We appreciate the constructive comments from two reviewers (Dr. Ann-Sofie Priergaard Zinck, and Dr. Mattia Poinelli). Our manuscript will be much improved by their input. As informed in the letter of requesting responses, this file contains author comments (ACs). The revised manuscript should not be prepared and submitted at this stage. In the following responses, we use "**bold**" text for comments, "non-bold" text for our responses, and "italic" for changed text in the later improved manuscript.

Referee #1

The authors present a new method for co-registering and temporally aligning REMA DEMs. This method is in itself quite interesting, and a good addition to existing methods which are more focused on ice shelf basal melting. The resulting DEMs are further applied to describe the 3D development of a rift and its mélange on the Filchner Ice Shelf. The 3D investigation reveals rapid expansion of the rift which is attributed to calved shelf ice from the walls within the rift. This study thus underscores the importance of high-resolution elevation models in understanding rift and mélange development.

As seen below I do have a few major comments related to this paper. First, I find the current structure of the Methods section confusing and difficult to follow and have made some suggestions on how to improve that. Secondly, the current manuscript gives false expectations of analysis of two rifts on the Filchner Ice Shelf, whereas only one is thoroughly studied. I, therefore, suggest performing the analysis to both rifts. Furthermore, the current manuscript is lacking a discussion of the method and results as well as a broader discussion of the impact of this study. Lastly, to make this new MDAM method valuable to the community I think that it is important that the code becomes publicly available.

Response:

1) We are performing the suggested restructure of the manuscript, see the detailed description in the following responses to the Major Comments.
2) As suggested, we have added the results of T2 into the manuscript, see the detailed description in the following responses to the Major Comments.
3) Yes, we are adding a Discussion section to address limitations of the methods, mélange dynamics learned, and impact of the results, as suggested.
4) We will select a public hosting website to post our MDAM code, data of the Filchner project (DEMs, TPs, and GCPs).

Major comments:

Structure of the Methods section:

The current structure of the Methods section makes it very difficult to follow the different steps as there are quite some jumps in the storyline. First, I miss a Data section in-between the Introduction and Methods sections. In the current manuscript, the data is briefly described in L135-155, which is after the presentation of the MDAM method. That location of the data description makes it very difficult to follow the MDAM method. It also breaks the flow of the methods as the reader must wait quite long from the first mentioning of the TPs and GCPs before their selection procedure is described. Secondly, there are Introduction elements present in the Methods (L120-129), which I suggest being moved to the Introduction. Finally, the Results section contains a lot of elements which I think belong in the Methods section (Sect. 3.1 and L289-298), as they contain information to the methods as opposed to presenting actual results.

Response:

We agree with the suggestions. We are restructuring the manuscript accordingly.

First, as suggested, we move the data description to the location between Introduction and Methods. Some minor revisions are made to provide the context and make this move smoothly.

Secondly, the Introduction elements presented in the Methods (L120-129) are moved to the Instruction section, as suggested.

Finally, we moved those elements in the Results section (Sect. 3.1 and L289-298) that contain methods information to the Methods section.

Rift T2:

You present both rifts T1 and T2 in the Methods and Fig. 3, but your analysis focuses solely on rift T1. I would, therefore, suggest that you include a similar analysis of T2 as the one you have made for T1. This will likely also strengthen your manuscript with regards to melange dynamics.

Response:

The corrected DEMs and measurements for T2 are readily available. We will add figures and data of T2 (see some of them here) to make the analysis more complete, as suggested. We will complete the relevant analysis in the revised manuscript later.

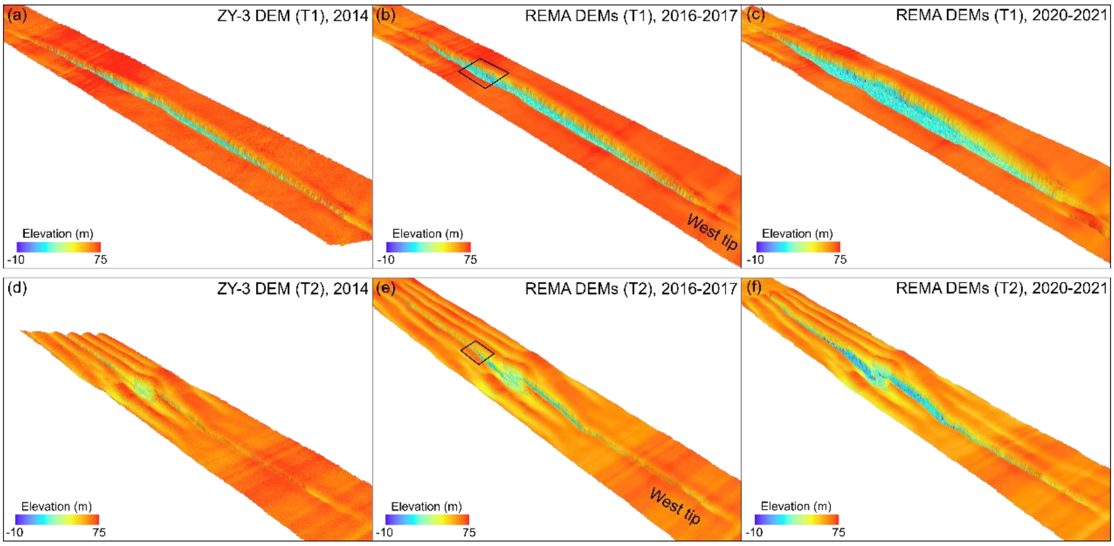
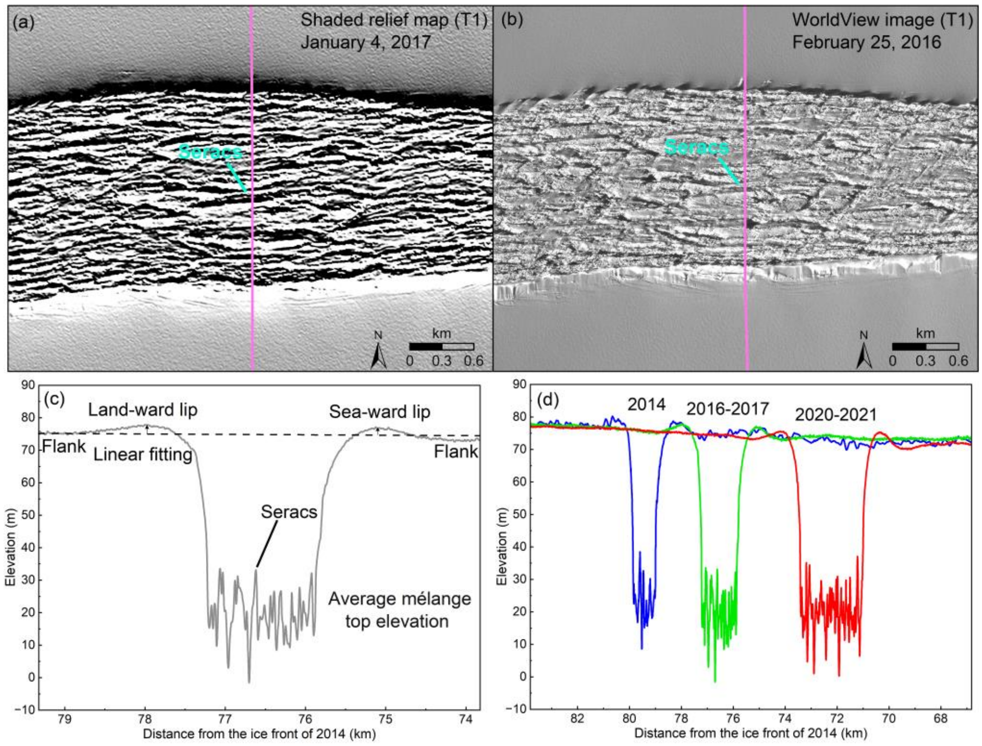


Figure 9. Multi-satellite DEM time series of the large rifts of T1 and T2 on Filchner Ice Shelf from 2014 to 2021: (a) and (d) reconstructed ZY-3 DEM of 2014, (b) and (e) bias-corrected REMA DEMs of 2016-2017, and (c) and (f) bias-corrected REMA DEMs of 2020-2021. The boxes in (b) and (e) indicate the corresponding sections of T1 and T2 where details of 3D structures and mélange are presented in Fig. 10.



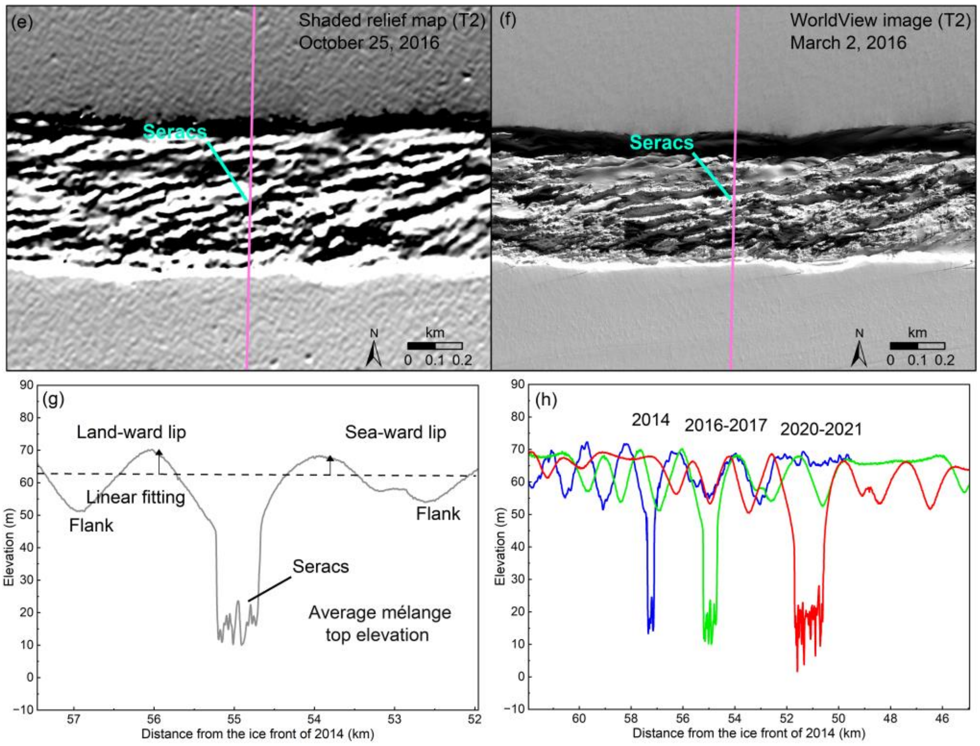


Figure 10. 3D sectional structure and mélange in T1 (a – d) and T2 (e – h): (a) shaded relief map of a section of T1 REMA DEMs of 2016-2017 (January 4, 2017) indicated by the box in Fig. 9b; (b) WorldView image (0.5 m resolution) of February 25, 2016; (c) elevation profile along the pink line in (a) and (b), and 3D rift and mélange structure parameters; and (d) rift and mélange changes along the profile from 2014 to 2021 (February 28, 2014 in blue, January 4, 2017 in green, and February 2, 2021 in red). (e) shaded relief map of a section of T2 REMA DEMs of 2016-2017 (October 25, 2016) indicated by the box in Fig. 9e; (f) WorldView image (0.5 m resolution) of March 2, 2016; (g) elevation profile along the pink line in (e) and (f), and 3D rift and mélange structure parameters; and (h) rift and mélange changes along the profile from 2014 to 2021 (February 28, 2014 in blue, October 25, 2016 in green, and February 3, 2021 in red). Elevation displayed in (a) and (e) is exaggerated by 10 times.

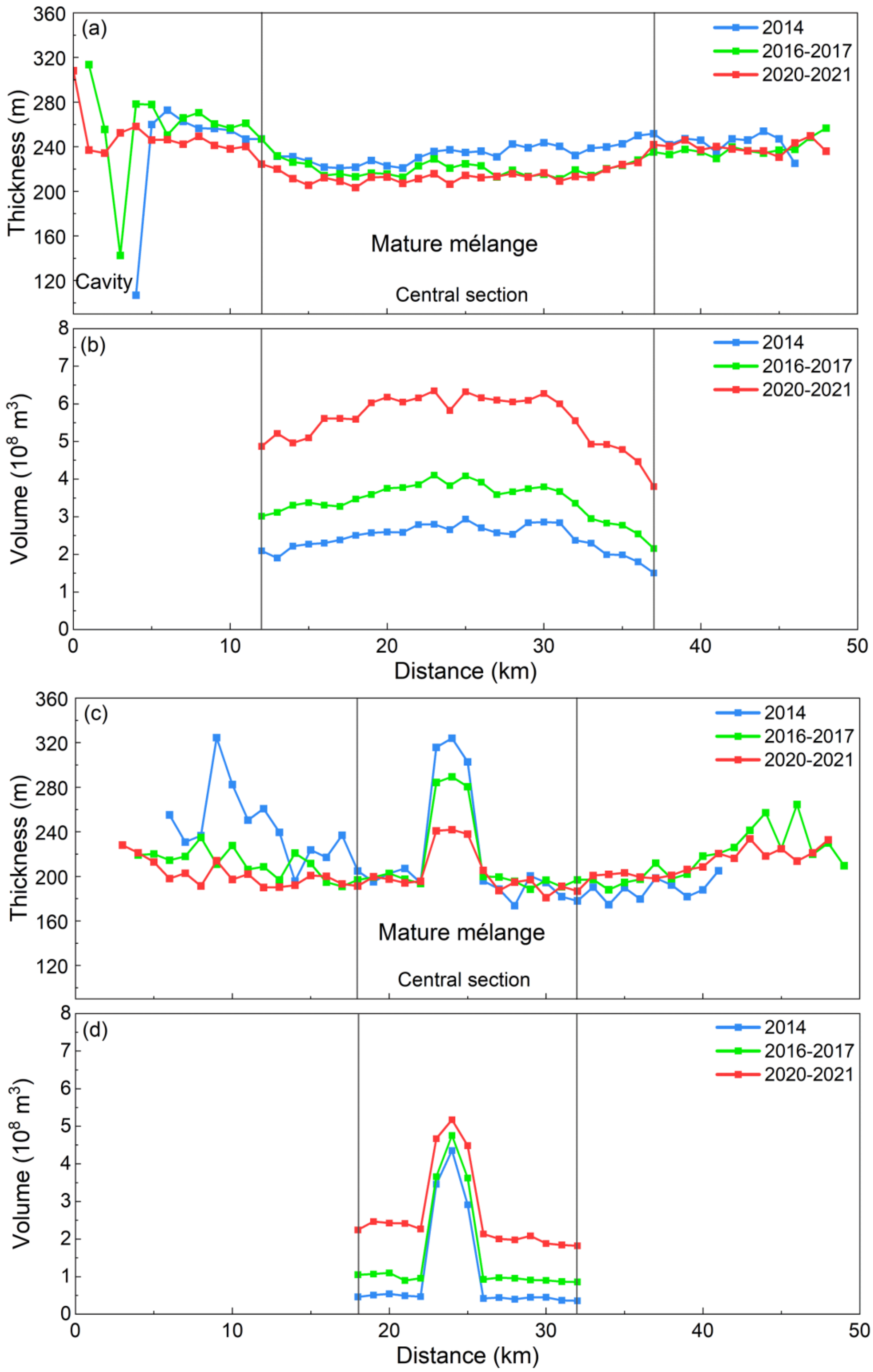


Figure 11. Thickness (a and c) and volume (b and d) of ice mélange inside the rift T1 and T2, respectively, from the multi-satellite DEM series from 2014 to 2021. Average thickness and volume of each transect that are separated every 1 km along the rift centerlines are illustrated from west tip to east tip

Table A4. Rift lip heights and differences measured for T1 and T2

T1

Transect ID from west tip to east tip (1 km separation)	Land-ward lip height (L) (m)	Sea-ward lip height (S) (m)	Difference (S-L) (m)
1	-1.67	0.54	2.21
2	3.58	4.53	0.95
3	2.68	4.65	1.97
4	0.84	1.72	0.88
5	4.39	1.49	-2.91
6	0.72	1.74	1.02
7	1.85	2.01	0.16
8	2.28	2.59	0.32
9	1.25	1.43	0.17
10	0.07	1.74	1.67
11	-1.57	1.84	3.40
12	-0.68	1.06	1.75
13	1.63	3.40	1.77
14	2.81	2.98	0.17
15	1.58	2.55	0.97
16	1.56	2.29	0.74
17	1.84	2.13	0.29
18	1.46	1.91	0.46
19	2.48	2.18	-0.30
20	1.65	1.89	0.24
21	1.91	1.82	-0.09
22	2.52	1.81	-0.71
23	1.99	1.37	-0.61
24	1.65	0.95	-0.70
25	1.70	1.03	-0.67
26	0.89	0.99	0.09
27	1.90	0.19	-1.71
28	0.98	0.05	-0.93
29	0.68	1.47	0.79
30	2.42	3.43	1.00
31	1.37	2.08	0.71
32	3.26	3.74	0.47
33	3.32	3.90	0.58
34	3.69	2.08	-1.61
35	3.71	4.80	1.09
36	1.95	1.90	-0.05
37	0.42	1.21	0.79
38	-0.27	-2.25	-1.98
39	2.77	3.48	0.71

40	2.52	1.35	-1.18
41	2.39	1.64	-0.74
42	2.02	1.10	-0.92
43	0.81	1.48	0.67
44	2.64	2.60	-0.05
45	4.62	4.19	-0.43
46	3.14	2.66	-0.48
47	-0.84	0.13	0.97
48	1.79	1.86	0.07
49	-1.40	-1.75	-0.35

Average rift lip height difference (seaward - landward) within the section of the T1 mature mélange: Mean: 0.03 m; Max: 1.77 m (13 km from the west tip)

T2:

Transect ID from west tip to east tip (1 km separation)	Land-ward lip height (L) (m)	Sea-ward lip height (S) (m)	Difference (S-L) (m)
1	0.43	2.98	2.55
2	0.56	0.67	0.11
3	-0.06	1.64	1.70
4	2.14	3.01	0.87
5	4.49	4.87	0.38
6	2.25	2.91	0.66
7	1.96	0.77	-1.19
8	2.04	2.69	0.65
9	-2.21	-1.81	0.40
10	-2.63	-0.92	1.71
11	0.06	0.54	0.48
12	-0.70	0.14	0.84
13	0.95	1.25	0.30
14	0.32	-0.94	-1.26
15	-0.33	-3.21	-2.88
16	-0.26	-2.41	-2.15
17	0.33	-0.94	-1.27
18	0.23	1.18	0.94
19	0.14	3.16	3.03
20	-1.55	4.58	6.13
21	-11.54	1.37	12.91
22	-7.76	-11.51	-3.75
23	-2.83	3.04	5.87
24	0.57	2.72	2.15
25	1.16	3.65	2.49
26	0.73	-16.66	-17.39

27	-18.62	-5.24	13.38
28	-0.31	-1.95	-1.64
29	2.49	-0.03	-2.52
30	1.75	1.64	-0.11
31	1.06	1.14	0.08
32	1.18	1.07	-0.11
33	0.62	-0.07	-0.69
34	1.89	1.45	-0.44
35	3.25	2.06	-1.19
36	2.86	2.84	-0.01
37	3.65	3.54	-0.11
38	4.66	4.38	-0.28
39	3.90	3.34	-0.56
40	4.34	3.54	-0.81
41	3.22	2.65	-0.56
42	3.01	2.05	-0.96
43	3.36	1.38	-1.98
44	3.58	1.67	-1.91
45	3.52	2.00	-1.53
46	3.53	1.65	-1.88
47	4.33	1.63	-2.70
48	5.32	1.68	-3.64
49	6.09	4.68	-1.42

Average rift lip height difference (seaward - landward) within the section of the T2 mature mélange: Mean: 0.6 m; Max: 13.38 m (27 km from the west tip)

Discussion:

The manuscript in its current state does not contain any discussion of the results. I, therefore, miss a separate Discussion section which should at least include a discussion on the following topics:

1.

A broader discussion of your MDAM method, including a discussion of the limitations of the method.

2.

A broader discussion on what you have learned about mélange dynamics because of this study.

3.

A discussion on the broader impact of your results. E.g., how do these results aid in assessing ice shelf instability, which you for instance mention in the Introduction.

Response:

Yes, we added a Discussion section to address these three points, along with those from Reviewer 2:

*"**4 Discussion***

The developed multi-temporal DEM adjustment model MDAM has shown its effectiveness in removing biases between adjacent multi-satellite sub-DEMs and establishing a unified and integrated DEM time series with an average elevation uncertainty of better than 0.24 m. We demonstrate the full 3D mapping capability for characterizing rift structure (rift lips, pre-mélange cavities, mélange seracs, etc.) and estimating dynamic mélange volume changes from the ICESat-2 controlled DEM time series, extending from rift topography and mélange thickness estimated along ground tracks from ICESat and ICESat-2 measurements in previous studies (Fricker et al., 2005; Walker et al., 2021). Such high-resolution mélange dynamic observations allow us to understand the mélange movement inside a closed environment of large Antarctic rifts, and to further study its role in rapid rift propagation and iceberg calving. To make this model working in a more dynamic open ocean environment, such as Pine Island and Thwaites ice shelves, modifications need to be carried out to address the rapid calving process with incoherent mélange changes in ice shelf front.

A thick mélange layer can effectively "freeze" a rift, enabling mechanical stress transmission between its flanks and ultimately suppressing rift propagation (Rignot, 1998; Larour, 2021). In this study, we show that seracs appearing on the mélange surface are a part of the infill inside rifts. They are formed from partial collapsing of rift flanks. We propose that the surface part of the bottom 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 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 increase ice front calving and effect the ice shelf stability.

Future calving triggered by T1 and T2 and the resulting ice front retreat may expose the ice shelf to increased warm water intrusion, a process simulated for the Larsen C ice shelf and supported by modelling results (Poinelli, 2023a and 2023b). Although the iceberg calved from the shelf front in 1986 is located inside the Passive Shelf Ice (PSI) area, meaning no actual buttress reduction for support from the ice shelf to the ice sheet (Doake, 1998; Fürst et al., 2016), the combined rifts of T1 and T2 propagated rapidly recently to cover ~58% the ice shelf laterally. In the context of global warming, this is particularly relevant for the Filchner Ice Shelf, as warm water has recently been observed near Berkner Island (e.g., Davis, 2022). Therefore, T1 and T2 have the potential to trigger a larger calving beyond the PSI boundary and could ultimately lead to destabilization mechanisms like those proposed for the Larsen C Ice Shelf."

Code and data availability:

A major part of this manuscript is the development of the MDAM method alongside with the resulting DEMs. I, therefore, think that it is necessary that the MDAM code (incl. TPs

and GCPs) becomes publicly available on e.g., GitHub to be a truly addition to the cryospheric community. Other similar methods (Shean et al. 2019 and Zinck et al. 2023) are likewise publicly available. Furthermore, it would be desirable to make the produced DEMs publicly available online.

Response:

The MDAM code (including TPs and GCPs) is now available at GitHub (https://github.com/menglianxia/MDAM).

The produced DEMs (including adjusted REMA DEMs of 2016-2017 and 2020-2021, and ZY-3 DEM of 2014) are available at https://doi.org/10.5281/zenodo.15260323 (Xia et al. 2025).

Reference:

Xia, M., Li, R., Scaioni, M., An, L., Li, Z., and Qiao, G.: Dataset belonging to the article: Building multi-satellite DEM time series for insight into mélange inside large rifts in Antarctica, Zenodo, https://doi.org/10.5281/zenodo.15260323, 2025.

Specific comments:

L12-15: The first two sentences of the abstract discuss "front calving", whereas this sentence discusses rift structural changes and mélange dynamics. I would suggest adding an extra sentence before this sentence which elaborates on mélange dynamics and how it is hypothesized to be related to front calving.

Response:

We now add a sentence: "*Mélange dynamics inside rifts is recognized to potentially influence the rift propagation and subsequent iceberg calving.*"

L14-17: Long and complex sentence. Consider splitting into two for clarity.

Response:

The sentence is split into two sentences: "*We propose an innovative multi-temporal digital elevation model (DEM) adjustment model (MDAM) to build a multi-satellite DEM time series from meter-level resolution small DEMs. It removes biases across large Antarctic ice shelves, as large as ~6 m in elevation, caused by tides, ice flow dynamics, and observation errors.*"

L14-15: Remember to explain acronyms. "We propose an innovative multi-temporal DEM…" → "We propose an innovative multi-temporal digital elevation model (DEM)…"

Response:

We changed it accordingly.

L17: Remember to explain acronyms. "Using 30 REMA…" → "Using 30 Reference Elevation Model of Antarctica (REMA)…"

Response:

We changed it accordingly.

L18: Consider changing to ", the second largest ice shelf in Antarctica." or remove entirely.
Response:
We changed it accordingly.

L24: You only use the acronym GSLR in this line and in L29, so I would write it out instead.
Response:
Thanks. The suggestion is well taken.

L26-27: Should be "The Antarctic Ice Sheet (AIS) has shown a persistent pattern of mass loss and has contributed to global sea level rise (GSLR) since the beginning of the satellite earth observation era in the 1960s (…"
Response:
We changed it accordingly.

L28: I don't understand the use of "Although" in the beginning of this sentence. I would rephrase this sentence with a focus on the importance of ice shelf calving instead of a focus on the grounding line.
Response:
We rephrased it to: "*The lost ice mass enters the Southern Ocean from ice shelves mainly through two processes, namely shelf front calving and basal melting, each accounting for ~50% (Depoorter et al., 2013; Liu et al., 2015; Smith et al., 2020; Greene et al., 2022)*".

L37: "advect to shelf front" → "advect to the shelf front"
Response:
It is so changed.

L38-41: I miss a clear definition of what a melange is.
Response:
The sentence is changed to: "*Furthermore, the importance and challenges on studying mélange (a mixture of shelf ice, snow, sea ice and water) changes in relation to fractures in both Greenland and Antarctica are fully recognized (Rignot and Macayeal, 1998; Larour et al., 2004 and 2021; Cassotto et al., 2021).*"

L56-57: Both Shean et al. 2019 and Zinck et al. 2023 handle heterogenous offsets between individual DEMs by applying dynamic corrections such as tides and by displacing the

DEMs based on ice flow. So, I am not sure that I agree that there is a lack in methods. However, both Shean et al. 2019 and Zinck et al. 2023 do their analysis with a focus on basal melting, and not with a focus on deriving elevation maps alone. I would, therefore, rephrase this sentence and make the focus on rifts and mélange dynamics stronger.

Response:

Agree. It is changed to: "*There is a lack of methods for handling heterogenous offsets between individual DEMs caused by rifts, mélange dynamics, and other factors in a dynamic Antarctic ice shelf environment.*"

L73: "the second largest in Antarctica" → "the second largest ice shelf in Antarctica"

Response:

Changed accordingly.

L74: "time series of 2014-" → "time series from 2014-"

Response:

Changed accordingly.

L74: "MDAM for quantitatively" → "MDAM by quantitatively"

Response:

Changed accordingly.

L83-89: You mention that you correct the DEMs for tides, but do you also correct the DEMs for the inverse barometer effect? And if not, what impact do you believe that to have on your results?

Response:

We did not apply inverse barometer effect (IBE) corrections to the DEMs explicitly. We performed the following analysis to show that this does not have an impact on our results.

We use the fifth-generation ECMWF reanalysis (ERA5), with an hourly interval and a spatial resolution of 0.25° × 0.25°, to calculate the IBE corrections. Based on the mean sea level pressure from 2014 to 2021, we computed the sea level pressure anomalies at the observation times for each DEM, and subsequently converted them into elevation changes using a rate of 1 cm/hPa (Padman et al., 2003; Chen et al., 2023).

The IBE corrections (influence on surface elevation) for all REMA DEMs of 2016–2017 on the ice shelf vary between –13.2 cm and 10.9 cm, those for all REMA DEMs of 2020–2021 on the ice shelf vary between –4.9 cm and 29.7 cm. We further did an experiment to find the IBE correction variation within smaller areas, namely within areas of individual DEMs. We found that the IBE correction changes little within a smaller DEM extent, with standard deviations up to 7 mm. That means that within the area of a DEM, the IBE correction can be treated as a constant.

On the other hand, in our MDAM model, elevation bias at TPs of each DEM is removed by a linear adjustment formula $a_o^k + a_1^k \, {Y_{OL}}_i^k$ where the IBE correction, now treated as a constant, is combined with the constant term a_o^k and corrected implicitly by the least-squares solution. The following is a numerical proof. For each DEM, we calculate the bias correction dz with and without the IBE correction.

REMA DEMs of 2016-2017:

DEM_ID	dz (no IBE correction) (m)	dz (with IBE correction) (m)	d_dz (m)
1	3.1462 ±0.0715	3.1464 ±0.0714	-0.0002
2	-1.1511 ±0.1325	-1.1499 ±0.1325	-0.0012
3	-1.0808 ±0.1775	-1.0785 ±0.1775	-0.0023
4	5.9135 ±0.2356	5.9168 ±0.2356	-0.0033
5	-5.7584 ±0.2938	-5.7547 ±0.2938	-0.0037
6	4.3821 ±0.3558	4.3853 ±0.3557	-0.0032
7	-0.2665 ±0.4265	-0.2648 ±0.4265	-0.0017
8	-1.0733 ±0.3817	-1.0731 ±0.3817	-0.0002
9	-1.9812 ±0.3268	-1.9848 ±0.3268	0.0035
10	-2.3278 ±0.2979	-2.3346 ±0.2979	0.0068
11	3.1072 ±0.2351	3.0997 ±0.2351	0.0075
12	2.6538 ±0.1933	2.6482 ±0.1933	0.0056
13	-2.3968 ±0.1619	-2.3994 ±0.1619	0.0026
14	-0.4772 ±0.0898	-0.4775 ±0.0898	0.0003

REMA DEMs of 2020-2021:

DEM_ID	dz (no IBE correction) (m)	dz (with IBE correction) (m)	d_dz (m)
1	-3.9234 ±0.1294	-3.9241 ±0.1293	0.0007
2	-1.0231 ±0.1379	-1.0231 ±0.1378	-0.0001
3	-2.8520 ±0.1477	-2.8506 ±0.1476	-0.0015
4	0.6495 ±0.1943	0.6503 ±0.1943	-0.0007
5	-0.2422 ±0.1684	-0.2419 ±0.1683	-0.0003
6	-1.2167 ±0.1784	-1.2169 ±0.1784	0.0002
7	0.1385 ±0.2629	0.1380 ±0.2628	0.0005
8	-1.3039 ±0.2795	-1.3046 ±0.2794	0.0007
9	2.0558 ±0.2143	2.0545 ±0.2143	0.0012
10	-0.7338 ±0.1628	-0.7343 ±0.1628	0.0004
11	-11.0123 ±0.1256	-11.0128 ±0.1256	0.0005
12	-1.7191 ±0.2013	-1.7187 ±0.2012	-0.0004
13	1.1548 ±0.2385	1.1537 ±0.2385	0.0011
14	2.1978 ±0.1969	2.1983 ±0.1968	-0.0005
15	-1.8438 ±0.1122	-1.8434 ±0.1122	-0.0004

The average difference between the resulting dz with and without the IBE corrections is 0.08 ± 0.47 cm (maximum 1.3 cm) for REMA DEMs of 2016–2017. The corresponding value for REMA DEMs of 2020–2021 is –0.01 ± 0.10 cm (maximum 0.27 cm). Similarly, for the ZY-3 DEM of 2014, the average difference does not exceed 2 cm.

Therefore, both methodological analysis and numerical experiments show that in our special case of using MDAM model to correct elevation bias, the IBE corrections can be treated as a constant within a small extent of the DEMs and can be taken care of by the linear correction model within the MDAM model. No explicit IBE corrections are needed here and no impact on the accuracy is found.

Reference:

Chen, H., Rignot, E., Scheuchl, B., and Ehrenfeucht, S.: Grounding Zone of Amery Ice Shelf, Antarctica, From Differential Synthetic-Aperture Radar Interferometry, Geophys. Res. Lett., 50, e2022GL102430, 10.1029/2022GL102430, 2023.

Padman, L., King, M., Goring, D., Corr, H., and Coleman, R.: Ice-shelf elevation changes due to atmospheric pressure variations, J. Glaciol., 49, 521-526, 10.3189/172756503781830386, 2003.

Hersbach, H., Bell, B., Berrisford, P., Biavati, G., Horányi, A., Muñoz Sabater, J., Nicolas, J., Peubey, C., Radu, R., Rozum, I., Schepers, D., Simmons, A., Soci, C., Dee, D., Thépaut, J-N., ERA5 hourly data on single levels from 1940 to present. Copernicus Climate Change Service (C3S) Climate Data Store (CDS), 10.24381/cds.adbb2d47 (Accessed on April 22, 2025), 2023.

L85: In case you are not aware of it, there is an updated version to the CATS2008 tide model (CATS2008_v2023). I do not think that it is necessary to change tide model for this paper, but it might be worth changing in potential future paper as the updated tide model also has an updated grounding line.

Response:

Thanks for the information. We will use the new version in future publications.

L87: When you mention the TPs here, I would make sure to refer to the later section where you elaborate on how these TPs are selected. I would also do the same for the GCPs.

Response:

In this paragraph we added text “*(see Section 2.2.2 for details)*” in places mentioning TPs and GCPs.

L89-92: I find this sentence quite complicated and difficult to follow. Consider splitting it into two, first one about the residuals (so the second part of the sentence). And secondly a sentence on the least-squares adjustment method.

Response:

We split it into two sentences: "*In the model inconsistencies at TP and GCP pairs are first reduced by the tide and velocity corrections, leaving the uncertainty originated from the sub-DEM production as residuals, including photogrammetric measurement errors and ephemeris data errors. Thereafter, we use the least-squares adjustment method (McGlone et al., 2004) to estimate the unknown bias corrections of all sub-DEMs by minimizing the residuals, (Li, 1998; McGlone et al., 2004; Shean et al., 2019).*"

L103: "given in a velocity map": What velocity map do you refer to here? In L88 you mention that you use the ITS_LIVE velocities (which could mean both the average product or image-pairs) and in Figure 1 you mention that you use the ITS_LIVE image-pair velocity maps. So, what ITS_LIVE velocity product do you use? And how does that relate to the acquisition time of the various sub-DEMs?

Response:

We added a sentence to explain it: "*Here we use averaged annual velocity maps of ITS_LIVE to avoid lower quality image-pair velocity maps potentially caused by low quality images and very short timespans between the pairs (Li et al., 2022).*"

L104: Could you give an example of how these epsilons could be interpreted? Do they represent the error?

Response:

The sentence is changed to: "($\varepsilon_{x_i}^{k}$, $\varepsilon_{y_i}^{k}$, $\varepsilon_{z_i}^{k}$) *represent residuals at TPs in the observation equations, including photogrammetric measurement errors and ephemeris data errors.*"

L105-108: I miss an explanation of what the GCP epsilons represent.

Response:

We added a sentence: "($\varepsilon_{x_i}^{GCP,k}$, $\varepsilon_{y_i}^{GCP,k}$, $\varepsilon_{z_i}^{GCP,k}$) *represent residuals at GCPs in the observation equations, describing inconsistencies between the integrated DEM and the outside control data (e.g., ICESat-2).*"

L108-112: You mention tilting in the y-direction and how you deal with that. But how do you deal with tilting in the x-direction?

Response:

This "tilting" in the Y-direction (ice flow direction) is dealt with by using the linear fitting method explained in the text (L108-112). We believe it is caused by advection of TPs and uneven ice shelf thickness (thicker from grounding line and thinner to shelf front). Since TPs "move" along the Y-direction, there is little "tilting" in the X-direction (cross shelf).

L116-117: If the "bias correction parameters" mentioned here correspond to the epsilons in eq. 1 and 2 then I would state that here. E.g. "Uncertainties of the estimated bias correction parameters ($\varepsilon_{x_i}^{k}$, $\varepsilon_{y_i}^{k}$, $\varepsilon_{z_i}^{k}$, $\varepsilon_{x_i}^{GCP,k}$, $\varepsilon_{y_i}^{GCP,k}$, $\varepsilon_{z_i}^{GCP,k}$) are computed…".

Response:

The sentence is changed to: "*Uncertainties of the estimated bias correction parameters ($\sigma_{x_i}^{k}$, $\sigma_{y_i}^{k}$, $\sigma_{z_i}^{k}$, $\sigma_{x_i}^{GCP,k}$, $\sigma_{y_i}^{GCP,k}$, $\sigma_{z_i}^{GCP,k}$) are computed through an error propagation within the optimization procedure.*"

L120-129: I think that this part belongs in the Introduction as it nicely frames the need of studying rifts at a high resolution. I would suggest to incorporate it into the last paragraph of the Introduction (L65-73) and move some of the technical parts of the last paragraph to the Methods section.

Response:

The paragraph is moved and revised accordingly.

L125: "Recently, two large rifts, T1 and T2,…" → "Recently, two large rifts, T1 and T2 (Fig. 3),…"

Response:

It is changed as suggested.

L127: "To study their…" → "Studying their…"

Response:

It is so changed.

L135-140: I would rephrase some of these sentences here to make it clear that you use the REMA strips. The first time that I read it I was in doubt as to whether you used the REMA strips or if you processed the WorldView images yourself.

Response:

It is now changed to make this clear: "*The sub-DEMs used in this study are REMA strips and a Ziyuan-3 (ZY-3) DEM which are generated from stereo satellite images of WorldView (Anderson and Marchisio, 2012) and ZY-3 (Wang et al., 2014), respectively. Both are formed by the along-track stereo mechanism (Li, 1998).*"

L135-149: What is the motivation behind the three different time periods (ZY-3: 2014, REMA: 2016/17 and 2020/21) that you use? Is part of the goal to also compare ZY-3 with REMA? And why do you only use ZY-2 for year 2014 now that it has a better coverage of

the rifts? I miss a clearer justification of the study period and of the use of different satellite products.

Response:

We added the following at the end of the paragraph: "*The ZY-3 DEM of 2014 has a full coverage of T1 and T2 without performing sub-DEM integration and can provide a reference for comparison with the adjusted sub-DEMs of REMA. These ZY-3 and REMA sub-DEMs form a seven-year long time series from 2014 to 2021 with a time interval of 3-4 years, within which shelf ice at any section would fall at least once from walls in to the rift so that elevation and volume changes can be calculated.*"

L147-148: Why do you present rift T2 here in the Methods section and in Fig. 3 when you do not present any results from the rift? I would suggest that you add a similar analysis of T2 as you have done for T1. That could potentially also strengthen your manuscript with regards to melange dynamics.

Response:

Please see the response to the relevant Major Comment.

L150: You mention that you use ICESat-2 data from 2019-2021 to co-register the 2014 ZY-3 DEM. How can you justify this 5-7 years gap in between acquisition times?

Response:

We added a sentence: "*To ensure that the GCPs are "stable" during the timespan between REMA and ICESat-2, these GCPs are further required to be on grounded features with a low velocity (< 10-20 m/y).*"

L135-155: I would suggest that you make a "Data" section between the Introduction and the Methods section, and that you move all of this to the new Data section.

Response:

Yes, we did it accordingly.

L196-198: How do you use ICESat-2 to determine the GCP elevations for the REMA 2016/17 DEMs? Do you just assume that the elevations at those points are constant in time? And if so, does that assumption hold? And what impact does it have on the results?

Response:

Please see the response above to "L150".

L199: "on the flowing ice of the ice shelf,…" → "on the floating part of the ice shelf,…"

Response:

It is so changed.

L226-227: How is that co-registration performed How is ICESat-2 used given the large time difference?

Response:

The sentence is changed to: "*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. An elevation accuracy of 0.30 m is achieved.*"

L233-242: As I understand the text here, you only validate the 2020/21 REMA DEM and not the ZY-3 2014 DEM and the 2016/17 REMA DEM. So how about those two other DEMs? How are they validated?

Response:

Here validation is a process where we use "ground truth" (ICESat-2) to verify the accuracy of a set of DEMs. This external assessment requires that the ground truth data and DEMs to be in the same place and cover the same period. In this way we prove that the 2020-2021 REMA DEM is of a high accuracy, 0.09 m on surface and 0.18 m on mélange.

On the other hand, the ground truth data of ICESat-2 do not cover the same periods of the 2016-2017 REMA DEM and the 2014 ZY-3 DEM. However, all three DEM sets use the "stable" grounded features on Berkner Island to Coats Land as GCPs, so that the accuracy of the grounded part of the DEMs are thus validated in a manner of internal assessment (Fig. 7, 0.14 – 0.30 m).

As explained in the manuscript, we use an internal assessment of inconsistencies or residuals at the TPs to estimate the accuracy of the floating part of these two DEMs. The residuals are in average 0.14 m for the 2016-2017 REMA DEM (Fig. 7) and 0.30 m for the ZY-3 DEM as assessed by using the bundle adjustment. They are at the same level of 0.18 m, the internal accuracy assessment for the 2020-2021 REMA DEM.

Therefore, we trust that the 2016-2017 REMA DEM and the 2014 ZY-3 DEM have the same quality as the 2020-2021 REMA DEM.

Sect. 3.1: In my opinion this section belongs in the Methods section and not in the Results.

Response:

This section (3.1) reports the results and performance of the proposed MDAM model. Then Section 3.2 reports the mélange dynamics application results. To maintain the logic flow, we hope that you would not mind that we keep this section in the Results.

L254-257: "… of 2014 where transects are spaced at…" → "… of 2014 with transects spaced at…"

Response:

Changed accordingly.

L264: Typo: I doubt that the rift is 4713.17 km long → it is probably 47.1317 km long.

Response:

Thanks. It is corrected.

L268-270: Interesting that the sea-ward side is mostly higher! Can you elaborate/speculate a bit on what the cause behind that could be?

Response:

We found that the landward wall produces more seracs than the seaward wall. This may cut the higher part of the undulation on the landward flank, so the remaining surface gets lower. We need more measurements and modelling efforts to prove this speculation.

L270-272: What does "The phenomenon" refer to in this sentence? Does it refer to the higher sea-ward side? And if so, what do they hypothesize as a reasoning for that?

Response:

We changed the sentence: "*This phenomenon of the greater heights of seaward rift lips based on the precise measurements from the bias-corrected sub-DEMs is consistent with the results for some rifts on other Antarctic ice shelves presented in Walker et al. (2019).*" We leave the reasoning for future paper(s) (see response above)

L277: Typo: YZ-3 should be ZY-3

Response:

Done.

L281: "We believe that this section of the rift…" → "We believe that this central section of the rift…"

Response:

Done.

L289-298: "To compute the corresponding… …in the mature melange section." Should be in the Methods section instead of in the results section.

Response:

This part is moved to the Methods section.

L305: I am not sure that I agree that the accuracy of all DEMs in general is 0.09 m as you only validate this for the 2020/21 DEMs.

Response:

Agree. The sentence is changed to: "*The bias-corrected multi-satellite DEM time series achieved an accuracy of 0.09 m for the 2020-2021 REMA DEM assessed by ICESat-2 validation, and 0.18 m for the 2016-2017 REMA DEM to 0.3 m for the 2014 ZY-3 DEM, respectively, estimated through the error propagation.*"

Figure 1: What small-coverage DEMs is it that you show on Figure 1a? Are those the REMA strips? I also miss an indication of the size of the strips relative to the ice shelf, so some sort of scale.

Response:

We added the suggested scale information: "*Figure 1. (a) High-resolution small-coverage DEMs (e.g., REMA strips of ~16~18 km ╳~110~120 km) are unified and integrated for accurate 3D rift structural and mélange dynamic monitoring in a large Antarctic ice shelf environment (e.g., ~165 km wide Filchner Ice Shelf) ……*"

Figure 3: How come there are GCPs on the ice shelf itself in panel b)? In the manuscript and Fig. 1 you mention that those are only on the grounded parts. Furthermore, the gery ZY-3 outlines in panel a) are very difficult to see, so I would choose a different color for those. I think that there is a typo in the colorbar of both panels, they say that the elevation go from -10 to -510. Finally, I would mark T1 and T2 in both panels.

Response:

In the new Data section, we added: "…… *In a special case we also select GCPs on the ice shelf where both the DEM images and ICESat-2 data were acquired within one day.*" Similar sentence is also added in the caption of Fig. 3.

In the following revised Fig. 3, please see that the ZY-3 outlines are changed to darker and thicker lines. "-500 m" is changed to 500 m. T1 and T2 are also marked in (b).

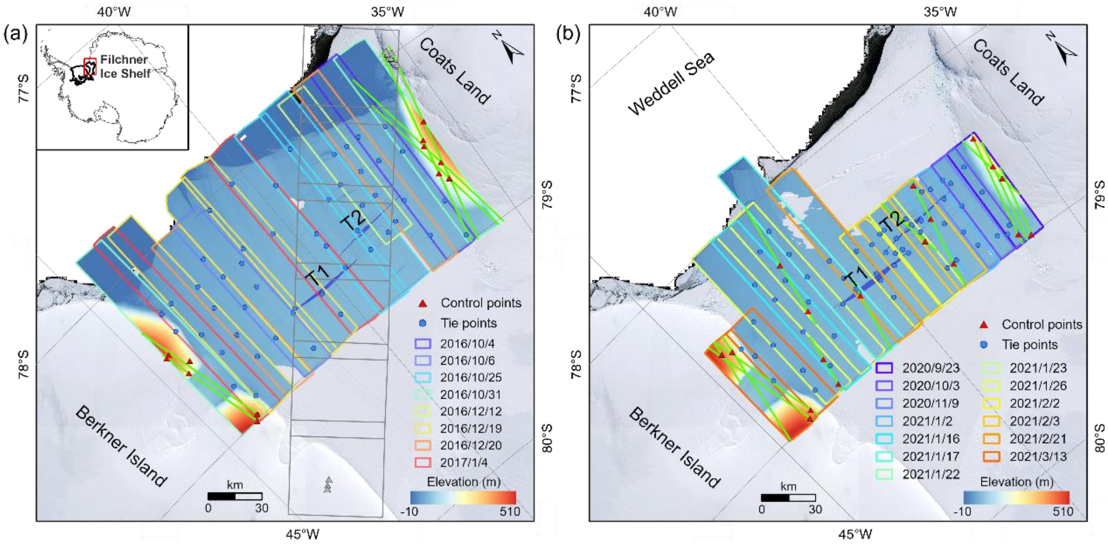
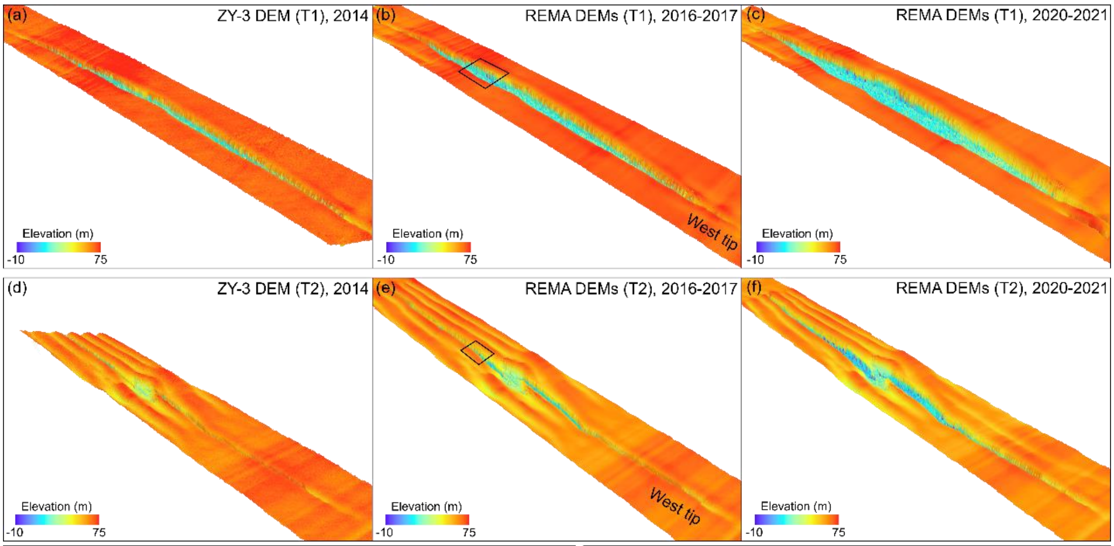


Figure 9: I would prefer to see these DEMs in 2D rather than 3D, as this 3D view does not allow for seeing the full depth of the rift. Secondly, I would consider adjusting the colorbar to make the ice shelf surface more visible without losing information from within the rift. Lastly, I miss a scale on the figures for reference, which will for instance make it easier to see by how much the rift has opened during the study period.

Response:

We provide now both 2D DEMs and 3D DEMs (probably 3D in Appendix?).



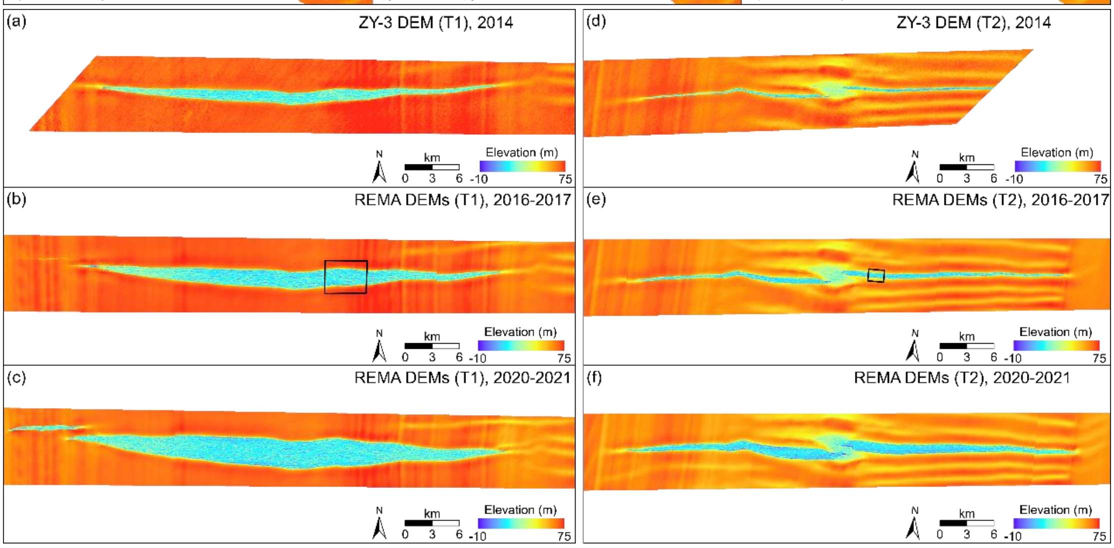


Figure 10: In panel c) and d) I would consider changing the x-axis to "Distance from the ice front" as that is an important parameter in terms of the calving risk.

Response:

It is changed to "Distance from the ice front of 2014". We also added Figs. 10e-10h for T2.

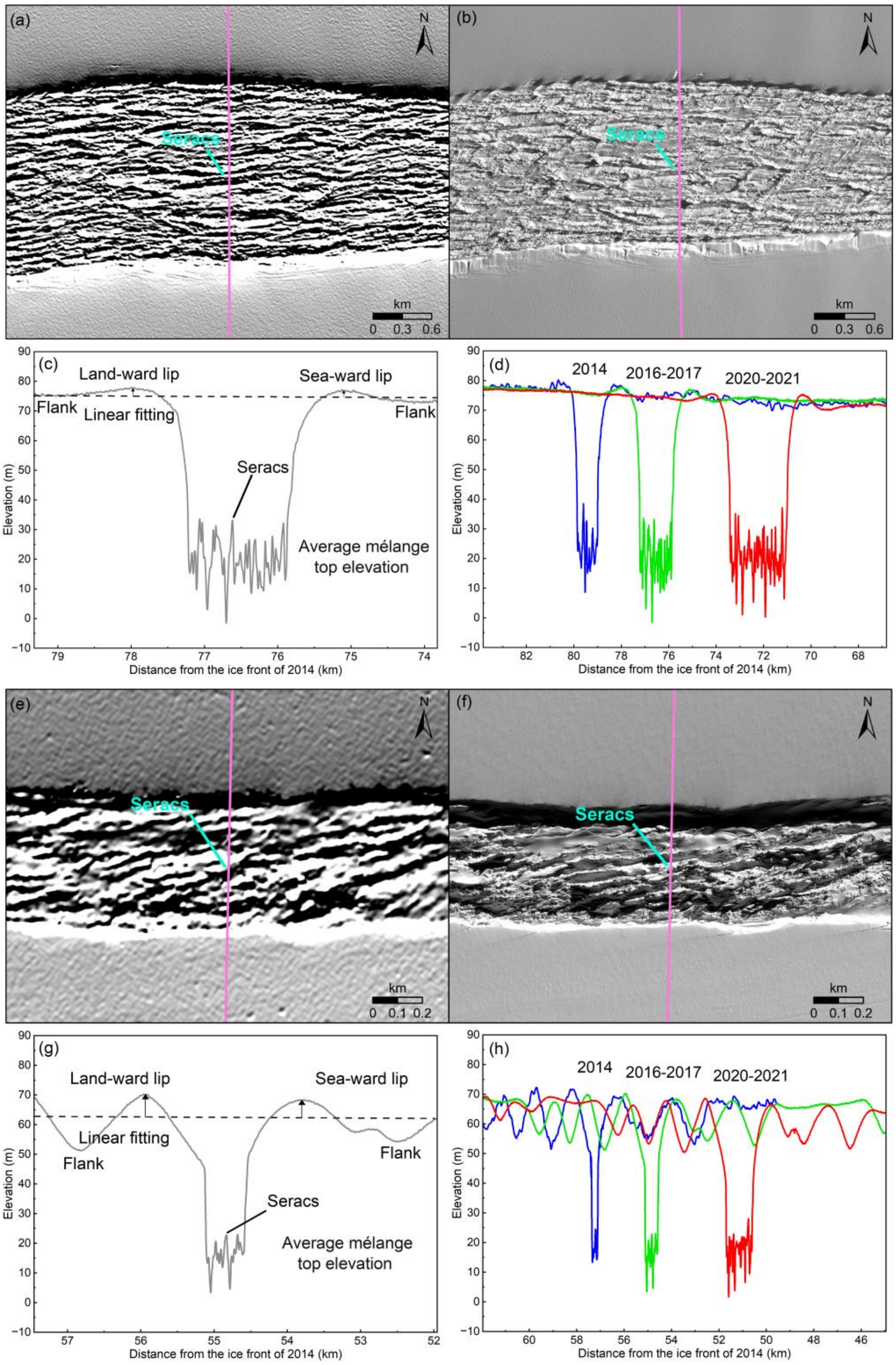
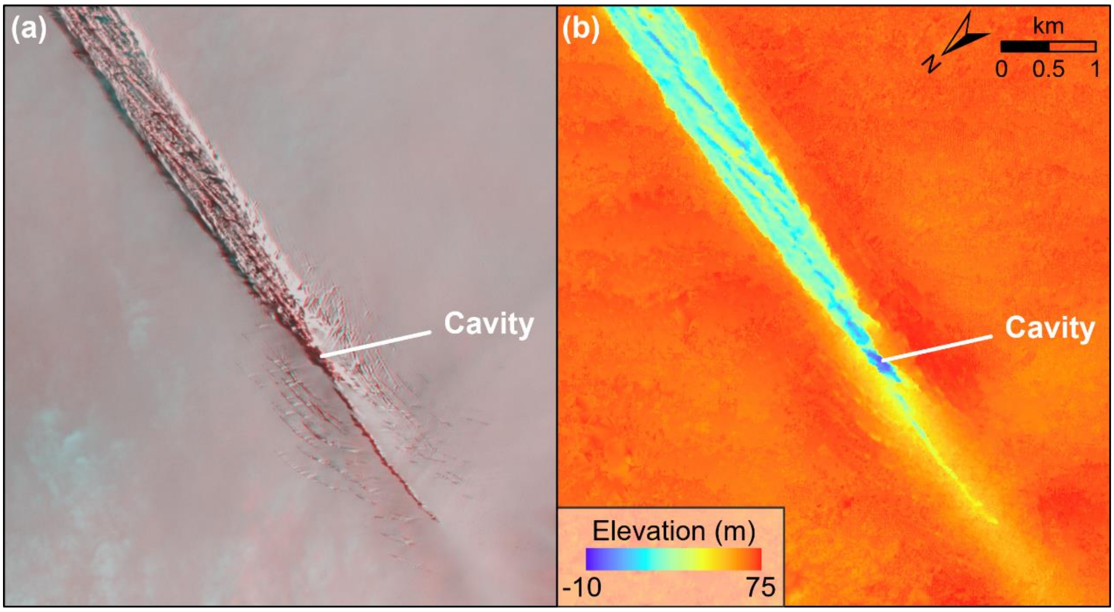


Figure A1: It is very difficult to see what is what on this figure. People that are not used to seeing stereo pairs plotted in this way will most likely not be able to tell that it is a cavity as opposed to a melange. Could you maybe show a stereo pair of a melange for comparison or add a colormap and colorbar which makes the cavity more visible?

Response:

We revised the figure by adding a 2D color elevation map where the cavity is represented in blue color. Hope this makes the cavity visible. We will also revise the manuscript to make it clear.



Data availability: How about the ZY-3 data? And will the DEM time series generated here also become publicly available somewhere?

Response:

Yes, we will make the ZY-3 DEM publicly available, along with the corrected REMA DEMs.

Code availability:

Will the MDAM code become publicly available? This paper is heavily based on the development of a new method, and I therefore think that it is important that that new method is also publicly available to the community.

Response:

The MDAM code (including TPs and GCPs) is now available at GitHub (https://github.com/menglianxia/MDAM).

The produced DEMs (including adjusted REMA DEMs of 2016-2017 and 2020-2021, and ZY-3 DEM of 2014) are available at https://doi.org/10.5281/zenodo.15260323 (Xia et al. 2025).

Reference:

Xia, M., Li, R., Scaioni, M., An, L., Li, Z., and Qiao, G.: Dataset belonging to the article: Building multi-satellite DEM time series for insight into mélange inside large rifts in Antarctica, Zenodo, https://doi.org/10.5281/zenodo.15260323, 2025.

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.

Response:

These references are cited in right places of the manuscript.