

We thank the Reviewer for the careful and constructive comments. The suggestions and corrections have greatly improved the quality of this manuscript.

Summary

The authors extend an existing unsupervised classification approach for detecting open water targets from radar altimeter waveforms, to include detection of thin-ice. The authors present the classification approach conceptually, apply it to Cryosat-2 L1B Ice Baseline D data waveforms then compare their results to existing thin ice detection techniques from passive microwave radiometry (SMOS sensor) and infrared data (MODIS sensor), as well as Sentinel-1 SAR imagery. A comparison is also made to another Cryosat-2 sea ice product, the AWI Cryosat-2 sea ice product v2.4. The Laptev Sea is the region of focus due to the occurrence of winter period thin ice areas from flaw leads and coastal polynyas. The classification is applied to Cryosat-2 data taken January through March over the 2011 to 2020 period. Overall, the method is promising for detection of thin-ice areas, as a potential improvement over the ESA Climate Change Initiative (CCI) algorithm described in Paul et al. (2018) which does not include this feature. With a better evaluation in comparison to the prepared MODIS thin-ice thickness data (see major comment below), the utility and limitations of the proposed algorithm will be better understood. The work is clearly justified, and as the authors state, knowledge of thin ice areas is important for sea ice mass balance work, and there are limited datasets for remote study of their properties and coupled processes. It should be a good contribution to TC and of interest to the readership after comments here, and in the other reviews, are adequately addressed.

Major comments:

1. The authors compiled a large number of overlaps between their classification and MODIS TIT information. Despite this, the use of MODIS TIT to understand classifier performance is limited to a brief statement about overall class assignments on lines 267-269. The MODIS TIT data are further used for assessing relationships between ice thickness categories and waveform properties, which adds value to the interpretation of classifier performance. However the paper would be much improved by using the MODIS TIT for more detailed comparisons to the UWC classification outputs, in order to better understand limitations and inform further classifier optimization. The comparison to the CCI data is much more informative.

Unfortunately, we cannot make the same comparisons between MODIS and UWC as we did between CCI and UWC, because the data come from different sensors and have different resolution. We are comparing two sensors with different resolution with CryoSat-2 and MODIS. A CryoSat-2 observation classified as sea ice in a MODIS pixel with thin ice may be a correct classification if small amounts of sea ice were present there or if the situation changed between the MODIS and CryoSat-2 images. For this reason a more detailed quantitative comparison is therefore not meaningful in our opinion.

2. The visual comparisons between the classification and coincident sensor data are helpful, and the authors put together a good summary of relationships between observed conditions in each comparison. The authors should provide a clear rationale for the choices made, in order to add confidence that these are un-biased assessments. It is apparent that the Cryosat-2, MODIS, and

Sentinel-1 comparison on 01 March 2018 is chosen due to the short time gap between all three acquisitions. The other comparisons are not as well justified, and it is likely there are several overlaps to choose from.

As the reviewer pointed out and it is also described in the manuscript, the triple comparison (CS-2, MODIS, S1) was chosen for the small time gap but as well for it being the only of its kind found in the analyzed time period. All other shown comparisons were chosen for the especially small time gaps and/or clear-sky conditions between acquisitions. However, all analyzed pairs of MODIS and CS-2 data were acquired within a 30 minute time gap as a minimum requirement for the comparison due to otherwise fast changing sea-ice conditions (see L61). We added the respective acquisition time differences to the respective figure captions.

Minor Comments (by line number):

L4: clarify that it is a Cryosat-2 based classification here

We agree.

L6: clarify what linear dependency is found (e.g. “between...x and y...”) or consider re-wording

We clarified the sentence as follows:

“Here, strong linear dependencies are found between binned thin-ice thicknesses up to 25cm thickness from MODIS and the CryoSat-2 waveform shape parameters that show the possibility to either develop simple correction terms for altimeter ranges over thin ice or to directly adjust current retracker algorithms specifically to very thin sea ice.”

L22: delete “in their retrieval capabilities as well as” and replace with “and”

We agree.

L26: comma after “sensors”

We agree.

L29: delete “are also prone to”

We agree.

L36: commas after “density” and “cover”

We agree.

L38: delete “But even when ... classified as sea ice”

We thank the reviewer for his suggestion. However, we rephrased the corresponding sentence as follows:

“For correct sea-ice classifications, the small freeboard values of thin ice (here defined as sea ice with a thickness up to 25 cm) are often lower than the precision of even the later synthetic aperture radar (SAR) altimeter sensors.”

L39: change “the later” to “recent” and “over” to “of” (i.e. freeboard of ice)

We agree.

L40: “from” Ku-band radar altimeters

We agree.

L44: delete “since the range ...depth.”

We agree.

L48: delete “on”

We rephrased the sentence and deleted “on”.

L49: delete “short comings and”

We agree.

L51: Make “However, at a lower spatial resolution ...” a new sentence

We agree.

L58: use “spatial and temporal resolutions” or “spatio-temporal resolution”

We agree and switch to spatio-temporal resolutions.

L65-68: “This study is structured into the following sections: Section 2 describes the data sets; Section 3 provides details on the unsupervised clustering for CryoSat-2 and the MODIS thin-ice thickness retrieval. Section 4 summarizes and discusses the results and implications on CryoSat-2 surface-type classification, and Section 5 concludes with an outlook.”

Thank you for the re-structuring of the sentence.

L70: “The following sub-sections highlight the data sets used ...”

We agree.

L74-75: delete “aiming at monitoring ...was placed”

We think that this sentence is a good introduction for the section "CryoSat-2 Level-1B Baseline-D data". This sentence provides the reader with some basic information about the main science goals of CryoSat-2 and serves as an introduction to the text that follows. Therefore, we decided to leave it in the manuscript.

L76: delete "Moreover,"

We agree.

L79: delete "mainly characterized ... ice cover,"

We agree.

L80: change "showing" to "with"

We agree.

L85: "This dataset comprises, ..."

We agree.

L86: comma after data, and delete "also", and add "on" after information

We agree.

L91: delete "As basis" and just use "MODIS" rather than writing it out

We agree.

L92: delete "MODIS sensors on board the polar orbiting"

We agree.

L93-94: The MODIS data access information can be moved to the data availability section

We agree and moved it to the data availability section

L96: delete "In a first step"

We agree.

L102: Add information about the temporal component, e.g. hourly data nearest to acquisition, daily average, etc.

We thank the reviewer for pointing this out to us and rephrased the sentence as follows:

"These fields comprise the 2 m air temperature, the 10 m wind-speed components, the mean sea-level pressure, and the 2 m dew-point temperature in hourly resolution."

L110: “and less rough surface under calm, low-wind, conditions.” The possibility of wind-roughened polynya and lead should be mentioned since this would also contribute strong backscatter and bright pixel values.

We add a sentence. Thank you for the hint.

L112: “e.g. on nilas ice, as they...”

We agree.

L115-116: move the introduction to Sentinel-1 to beginning of the section

We agree.

L118-120: Since the Sentinel-1 data are used only for visual assessment, the processing steps are likely straightforward and could be described briefly here.

We add a sentence. However, it must be really mentioned that only standard methods, provided by the SNAP Toolbox, are applied.

L123-125: delete the first sentence

The sentence is intended to softly introduce the reader to the subject matter of Section 3. We would therefore like to keep the sentence.

L127: change “keeping” to “enabling”

We agree.

L129: delete “used”

We agree

L130: clarify what is meant by a Cryosat-2 observation

We add “altimeter”.

L131: sentence “The number of useable ...” is not necessary because of previous descriptions

We agree and removed the sentence.

L139: delete “has”

We agree

L143: put a comma after “clustering” and delete “next classification steps consist of an”

We rephrased the sentence.

L148: delete “so called” and “followed”

We partly agree with the reviewer and deleted “so-called”. However, we keep “followed” since it introduces the subsequent list.

L163” here, and elsewhere, just use the abbreviation after it has been defined (i.e. MP)

We changed that. However, we kept the full-name in the captions of figures and tables.

L167: nilas

We agree

L168: delete “of”

We agree

L170: also compare to wind-roughened water

We have found that thin-ice reflections are very close to lead-like reflections. However, with less MP and a slightly wider Wwidth. This is especially true when leads have recently frozen over and a thin layer of ice has formed. Nevertheless, we point out in the Outlook that further research is needed to find out how the thin ice in combination with different wind speeds affects the waveforms. However, this is not part of the current study.

L176: as mentioned above for MP, just use “IST” since it was defined earlier

We changed all occurrences of ‘ice-surface temperature’ as well as ‘sea-ice-surface temperature’ to ‘IST’ after it was first defined as an abbreviation.

L191: Change text to “The very high spatial and temporal resolution altimetry”

We agree. In reference to the previous comment, we agreed on “The very high spatio-temporal resolution altimetry ...”

Figure 2 caption: use italics for words in quotes (and delete quotation marks)

We agree.

L199: use “subsets” in place of “zoomed-in snippets”

We agree.

L200: pluralize to “results”

We agree.

L207: delete “and, therefore, no truth is available”

We agree.

L207-209: provide some indication of what is meant by lead or thin-ice surface being very small (how small)

Added “, i.e. less than 1% of the illuminated surface (Drinkwater et al., 1991)”

L215: comma after “Northwards”

We agree.

L216: delete “in ice thickness”

We agree.

L222: delete “in a quantitative analysis”

We agree.

L223: change “acquired at” to “from”

We agree.

L224: delete “from each other”

We agree.

L229: recommend to change “supposedly” to “likely”

We agree.

L233: How is thin ice labelled correctly as lead and not thin ice?

This area is very close to 0 cm in the MODIS TIT plot. This region is a mixture of small thin ice patches and open water spots. The spatial resolution of MODIS, however, makes it impossible to distinguish between these surface properties on a finer scale. The CryoSat-2 altimeter observations, however, are superimposed on the much stronger backscattering lead reflections in this region, thus the waveforms are considered as lead returns.

L239: change “blended with” to “compared to”

We agree.

L270: “TIT”

We agree.

L272: “TIT”

We agree.

L273: delete “spatiotemporally”

We agree.

L276: “deviations”

We agree.

L286: delete “However”

We agree.

L287: change “this” to “a”

We agree.

L293: change “Contrariwise” to “In contrast” and use “LEP” only since it is already defined

We agree.

L304: citation needed

We thank the reviewer for this comment. We added a reference instead of the placeholder.

L309: use LEW

We agree.

L331: delete comma after “both”

We agree.

L334: “(WMO, 2014)”

We agree.

L346: delete “in general”

We agree.

L350: delete “in general” and comma after “both”

We agree.