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Interactive comment on "Satellite altimetry detection of ice shelf-influenced fast ice" *by* Gemma M. Brett et al.

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Authors Response to Anonymous Referee #2

Authors: We thank the reviewer for taking the time to review our manuscript. However, we do not agree with the reviewer's general assessment. We have considered each comment and modified the manuscript according to suggested changes where we agree and provided a justification where we do not. We hope that the responses given below have addressed the reviewer's comments.

Referee 2: Fast ice is an important component of the Antarctic climate system, especially for a better understanding of processes between ice shelf and ocean. It is therefore out of question that there is a great interest in the community to obtain better

estimates of the thickness of the solid ice over the whole area and thus to be able to conduct further calculations of sea ice volume in the next step.

Author Response: The objective of this study was not to obtain sea ice thickness to underpin sea ice volume calculations but to investigate whether a satellite altimeter (Cryosat-2 (CS2) available during our study period) can detect a known spatial pattern of higher freeboard driven by supercooled ISW in McMurdo Sound. It seems that the main objective of this study which was clearly identified by reviewers 1 and 3, and explicitly stated in the abstract, introduction and implicit throughout the text (L9-11; L14-15; L75-77; L85-87; L270-272; L324-327; L420-426; L434-435; L457-460; L465-472) has been overlooked by reviewer 2.

We will emphasise the main objective and highlight that this is the first study to apply satellite altimetry to specifically detect ice shelf-influenced fast ice freeboard by changing the statement on L85 to the following:

'For the first time, we investigate whether the CS2 satellite radar altimeter can detect the influence of ISW on fast ice in McMurdo Sound by consistently identifying the higher ice freeboard caused by thicker ice shelf-influenced fast ice combined with the buoyant forcing of the SPL beneath.'

Referee 2: However, the manuscript still shows fundamental weaknesses at this stage, so that it needs to be extensively revised before the work can be published. That is why I only mention here general remarks, which should be implemented first, before in a next iteration more detailed points can be raised.

Author Response: Please refer to the responses given the general comments below.

Referee 2: General Comments: Discussion paper 1. I see a major mismatch between the title, the objectives and the actual content of the manuscript. What is basically done in the manuscript is to compare measured on-site freeboard values related to fast-ice and platelet ice thickness with satellite retrieved freeboard values.

Author Response: This comment is not relevant if the reviewer has misunderstood the objective of the study as stated above “to obtain better estimates of the thickness of the solid ice over the whole area and thus to be able to conduct further calculations of sea ice volume in the next step.”

The motivation is to use a standard satellite elevation product (ESA L2 Baseline C SIN product) and existing and proven methods to obtain fast ice freeboard (as developed and demonstrated in Price et al. 2015) to assess whether a satellite altimeter is capable of detecting a known pattern of higher freeboard driven by supercooled ISW outflow in McMurdo Sound.

We will emphasise the main objective and highlight that this is the first study to apply satellite altimetry to specifically detect ice shelf-influenced fast ice freeboard by changing the statement on L85 to the following:

‘For the first time, we investigate whether the CS2 satellite radar altimeter can detect the influence of ISW on fast ice in McMurdo Sound by consistently identifying the higher ice freeboard caused by thicker ice shelf-influenced fast ice combined with the buoyant forcing of the SPL beneath.’

To do this, we obtained freeboard measurements from the CS2 satellite altimeter using a supervised freeboard retrieval procedure where the reference open water and relative Sea Surface Height was manually identified using satellite imagery (L215-220). That is, the CS2 freeboard was determined independently. The in situ freeboard measurements were used to assess and validate the satellite altimeter obtained freeboard and to constrain the best-match freeboard interface for ice thickness calculations (L223-224; L251-254). We then assessed regional spatial and linear trends in CS2 freeboard and CS2 ice thickness to discern if the CS2 radar altimeter could consistently detect the known pattern of fast ice freeboard (driven by the combination of the thicker ice shelf-influenced fast ice and the buoyancy of the SPL) in McMurdo Sound over multiple years as described throughout section 4.

Referee 2: However, this does not reflect the actual influence of ISW on the fast ice, as ISW is not necessarily the same as platelet ice.

Author Response: We do not understand this statement. ‘Potentially’ supercooled Ice Shelf Water (ISW) (i.e., the definition of ISW) in the upper surface ocean promotes sea ice formation and causes it to be thicker by stabilising the upper surface layer, by hindering vertical mixing and insulating sea ice from warmer subsurface waters below. Thicker Ice Shelf Water influenced sea ice inherently has a higher freeboard than sea ice without this influence.

Platelet ice is a direct manifestation and distinct signature of ‘in situ’ supercooled ISW at the ocean surface which causes the fast ice freeboard to stand higher through two effects: 1) the fast ice is thicker by platelet ice accumulation, and augmented growth through heat flux to the heat-deficit in the ocean induced by ‘in situ’ supercooled Ice Shelf Water, and 2) the buoyancy effect of the SPL if present.

Satellite altimetry measurements cannot differentiate between higher freeboard driven by ‘in situ’ or ‘potentially’ supercooled ISW but as showcased here, can identify a region where the fast ice freeboard near an ice shelf has significantly higher than average freeboard due to the influence of ISW in the upper surface ocean. The presence of ‘in situ’ supercooled ISW in the upper surface and its influence on fast ice and SPL formation in McMurdo Sound have been well observed in multiple studies as described in the introduction and explicitly stated on L87-89. When we refer to supercooled ISW in the text, we are referring to ‘in situ’ supercooling according to the commonly used nomenclature. To clarify, we will explicitly state this in the introduction.

Referee 2: 2. Therefore, a fundamental revision of clearly stated objectives is required, which are then also addressed accordingly in the manuscript.

Author Response: We reiterate that it seems that the main objective of this study which was clearly identified by reviewers 1 and 3, and explicitly stated in the abstract, introduction and implicit throughout the text (L9-11; L14-15; L75-77; L85-87; L270-272;

L324-327; L420-426; L434-435; L457-460; L465-472) has been overlooked by reviewer 2.

Referee 2: 3. All applied methods in the manuscript are very poorly presented, so that it is not always 100% clear what was really done in detail. Therefore, in order to be able to judge the exact quality and reliability of the analyses presented, they must be made clearer. Furthermore, there is no clear distinction between the work/analyses presented here and what was done in previous work.

Author Comment: We thank the reviewer for their comment.

The motivation is to use a standard satellite elevation product (ESA L2 Baseline C SIN product) and existing and proven methods to obtain fast ice freeboard (as developed and demonstrated in Price et al. 2015) to assess whether a satellite altimeter is capable of detecting a known pattern of higher freeboard driven by supercooled ISW outflow in McMurdo Sound. To summarise, much of the method is not novel but the application is. We have made the following changes to emphasise the previous work by Price et al. 2014 and 2015 that underpins the methodology applied in this study.

1) To emphasise that the main method used in the study has been developed in detail in previous satellite altimetry work in McMurdo Sound, we have moved the paragraph in section 2 (L115-124) to L85 and added the following sentence at the end of this paragraph:

'Price et al. (2015) developed the method applied in this study to obtain CS2 fast ice freeboard in McMurdo Sound in 2011 and 2013 and the relevance of this work to this study is described in more detail in section 2.2'

We will emphasise that this is the first study applying satellite altimetry to specifically detect ice shelf-influenced fast ice freeboard by changing the statement on L85 to the following:

'For the first time, we investigate whether the CS2 satellite radar altimeter can detect

the influence of ISW on fast ice in McMurdo Sound by consistently identifying the higher ice freeboard caused by thicker ice shelf-influenced fast ice combined with the buoyant forcing of the SPL beneath.'

We will also highlight and emphasise the methods that are novel throughout the text. Novel aspects of the study are as follows:

- The application of satellite altimetry to identify a known pattern of higher freeboard caused by thicker ice shelf-influenced fast ice combined with the buoyant forcing of the SPL which both result from supercooled ISW outflow.

- The method to identify the best-matching freeboard interface for individual CS2 tracks as described in L251-260 and L401-405.

- Calculation of ice thickness from CS2 freeboard in McMurdo Sound for multiple years and comparison with interpolated in situ measured ice shelf-influenced fast ice and SPL and their combined Mass Equivalent Thickness (MET). L236-249; L290-327; Figures 4 and 5.

- Assessment and comparison of regional trends in CS2 freeboard (Table 1), and linear trends in CS2 ice thickness towards the McMurdo Ice Shelf in a region with significant ISW influence (centre) and another region with less pronounced ISW influence (east) (Figure 4).

- Assessment of spatial patterns of CS2 freeboard and CS2 ice thickness and comparison with in situ observed distributions of ice shelf-influenced fast ice and SPL (presented as a combined Mass Equivalent Thickness (MET)) (Figure 5).

Referee 2: 4. The snow cover on Antarctic sea ice is known to play a crucial role in both remote sensing and the buoyancy principle of sea ice. Even though the time series shown here seems to have a negligible snow thickness, this cannot be neglected in such a study. Instead, much more attention must be paid to potential difficulties caused by superimposed ice, snow ice or severe snow metamorphism.

Author Response: The snow was not neglected in our analyses by any means. In fact, this study is rare in that we had four years of in situ measurements of snow depth available to be able to constrain the effects of the snow layer. The importance of snow is dealt with throughout the document, and the limitation is revisited in the outlook section on L438 and L475 of the conclusion. Snow depressed negative freeboard or surface flooding was not observed, and we have added the following sentence on line 152 to clarify this:

“The snow layer can depress the freeboard and result in flooding of the sea ice surface and the formation of meteoric ice which can contribute to freeboard (Maksym and Markus, 2008). Snow-depressed negative freeboard or surface flooding were not observed at drill hole sites in McMurdo Sound in late spring. Multiple ice core studies carried out in the region over winter and in late spring revealed no contribution of meteoric ice to the fast ice cover in McMurdo Sound (e.g. Dempsey et al., 2010, Gough et al., 2012)’

We discuss how the snow layer in McMurdo Sound would affect the results of this study on L412-417 highlighting that the snow distribution from west to east was advantageous in that we could have confidence in that the trends in higher freeboard in the centre of the sound (where the snow is thin and loosely-packed) did not result from the addition of the snow layer which would have a more significant effect in the east where the snow is deeper.

Referee 2: 5. Moreover, this very thin layer of snow raises serious doubts as to the extent to which such a study can be used beyond the study area shown here. Indeed, a stronger positive freeboard of fast ice areas is not only due to the buoyant platelet layer. Instead, studies, e.g. in Atka Bay (Arndt et al., 2020), have shown that it is not the platelet ice that is the decisive component for the freeboard of the fast ice, but the snow cover. I therefore strongly recommend to do similar sensitivity studies for this region - and also to use data from previous years to emphasize that in McMurdo Sound there is always this low snow load. Even if this is the case, the conclusions must still

be strongly weakened, because a strong positive freeboard can have different reasons – which cannot be quantified with CryoSat alone.

Author Response: McMurdo Sound does present favourable conditions for such a study with relatively thin snow cover and smooth fast ice (the potential limitation of inadequate snow knowledge is reiterated on L438 and in the conclusion on L475). This, along with the availability of multiple years of in situ measurements and detailed knowledge of ISW processes in the region is why we chose McMurdo Sound for our analysis as stated on L87-89. This study is a proof of concept demonstration (L486-488)) that CS2 is capable of detecting this signal of ISW influence in fast ice freeboard with the right conditions and information. It is a first step in the development of a satellite-based method (L434) to identify and potentially monitor regions where ISW (in situ supercooled or not) is outflowing in the upper surface ocean and is influencing fast ice formation.

The community has very little knowledge of the snow distribution around Antarctica and we will not know if this can work in other locations until we try. However, this proof-of concept study shows that it can work in the conditions in McMurdo Sound and is certainly worth pursuing elsewhere, especially when combined with auxiliary satellite information. ICESat-2 data is now available and is providing highly detailed snow freeboard information which has promise to be used in tandem with CS2 to obtain information on the snow cover as stated on L439-441.

We are aware of the Arndt et al. 2020 study and the frequent negative freeboard they observed from snow loading given that the snow depths in Atka Bay were up to 0.89 m. Atka Bay and McMurdo Sound represent a tiny fraction of a $\sim$45, 000 km Antarctic coastline, 74% of which is fringed by outlet glaciers and ice shelves. This in itself highlights the paucity of observations of ice shelf-influenced fast ice or indeed ordinary fast ice on the Antarctic coastline and the dependence of our knowledge of fast ice/ISW processes on a small handful of sampling locations that happen to be situated near and accessible from Antarctic research bases. There is very much a need for a satellite-based method to identify these important regions. We will reiterate throughout the text that this is a proof of concept study and further work is required to reveal similar areas of ISW influenced fast ice elsewhere on the Antarctic coastline. To acknowledge this limitation, we have added the following statement in section 5.4 on L435:

'The smooth gradients in fast ice and SPL thickness and low snow coverage in McMurdo Sound present favourable conditions for the CS2 radar altimeter to detect higher ice shelf-influenced freeboard. However, more challenging conditions for satellite altimetry are likely to be presented elsewhere on the Antarctic coastline. A recent drill hole assessment of supercooled ISW-influenced fast ice in Atka Bay observed deep snow accumulations of up to 0.89 m which resulted in frequent negative fast ice freeboard regardless of the buoyant forcing of a substantial SPL beneath (Arndt et al., 2020). As far as we are aware, Atka Bay and McMurdo Sound are the only two locations on the Antarctic coastline with multiple years of in situ measurements of ice shelf-influenced fast ice, SPL and snow highlighting the need for a satellite-based method to identify other regions where ISW is present in the upper surface ocean and influencing fast ice formation.'

Referee 2: 6. Referring to the previous point, the work shown here would greatly benefit from putting the measured snow, fast ice and platelet ice thicknesses into a more global context with measurements from other regions or other points in time in the same region.

Author Response: As far as we are aware McMurdo Sound and Atka Bay are the only locations where this level of detailed in situ information on coincident snow depths, fast ice and sub-ice platelet layer thickness has been collected and published. We are confident that these are the only locations where multiple years of these measurements have been collected. We have now referred to the Arndt study to highlight the challenge of the snow in the successful application of this method in L435 as stated in the previous comment. We do not understand how this work can be put into a 'global context' when this process has only been observed to occur in Antarctica, and in this detail

in only two locations in Antarctica. The 'other points in time in the same region' was addressed by applying our assessment over four years and then discussing the findings extensively in the text with respect to previous work carried by Brett et al. (2020), and Price et al., (2014), (2015), (2019) amongst others.

Referee 2: Otherwise, the results found here are unfortunately not very reliable and raise great doubts that they can be applied on a larger scale.

Author Response: We question how the results presented in this study are not very reliable and strongly disagree with this comment. In fact, we present arguably some of the most reliable CS2 information obtained in the Antarctic as it has been very well validated with multiple years of in situ information in a region with well understood ice formation and ISW processes. We would like to reiterate that this study is rare in that we had multiple years of in situ measurements of coincident freeboard, fast ice and sub-ice platelet layer thickness and snow depths to validate and compare with the independently obtained CS2 freeboard. The only other location with this information available (and published) is in Atka Bay which as the reviewer has already pointed out is subject to deep snow accumulations and thus significant snow loading and depression of the fast ice freeboard. As explained in the manuscript, the applicability of our method to a larger scale will critically depend on the quantification of the snow layer (L438; L449-451).

Additional References ARNDT, S., HOPPMANN, M., SCHMITHÜSEN, H., FRASER, A. D. & NICOLAUS, M. 2020. Seasonal and interannual variability of landfast sea ice in Atka Bay, Weddell Sea, Antarctica. The Cryosphere, 14, 2775-2793.

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