic method has been developed, please describe it.

l. 144: “In the present investigation, the cluster number is set to 25. Following Dettmering et al. (2018), by using this number an overall agreement of about 97% can be achieved.”

Against what data this overall agreement was determined? Using data in this paper? If so then it is not a good way for the paper ‘progress’. It raises a question that have you tested other numbers of clusters, conducted accuracy analyses, selected 25, and then present accuracy results for this number of clusters.

l. 156: “Moreover, in the quantitative comparison (Sec. 4.2) two additional features are included, which are not used for the UWC:”

Please explain why they are not used in the UWC.

l. 162: “Figure 2 shows the assignment of 25 clusters to 5 different surface types (compared to 4 in the original UWC approach): undefined, sea ice, thin-ice, lead, and ocean.”

Again here you could describe whether lead class has only open water surface, or if it can have also very thin ice. What is the maximum width of your leads?

Numbers in the color bars in Figure 3 have too small font size.

4. Results and discussion

"The first part of this section shows visual comparisons between CryoSat-2 and MODIS as well as Sentinel-1. The second part will then focus on a quantitative analysis of the results."

> You could mention that quantitative analysis includes Sections 4.2 and 4.3, if I have understood correctly.

l. 207: "From the altimetry point of view, off-nadir effects may overlay clear leads or thin-ice radar echoes,"

> Explain what are these off-nadir effects and how they change waveform parameters.

l. 217: "Qualitatively, the respective classifications appear within expectations"

> What are these expectations, how are they quantified?

l. 219: "However, a direct distinction between thicker sea-ice and thin-ice areas is not possible due to the coarse pixel resolution of MODIS in comparison to CryoSat-2."

> Is really always the case? A MODIS pixel cannot be covered fully by thin ice or thicker sea ice?

l. 228: "The polynya observed by MODIS appears very bright in the SAR image and is supposedly caused by a rough sea-ice surface due to the presence of frost flowers"

> How about possibility that thin ice has rough surface from finger rafting or it has broken to many small floes and frozen again?

Figure 5: What yellow color shows here?

Figure 6: What red color shows here?

l. 241: "In order to account for the much coarser spatial resolution of 12.5km×12.5km for SMOS, CryoSat-2 classifications are aggregated into bins with a length of 12.5km."

> How many CS2 surface classification datapoints there are typically in a SMOS SIT pixel?
>
> Note that the SMOS daily SIT chart has 12.5 km pixel, but the original SMOS TB swath data has 35–50 km pixel resolution, and these swath TB's are aggregated to daily TB 12.5 m grid.
>
> In your CS2 vs. SMOS comparison you should also take into account the accuracy of the SMOS SIT: SMOS SIT underestimates sea ice thickness on average by about 50%–60%, and the root mean square difference to validation datasets was 0.31 m:
>
> L. Kaleschke et al., "SMOS sea ice product: Operational application and validation in the Barents Sea marginal ice zone," Remote Sens. Environ., vol. 180, pp. 264–273, Jan. 2016
>
> Did you screened SMOS SIT data using uncertainty and saturation ratio given in the SIT data? "Data with an uncertainty > 1 m or with a saturation ratio near 100% should not be used.", from X. Tian-Kunze. (Nov. 2018). SMOS Sea Ice Thickness ReadMe-First Technical Note (RM-TN).

The used SMOS SIT dataset should be described under Dataset Section.

In Figure 7 the numbers in the color scales are too small.

In Figure 8 the gray bars have poor visibility.

l. 287: "This might be due to an enhanced error budget in the first two thin-ice thickness groups"

> What you mean by this enhanced error budget? Please explain in the paper.

l. 290: "The remaining four waveform features, i.e., Wdecay, WfitMAD, LEW, and LWP, feature an apparent correlation, however, it is less clear than the ones we observed with MP, Wwidth, and TES"

Please give numerical correlations in the text.

l. 308: “The flags in the l2i files are based on monthly thresholds for the backscatter coefficient sigma0, the leading-edge width, and pulse peakiness as well as supported by sea-ice-concentration data as sea-ice mask.”

Give source of SIC data in the paper.

l. 324: “It should be noted that we define a lead here in the sense of satellite altimetry as an open-water lead, which provides a true sea-surface-height observation without any bias introduced by thin-ice freeboard.”

This lead class definition should be earlier in Method Section. Does thin ice really give any freeboard bias in the CS2 data? Lets say 20 cm of thin ice, freeboard is ~1 cm, can this be detected in one CS2 waveform turned into a freeboard? I would assume it is more possible in large averaging of single freeboards, but then you don’t have fixed thin ice target for several weeks or days.

l. 333: “Finally, it must be noted that the official definition of the World Meteorological Organisation (WMO) for the term lead includes thin ice with a thickness of up to 30 cm (wmo, 2014).”

This kind of ice type definition should in Introduction.

5. Summary and outlook

l. 366: “In contrast, sea-ice classifications also show up in SMOS-derived thin-ice regions.”

Here you should investigate the effect of the SMOS SIT accuracy on your comparison results.