We appreciate the constructive comments from the editor and two reviewers (Dr. Ann-Sofie Priergaard Zinck, and Dr. Mattia Poinelli). Our manuscript is much improved by their input. In the following responses, we use "**bold**" text for comments, "non-bold" text for our responses, and "italic" for changed text in the revised manuscript.

Referee #1

The manuscript "Building multi-satellite DEM time series for insight into mélange inside large rifts in Antarctica" by Xia et al. presents a novel approach to monitor rifts' infill on the Filchner-Ronne ice shelf using observations from different satellites at high resolution. This is a revised version of the manuscript. I commend the authors for the time and effort spent in addressing my long list of comments. In particular, the addition of the discussion and the analysis on the second rift strongly improves the impact of this manuscript, in my opinion.
Overall, I believe that this paper is now suitable for publication in the Cryosphere. Below, I provide a list of minor comments and suggestions that I hope will further strengthen the manuscript.
Response:
Thanks for the suggestions. They are fully considered and implemented.

L13: I still thing the "significant gap" is rather vague statement. What is missing? Why is missing? Authors point at observations, but what is the reason why these observations are missing. I understand that these are trivial points, but they need to be specified. What about something along the line of: 'high resolution observations are scarce … which then leads to an understand of …, ultimately three dimensional changes are missing'. In the introduction there is a clear indication of available satellites (IceSat, Cryosat, etc) and their inability to capture small scale rift dynamics. This is the research gap: most satellites cannot capture the details of these rifts, but the authors' approach and the use of ZY-3 is the key strength of this paper. Please make this concept clear in the abstract (Line 13).
Response:
We changed it to "*However, large-scale, high-resolution three-dimensional (3D) observations are scarce, which leads to their inability to capture small scale rift dynamics. Ultimately, the lack of knowledge in 3D rift structural changes and mélange dynamics hinders our understanding of the role of mélange in ice shelf retreat and mechanisms underlying the weakening of ice shelf stability.*"

L25: 'can be applied for research'. This is also rather vague. What research?
Response:
We changed it to "*…… can be applied for quantifying ice shelf instability and ……*"

L28: The Antarctic Ice Sheet …

Response:

We changed it accordingly.

L44: 'There has been a lack'. Please revise this sentence by pointing at the actual gap, scarce observations? Poor sensors? Absence of sensors with necessary accuracy?

Response:

It is changed to: "*However, large-scale high-resolution observations are scarce. Small scale mélange textures and 3D rift dynamics cannot be captured with a necessary accuracy.*"

L50: 500 m for ICESat …

Response:

We changed it to "*the 500 m for ICESat …*".

L51: Those? Maybe observations?

Response:

It is changed to "*The DEMs ……*"

L75: What do you mean with 'control the overall geometry'?

Response:

We changed it to "*Since the GCPs are selected where ICESat-2 altimetric data are available, the connected DEM time series are then geometrically controlled at a centimeter elevation accuracy (Markus et al., 2017).*"

L85: I do not think 1996 (and 1963?) can be considered 'recent'. Also please edit to 'were detected' and not 'are'.

Response:

We deleted "*Recently,*" and changed "*are*" to "*were*".

Figure 9: Really nice figure.

Response:

Thanks.

L344: What type of modifications are needed?

Response:

We added a sentence: "*For example, tie points between adjacent sub DEMs may be selected with decreased time intervals to minimize the uncertainty caused by the compensation using ice velocity maps.*"

Referee #2

Overview:

I appreciate that the authors have done their best to address the comments from both me and the other reviewer. I do, however, still have a few concerns with regards to the novelty and impact of the paper. A DEM-registration method, as MDAM presented here, is in itself not novel, as similar approaches already exist. Therefore, I think that the paper requires a stronger analysis and discussion of the observed mélange dynamics to be impactful enough to be published. Please see my comments below for a more elaborate suggestion on how to achieve that. All line numbers refer to the track-changes version of the manuscript.

Minor comments:

MDAM method:

The authors present their DEM-registration method MDAM as being the only existing method which can be used to study 3D melange dynamics, which I would disagree with. While existing methods (e.g., Shean at al. 2019 and Zinck et al., 2023) do not use their DEM-registration methods to study melange dynamics, it does not mean that they cannot be used for that. I do find the MDAM method to be a good addition to the existing methods, but it should be clearly acknowledged that other methods do exist. Furthermore, I miss a discussion of the limitations of the MDAM method. For instance, it seems that both TPs and GCPs are manually chosen, which makes the MDAM method difficult to upscale to larger regions as it would require a significant amount of manual labour. Secondly, the authors mention that the method requires adjustment to be applied to areas such as Pine Island and Thwaites. What adjustments would that be? And why?

Response:

In responding to this major comment and the relevant specific comments bellow, we made changes to address the above concerns:

We added a statement to clearly acknowledge that other methods do exist: "*…… Furthermore, REMA DEMs are registered to a control data set, such as airborne altimetric data or satellite altimetric data of ICESat and CryoSat-2 (Howat et al., 2019; Shean et al., 2019; Zinck et al., 2023). While the existing methods can be used to register DEMs, there is a need to develop a strict mathematical model to systematically improve the registration accuracy and to study mélange dynamics*."

We also indicate the limitations of the current MDAM method by explicitly stating that the *GCP* and *TP* selection procedures are "manual": "The above GCP selection method is implemented as a manual procedure." "The TP selection method is also implemented as a manual procedure."

And applications in Pine Island and Thwaites where ice velocity is significantly faster, additional modification is needed: "…… *To make this MDAM model working in a more dynamic open ocean environment, such as Pine Island and Thwaites ice shelves where ice velocity is significantly higher, modifications need to be carried out to address the rapid calving process with incoherent mélange changes in ice shelf front. For example, tie points between adjacent sub DEMs may be selected with decreased time intervals to minimize the uncertainty caused by the compensation using ice velocity maps.*"

Mélange dynamics analysis and discussion:

You discuss a few causes behind the observed rift widenings. However, I am still left with an impression that I do not know what caused the widening of the rifts. Why did the mélanges not freeze the rifts? How do you expect the rifts to continue their development? Is there anything to learn from the evolution of rift T2, which seems to be two rifts approaching each other and potentially merging? I think that the manuscript could benefit from a more detailed discussion on the impacts of the results. What have we learned from these results which we did not already know? Having a more detailed discussion on that would increase the impact of the paper, its findings, and also on the MDAM method itself.

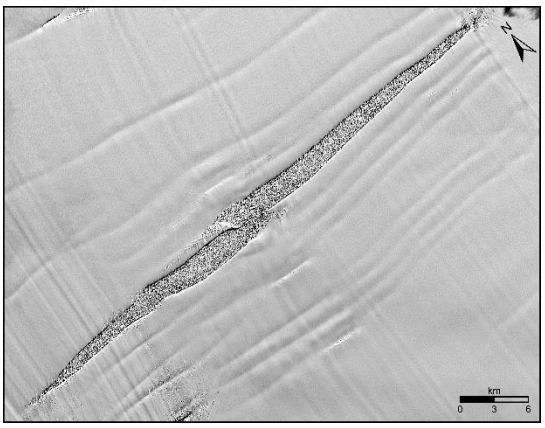
Response:

We appreciate your comments and questions regarding to mélange dynamics analysis and discussion. We revised the entire second paragraph in the Discussion section to address the relationship between mélange layer thinning and widening:

"*A thick mélange layer can effectively "freeze" a rift, enabling mechanical stress transmission between its flanks and ultimately suppressing rift propagation (Rignot and MacAyeal, 1998; Larour et al., 2021). In this study, we show that the mélange thickness in T1 and T2 decreased as the rifts widened. Thus, the mélange layer may have thinned for a relatively long period, passing a possible stage of rift freeze. We further propose that the mélange production itself is related to the rift widening process. The seracs inside the rifts are formed from partial collapsing of rift flanks. We suggest that the bottom part of the rift wall is first excavated through interactions by tides (Padman et al., 2002 and 2008), melting caused by intrusion of warmer sea water into the rift (Poinelli et al., 2023a), and other factors. This, in turn, causes the collapse of the upper part of the rift flank due to the removal of the bottom support. This process, like coastal bluff erosion, repeats itself and becomes one of the mechanisms that widen the rift and increase the mélange volume. We find that the increased mélange volume in a rift promotes its widening rate.*"

As suggested, we defined two rift centerlines for T2 so that the middle part of T2 does not look odd in Fig. 11. Originally, T2 initiated at the location of its current middle part. It then stopped to propagate and, instead, developed two long cracks, extending laterally in opposite directions with an offset in the middle. Now the cracks become two sub-rifts with their own mélange

layers. We believe that these two sub rifts will completely merge soon (see the Landsat 9 image of September 30, 2025 below). We also believe that one day T1 and T2 will merge, shortly before large icebergs will be formulated (like these in 1986). We are doing a systematic study of these processes and hope that we can report the results soon. Thanks again.



Results/Methods structure:

The restructuring of the Data and Methods section has improved the readability of the paper greatly. However, there are still Methods elements present in the first section of the Results. In my opinion most of section "3.1 Bias correction and adjusted DEM time series" belongs in the Methods part of the paper and not in the Results, as it describes how you generate the final DEM timeseries. You could keep the figures in the Results, including a description of the improved uncertainty after the bias-correction. However, the sentences describing how you calculate different components (i.e. assigning different weights to TPs in L242-249, the validation method of the bias correction and the data used therefore in L283-291, etc.) should be moved to the Methods section in my opinion. You could also choose to move the entire section to the Methods.

Response:

We moved the content of L242-249 to the Methods section, as suggested.

We felt that the validation part of L283-291 describes the result of using ICESat-2 data to check the adjusted DEMs. Considering both the order of the data processing result sequences and the nature of the actual computational results of this part, they would better stay in the Results section, hoping that you would agree.

While rifts and calving are natural processes in the life cycle of ice shelves, the calving of their seaward-most extensions does not necessarily lead to significant upstream glacier acceleration. I have not performed the calculations myself, but rifts T1 and T2 on the Filchner-Ronne Ice Shelf (FRIS) appear to lie beyond the 'compressive arch' (Doake, 1998), suggesting they may not directly precondition the ice shelf for collapse—similar to

the 'passive portion' described by Fürst et al. (2016). This raises a key question: if these rifts are not an immediate destabilizing factor for FRIS, why is their study important?

Response:

T1 and T2 are actually located in south of the passive ice boundary (green line in Fig. A1). We revised the paragraph to point out the potential destabilization: "*Although the icebergs calved from the shelf front in 1986 are mostly located inside the passive shelf ice area (Fig. A1), meaning no significant buttress reduction from the ice shelf (Doake et al., 1998; Fürst et al., 2016), the combined rifts of T1 and T2 propagated rapidly recently and have already covered ~58% the ice shelf laterally from Coats Land to Berkner Island. They have the potential to cause a calving before reaching the passive shelf ice boundary (green line in Fig. A1). Furthermore, warm water observed near Berkner Island (Davis et al., 2022) may accelerate the propagation processes of T1 and T2 and destabilize the ice shelf through a mechanism like that proposed for the Larsen C Ice Shelf (Poinelli et al., 2023a and 2023b).*"

Specific comments:

L40-45: I would suggest rephrasing it to something like this: "Mélanges inside rifts, which consist of shelf ice, snow, sea ice, and water, have been investigated in relation to ice shelf fracturing in Antarctica and glacier calving in Greenland (References). Specifically, reductions in mélange thickness have been observed during rift widening on the Amery, Ronne, and Larsen C ice shelves (References). Furthermore, modelling results indicate that a mélange may …"

Response:

We have rephrased the sentences accordingly: "*Mélanges inside rifts, which consist of shelf ice, snow, sea ice, and water, have been investigated in relation to ice shelf fracturing in Antarctica and glacier calving in Greenland (Rignot and MacAyeal, 1998; Larour et al., 2004; Cassotto et al., 2021). Specifically, reductions in mélange thickness have been observed during rift widening on the Amery, Ronne, and Larsen C ice shelves (Fricker et al., 2005; Walker et al., 2021; Larour et al., 2021). Furthermore, modelling results indicate that a mélange may……*"

L63-64: This is where I suggest you to be careful with how you present the MDAM method as this sentence still reads as if there is a general lack of methods handling heterogenous offsets between individual DEMs. I, therefore, suggest you to acknowledge that other methods already exist, but all with a different goal in mind, than the 3D mélange dynamics presented in this paper.

Response:

Thanks for your comment. We changed it to: "*While the existing methods can be used to register DEMs, there is a need to develop a strict mathematical model to improve the registration accuracy and to study 3D mélange dynamics.*"

L190-204: Are the GCPs manually chosen? Or are they "computationally" selected based on the mentioned criteria? Please mention what you did in a revised manuscript.

Response:

We added a sentence at the end of the paragraph: "*The above GCP selection method is implemented as a manual procedure.*"

L210-224: Is it correctly understood that the TPs are manually selected? If so, please state that explicitely in the manuscript.

Response:

Similarly, we added a sentence at the end of this paragraph: "*The TP selection method is also implemented as a manual procedure.*"

L236-237: The comment about the observed melange thinning seems misplaced here in the Methods section. I would suggest to move it to the Results or Discussion.

Response:

It is moved to the Results section: "…… *It may also indicate that the stress propagation between flanks may be compromised (Larour et al., 2004).*"

L241-292: This is the part which I suggest that you (partly) move to the Methods section of the paper.

Response:

We added a new subsection in the Methods section, to which we moved the method-related text in "L241-292".

"*2.4 Bias correction*

The proposed MDAM system estimates the bias corrections $(dX^k,\ dY^k,\ dZ^k)$ *for all sub-DEM* DEM^k *(k = 1, 2, …, N) through the least-squares procedure where their uncertainties are provided in the covariance matrix (McGlone et al., 2004). The REMA DEMs of 2016-2017 consists of 14 sub-DEMs that cover the entire front part of Filchner Ice Shelf (Fig. 3a). We use 12 GCPs that are measured by using ICESat-2 data to tie the connected DEMs to the grounded regions of Berkner Island and Coats Land where the average ice flow speed at the GCPs is ~8 m y-1. In total 51 TPs are used to connect the sub-DEMs on the floating part of the ice shelf, with 3-4 evenly distributed TPs in each overlapping area. Horizontal displacements at the TPs caused by the ice flow are on average ~90 m and are corrected by using the velocity map (Gardner et al., 2019). We establish the observation equations in Eqs. (1) and (2) using different weights. The weights for TPs are computed as inverse distances from the TPs to the nearest GCPs on grounded regions. Hence, the weights for GCPs are set to 1. Those TPs that are farther away from the grounded regions have smaller weights.*

We process the second set of REMA DEMs of 2020-2021 (Fig. 3b) in the same way in the least-squares process. In addition, the ZY-3 DEM of 2014 is reconstructed as a cross-ice-shelf DEM

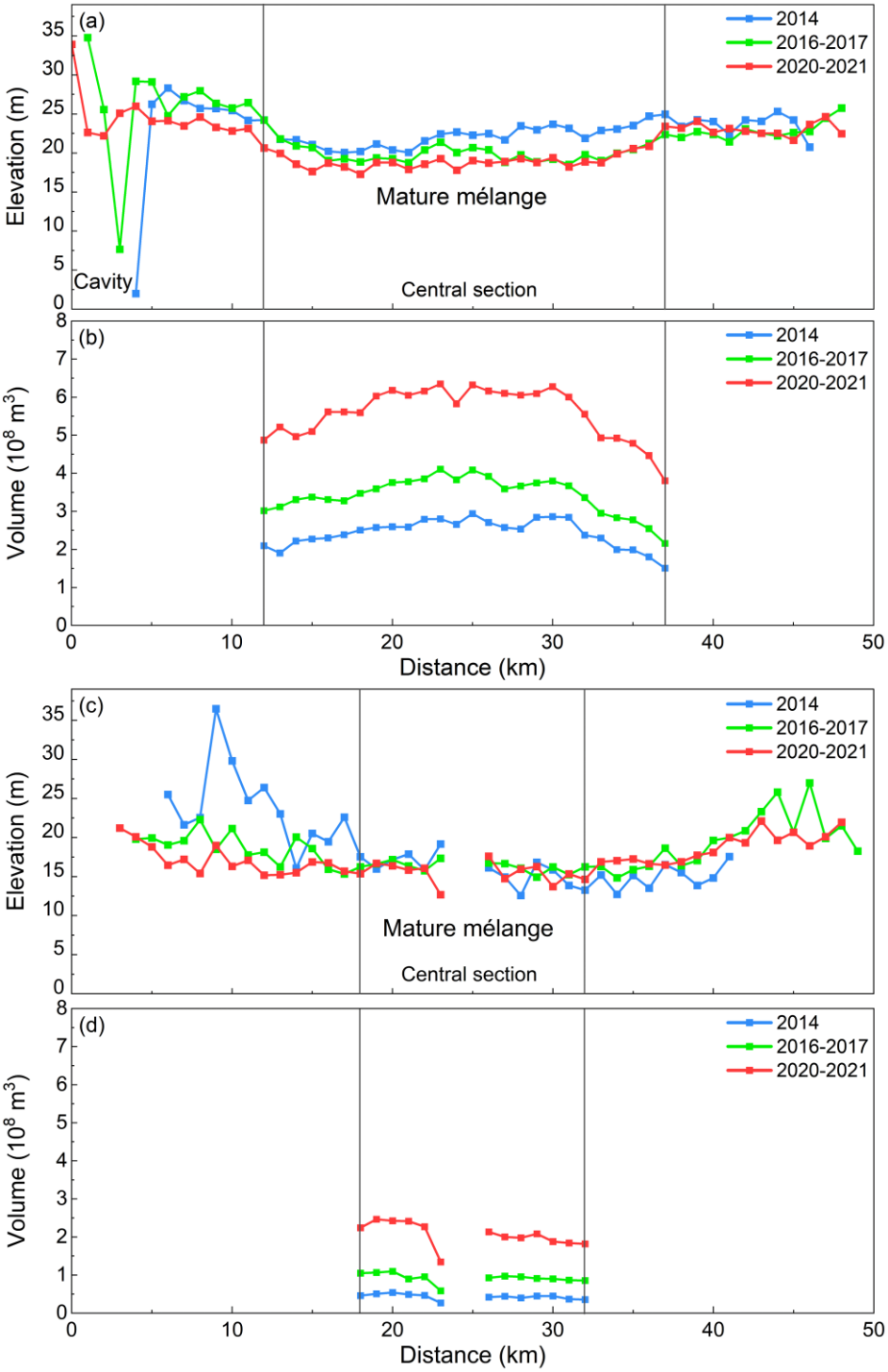
and does not need to go through this bias-correction process. The DEM is co-registered to the ICESat-2 ATL06 data of 2019 through a bundle adjustment procedure (McGlone et al., 2004; Li et al., 1998 and 2017b) using GCPs that are selected from "stable" features in the same way for those used in REMA sub-DEM co-registration."
The remaining part in 3.1 is also revised accordingly.

Table 1: I do not see the need for this table as the numbers are illustrated much better in Figure 6 and 7.
Response:
Table 1 is now merged in to Table A2 in Appendix A.

Figure 10: Please specificy in both figure and caption which is T1 and which is T2.
Response:
Thanks for your suggestion. "*T1*" and "*T2*" are added in Figures 10a, 10b, 10e, 10f and the caption.

L321-322: I would suggest to reduce the number of digits: 47.132 km → 47.1 km, 48.324 km → 48.3 km, 1.457 km → 1.5 km, 1.532 km → 1.5 km
Response:
We changed them as suggested.

Figure 11: Would it maybe make more sense to use two different centerlines for T2 as it seems from Fig. A2 that T2 is maybe two separate rifts approaching eachother rather than one long rift. This would also help to avoid confusion as to why the elevation and volume is so much higher/bigger in the middle of the central section of T2.
Response:
Thanks for the suggestion. Now, we defined two centerlines for T2 and recalculated elevation and volume changes. They are updated in text.



"*The established DEM time series unveils an overall decrease of 1.8 ± 0.6 m, at a rate of -0.4 ± 0.1 m y-1, in mélange elevation inside the two rifts from 2014 to 2021 (3.1 ± 0.4 m and 0.4 ± 0.4 m inside T1 (excluding cavity) and T2, respectively) (between blue and red lines in Figs. 11a and 11c). Correspondingly, the mélange thickness decreased by 10.0 ± 3.3 m (1.6 ± 0.4 m y-1) during the period (19.7 ± 2.5 m and 2.8 ± 2.2 m for T1 and T2, respectively). This mélange thickness reduction observed during rift widening on Filchner Ice Shelf coincides with the*

earlier findings on Amery Ice shelf, Ronne Ice Shelf, and Larsen C Ice Shelf (Fricker et al., 2005; Walker et al., 2021; Larour et al., 2021). It may also indicate that the stress propagation between flanks may be compromised (Larour et al., 2004). More importantly, our results indicate that despite the significant decrease in mélange elevation from 2014 to 2021 (Figs. 11a and 11c), the inferred periodical mélange volumes reveal a rapid expansion of the mélange by $(10.15 \pm 0.03) \times 10^9$ *km*^{3} *(151%) during the period,* $(7.93 \pm 0.03) \times 10^9$ *km*^{3} *for T1 and* $(2.22 \pm 0.01) \times 10^9$ *km*^{3} *for T2, respectively (Fig. 11), mainly attributed to newly vacated space due to partial collapse of rift flanks, associated rift widening, and other rift-mélange interaction factors.*"

L375-377: I don't fully understand this sentence. What does "this model" refer to? Is that MDAM? And if so, why wouldn't it work for Pine Island and Thwaites? What adjustments would be needed?

Response:

We revised the sentences to clarify the issue: "*…… To make this MDAM model working in a more dynamic open ocean environment, such as Pine Island and Thwaites ice shelves where ice velocity is significantly higher, modifications need to be carried out to address the rapid calving process with incoherent mélange changes in ice shelf front. For example, tie points between adjacent sub DEMs may be selected with decreased time intervals to minimize the uncertainty caused by the compensation using ice velocity maps.*"

L378-386: You mention that a thick melange layer can freeze a rift, but that is clearly not what happens at T1 and T2. Why is that? This entire paragraph in general seems loosely connected. As in, how does the fact that a thick melange layer can freeze rifts relate to the next sentence seracs inside the melange?

Response:

We revised the entire paragraph to make it consistent to explain the relationship between the mélange layer and widening:

"*A thick mélange layer can effectively "freeze" a rift, enabling mechanical stress transmission between its flanks and ultimately suppressing rift propagation (Rignot and MacAyeal, 1998; Larour et al., 2021). In this study, we show that the mélange thickness in T1 and T2 decreased as the rifts widened. Thus, the mélange layer may have thinned for a relatively long period, passing a possible stage of rift freeze. We further propose that the mélange production itself is related to the rift widening process. The seracs inside the rifts are formed from partial collapsing of rift flanks. We suggest that the bottom part of the rift wall is first excavated through interactions by tides (Padman et al., 2002 and 2008), melting caused by intrusion of warmer sea water into the rift (Poinelli et al., 2023a), and other factors. This, in turn, causes the collapse of the upper part of the rift flank due to the removal of the bottom support. This process, like coastal bluff erosion, repeats itself and becomes one of the mechanisms that widen*

the rift and increase the mélange volume. We find that the increased mélange volume in a rift promotes its widening rate, and may further impact the ice shelf stability."

L385-386: Calving does not necessarily impact ice shelf stability and as you mention in the following paragraph it seems that these rifts are in areas which do not provide much buttressing. I would, therefore, suggest that you remove the ice shelf stability part of this sentence.

Response:

Yes, we deleted the second half of the sentence.

L385: Change Passive Shelf Ice (PSI) to passive shelf ice. There is no need for an acronym which you only use two times.

Response:

They are changed in all places, except one in the caption of Figure A1 because it is marked in the figure.

L404-405: Could you clarify how the MDAM system can bu used to study ice shelf instability and sea level rise contribution?

Response:

This sentence is deleted.

Typos and grammar:

General grammar comment: The manuscript misses quite a few definitive articles ("the") throughout the text, which makes the text difficult to follow at times. I have only marked a few of them in my review, but I recommend the authors to make use of a grammar tool or similar to locate the remaing missing definitive articles.

Response:

Thank you for your comment. We have checked the usage of the definite article "the" and made changes throughout the entire manuscript.

L28: Antarctic Ice Sheet (AIS)… → <u>The</u> Antarctic Ice Sheet (AIS)…

Response:

We changed it accordingly.

L49: Be aware of using the definite article "the". Change "earth surface features" to "<u>the</u> Earth's surface features"

Response:

We changed it accordingly.

L52-55: Be aware of using the definite article "the". Change to:"… for example, the 500 m ICESat (Dimarzio et al., 2007) and ICESat-2 (Shen et al., 2022) DEMs, and the 1000 m CryoSat-2 DEM (Slater et al., 2018). Those from optical and SAR satellite stereo mapping data are of higher resolutions and have the potential for geometric modeling and analysis of rifts and mélange features, including the 90 m TanDEM-X DEM (Wessel et al., 2021), the 30 m ASTER DEM (Tachikawa et al., 2011), and especially, the 2 m REMA DEM (Howat et al., 2019)."

Response:

Thanks. We changed them accordingly.

L68-69 (Figure 1 caption): Be aware of using the definite article "the". Change to "The LIMA mosaic … the RAMP DEM …"

Response:

They are added.

L81: Change to "The validated MDAM is applied to the Filchner…"

Response:

We changed it accordingly.

L83: Change to "… is the second largest ice shelf in Antarctica."

Response:

We changed it accordingly.

L125: Be aware of using the definite article "the". Change to: "at the two shelf margins"

Response:

We changed it accordingly.

L126: Change "cover the floating ice of the ice shelf." to "cover the floating ice shelf".

Response:

We changed it accordingly.

L155: Change to "In a similar way,"

Response:

We changed it accordingly.

L246: Change to: "on average"

Response:

We changed it accordingly.

References:

Shean, D. E., Joughin, I. R., Dutrieux, P., Smith, B. E., and Berthier, E.: Ice shelf basal melt rates from a high-resolution digital elevation model (DEM) record for Pine Island Glacier, Antarctica, The Cryosphere, 13, 2633–2656, https://doi.org/10.5194/tc-13- 2633-2019, 2019.

Zinck, A.-S. P., Wouters, B., Lambert, E., and Lhermitte, S.: Unveiling spatial variability within the Dotson Melt Channel through high-resolution basal melt rates from the Reference Elevation Model of Antarctica, The Cryosphere, 17, 3785–3801, https://doi.org/10.5194/tc-17-3785-2023, 2023.

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