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). 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 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 have performed 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 have posted our MDAM code and data of the Filchner project (DEMs, TPs, and GCPs) to the GitHub and the Zenodo, respectively. See the detailed description in the following responses to the specific comment.

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 Method. Some minor revisions are made to provide the context and make this move smoothly.

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

Finally, we moved those elements in the Results section (Sect. 3.1 and L289-298) that contain methods information to the Method 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 have added figures and data of T2 (see some of them here) to make the analysis more complete, as suggested. We have completed the relevant analysis in the revised manuscript.

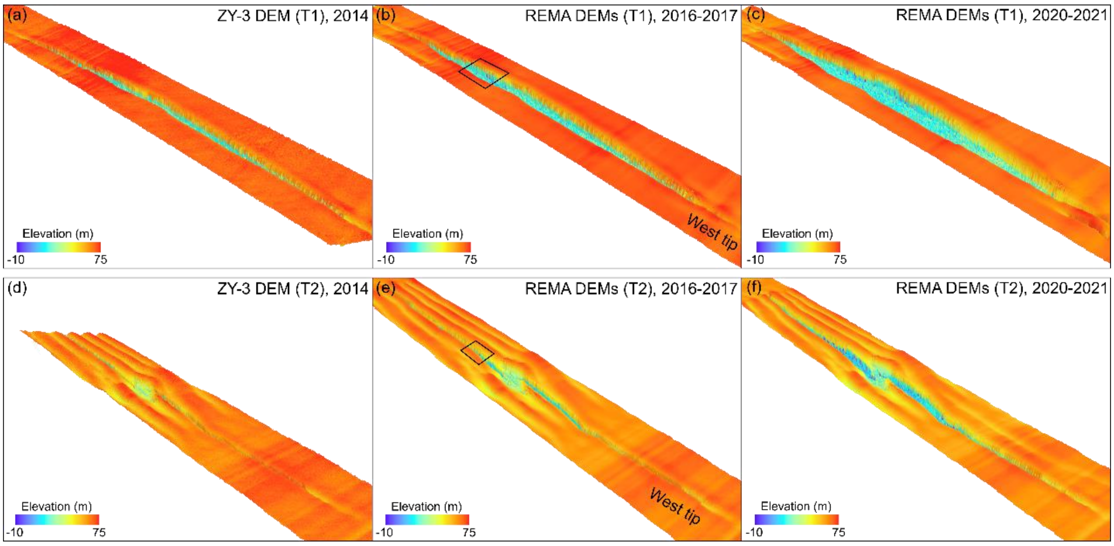
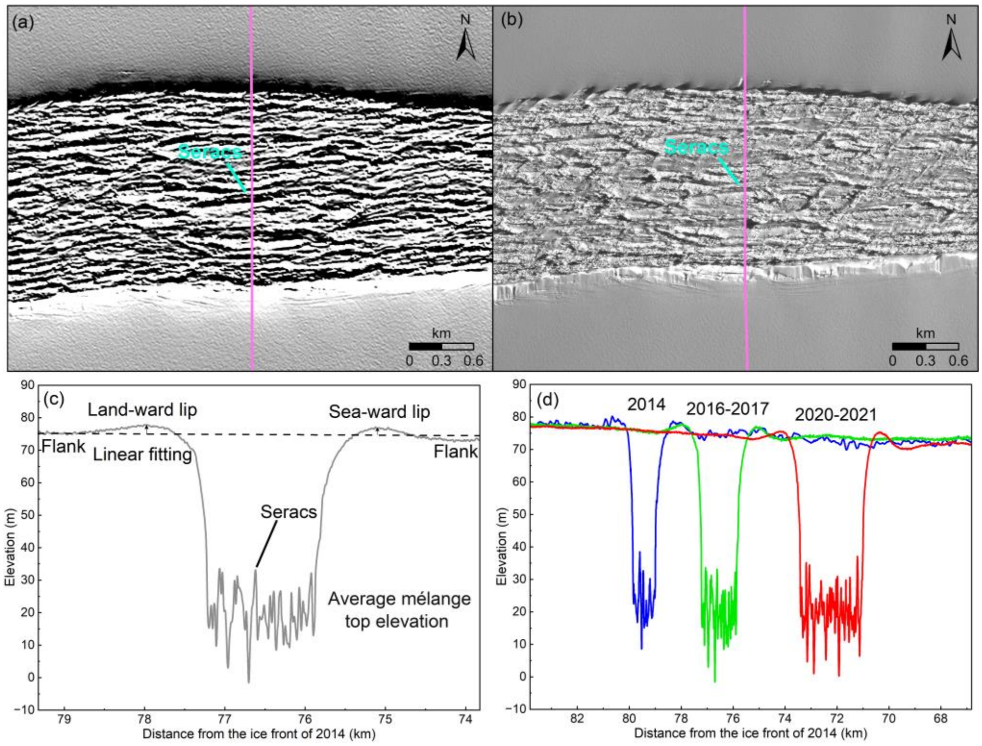


Figure 9. Multi-satellite DEM time series of the large rifts of T1 and T2 on Filchner Ice Shelf from 2014 to 2021: (a) and (d) reconstructed ZY-3 DEM of 2014, (b) and (e) bias-corrected REMA DEMs of 2016-2017, and (c) and (f) bias-corrected REMA DEMs of 2020-2021. The boxes in (b) and (e) indicate the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



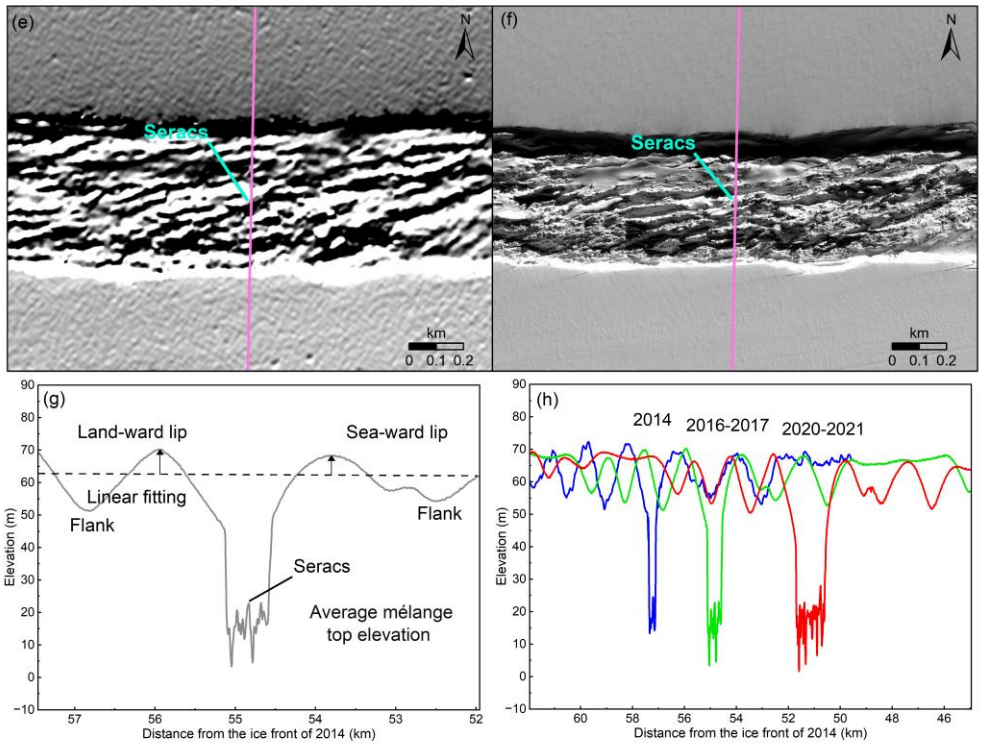


Figure 10. 3D sectional structure and mélange: (a) and (e) are sectional shaded relief maps of REMA DEMs of 2016-2017 (January 4, 2017 and October 25, 2016) indicated by the boxes in Fig. 9; (b) and (f) are WorldView images (0.5 m resolution) of February 25, 2016 and March 2, 2016; (c) and (g) are elevation profiles along the pink lines in (a) and (e), and 3D rift and mélange structure parameters; (d) and (h) are rift and mélange changes along the profiles from 2014 to 2021 (2014 in blue, 2016-2017 in green, and 2020-2021 in red). Elevation displayed in (a) and (e) are exaggerated by 10 times.

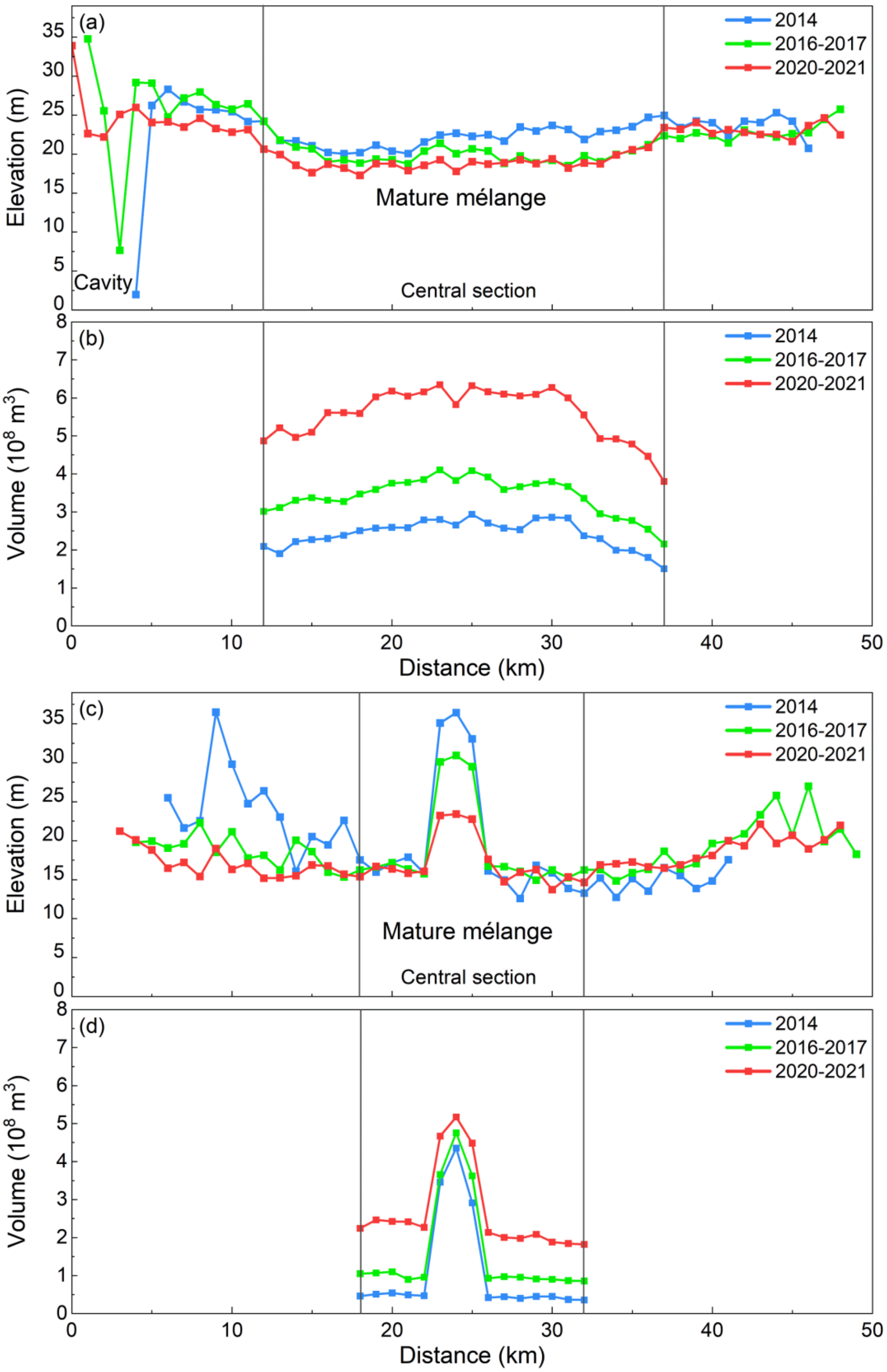


Figure 11. Elevation (a and c) and volume (b and d) of ice mélange inside the rifts T1 and T2 from the multi-satellite DEM series from 2014 to 2021. Average elevation and volume of each transect that are separated every 1 km along the rift centerline are illustrated from west tip to east tip.

Table A3. Heights of rift lips measured on the land-ward (L) side and sea-ward (S) side, and their difference

(S-L) at each transect along the centerlines of Rift T1 and T2 (REMA DEMs of 2016-2017).

Rift 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)
0	-1.7	0.5	2.2
1	3.6	4.5	1.0
2	2.7	4.7	2.0
3	0.8	1.7	0.9
4	4.4	1.5	-2.9
5	0.7	1.7	1.0
6	1.8	2.0	0.2
7	2.3	2.6	0.3
8	1.3	1.4	0.2
9	0.1	1.7	1.7
10	-1.6	1.8	3.4
11	-0.7	1.1	1.7
12	1.6	3.4	1.8
13	2.8	3.0	0.2
14	1.6	2.6	1.0
15	1.6	2.3	0.8
16	1.8	2.1	0.3
17	1.5	1.9	0.5
18	2.5	2.2	-0.3
19	1.6	1.9	0.2
20	1.9	1.8	-0.1
21	2.3	1.6	-0.7
22	2.0	1.4	-0.6
23	1.7	0.9	-0.7
24	1.7	1.0	-0.7
25	0.9	1.0	0.1
26	1.9	0.3	-1.6
27	1.0	0.1	-0.9
28	0.7	1.5	0.8
29	2.4	3.4	1.0
30	1.4	2.1	0.7
31	3.3	3.7	0.5
32	3.3	3.9	0.6
33	3.7	2.1	-1.6
34	3.7	4.8	1.1
35	2.0	1.9	0.0
36	0.4	1.2	0.8
37	-0.3	-2.3	-2.0
38	2.8	3.5	0.7

39	2.5	1.3	-1.2
40	2.4	1.7	-0.6
41	2.0	1.1	-0.9
42	0.8	1.5	0.7
43	2.6	2.6	0.0
44	4.6	4.2	-0.4
45	3.1	2.7	-0.5
46	-0.8	0.1	1.0
47	1.8	1.9	0.1
48	-1.4	-1.8	-0.4

Average lip height difference (s – l) within the section of mature mélange of T1: 0.1 m (max 1.8 m at 12 km from west tip).

Rift 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)
0	0.4	3.0	2.5
1	0.6	0.7	0.1
2	-0.1	1.6	1.7
3	2.1	3.0	0.9
4	4.5	4.9	0.4
5	2.3	2.9	0.7
6	2.0	0.8	-1.2
7	2.0	2.7	0.7
8	-2.2	-1.8	0.4
9	-2.6	-0.9	1.7
10	0.1	0.5	0.5
11	-0.7	0.1	0.8
12	0.9	1.2	0.3
13	0.3	-0.9	-1.3
14	-0.3	-3.2	-2.9
15	-0.3	-2.4	-2.2
16	0.3	-0.9	-1.3
17	0.2	1.2	0.9
18	0.1	3.2	3.0
19	-1.6	4.6	6.1
20	-11.5	1.4	-
21	-7.8	-11.5	-3.7
22	-2.8	3.0	5.9
23	0.6	2.7	2.2
24	1.2	3.6	2.5
25	0.7	-16.7	-
26	-18.6	-5.2	-

27	-0.3	-1.9	-1.6
28	2.5	0.0	-2.5
29	1.8	1.6	-0.1
30	1.1	1.1	0.1
31	1.2	1.1	-0.1
32	0.6	-0.1	-0.7
33	1.9	1.5	-0.4
34	3.3	2.1	-1.2
35	2.9	2.8	0.0
36	3.6	3.5	-0.1
37	4.7	4.4	-0.3
38	3.9	3.3	-0.6
39	4.3	3.5	-0.8
40	3.2	2.7	-0.6
41	3.0	2.0	-1.0
42	3.4	1.4	-2.0
43	3.6	1.7	-1.9
44	3.5	2.0	-1.5
45	3.5	1.7	-1.9
46	4.3	1.6	-2.7
47	5.3	1.7	-3.6
48	6.1	4.7	-1.4
49	5.0	6.2	1.2

Average lip height difference (s – l) within the section of mature mélange of T2: 0.2 m (max 5.9 m at 22 km from 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. We demonstrate the full 3D mapping capability of 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 and MacAyeal, 1998; Larour et al, 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 seawater 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 increase ice front calving and effect the ice shelf stability.

Although the iceberg calved from the shelf front in 1986 is mostly located inside the Passive Shelf Ice (PSI) 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. As warm water has recently been observed near Berkner Island (Davis et al., 2022), T1 and T2 have the potential to trigger a larger calving beyond the PSI boundary, which may be caused by a destabilization mechanism like that proposed for the Larsen C Ice Shelf (Poinelli et al., 2023a and 2023b)."

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 to “*, the second largest ice shelf in Antarctica.*”

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, mélange (a mixture of shelf ice, snow, sea ice and water) changes related to ice shelf fracturing in Antarctica and glacier calving in Greenland are studied (Rignot and MacAyeal, 1998; Larour et al., 2004; 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 detailed description in Section 2.3)*" 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, ITS_LIVE image-pair velocity maps are selected to spatially match the extent of each sub-DEM and to temporally align as closely as possible with the acquisition times of two adjacent sub-DEMs.*" Most sub-DEMs and the corresponding velocity maps show good temporal overlap.

REMA DEMs of 2016-2017:

ID of adjacent sub-DEMs	Time span of adjacent sub-DEMs	Time span of image-pair velocity map
1, 2	2016/10/31-2017/01/04	2016/11/01-2017/01/04
2, 3	2016/12/19-2017/01/04	2016/12/19-2017/01/04
3, 4	2016/12/19-2016/12/20	/
4, 5	2016/10/06-2016/12/20	2016/10/06-2016/11/07
5, 6	2016/10/06-2016/12/19	2016/10/06-2016/11/07
6, 7	2016/12/19-2016/12/19	/
7, 8	2016/12/19-2017/01/04	2016/12/19-2017/01/04 2016/10/31-2017/01/03
8, 9	2016/10/25-2017/01/04	2016/10/31-2017/01/03
9, 10	2016/10/25-2016/10/25	/
10, 11	2016/10/25-2016/12/12	2016/10/08-2016/11/25
11, 12	2016/12/12-2016/12/20	2016/10/31-2017/01/03
12, 13	2016/10/04-2016/12/20	2016/10/31-2017/01/03
13, 14	2016/10/04-2016/10/31	2016/09/29-2016/10/31 2016/10/06-2016/11/07

REMA DEMs of 2020-2021:

ID of adjacent sub-DEMs	Time span of adjacent sub-DEMs	Time span of image-pair velocity map
1, 2	2021/03/13-2021/03/13	/
2, 3	2021/01/26-2021/03/13	2020/11/23-2021/02/21
3, 4	2021/01/16-2021/01/26	2020/11/23-2021/02/21
4, 5	2021/01/16-2021/01/26	2020/10/04-2021/02/09

5, 6	2021/01/17-2021/01/26	2020/10/04-2021/02/09
6, 7	2021/01/17-2021/02/21	2021/01/07-2021/02/08
7, 8	2021/02/02-2021/02/21	2021/01/07-2021/02/08
8, 9	2021/02/02-2021/02/03	/
9, 10	2021/01/26-2021/02/03	2021/01/07-2021/02/08
10, 11	2021/01/26-2021/02/03	2021/01/07-2021/02/08
11, 12	2021/01/22-2021/02/03	2021/01/07-2021/02/08
12, 13	2020/11/09-2021/01/22	2020/11/14-2021/01/23
13, 14	2020/10/03-2020/11/09	2020/10/29-2021/01/07
14, 15	2020/09/23-2020/10/03	2020/10/03-2020/12/22

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:

According to Shean et al. (2016, 2019), a limited number of REMA strips longer than 110 km may exhibit "tilting" in the y-direction (along-track). Here it is approximately aligned with the ice flow direction on the Filchner Ice Shelf. This type of tilting typically ranges from ~1 to 3 m. Tilting in the x-direction (across-track) also occurs occasionally, but within a smaller magnitude (~1 m).

We only correct for the tilting in the primary (y) direction. Since the ground control points are distributed on both sides of the ice shelf, the influence of cross-track (x-direction) tilting can be effectively constrained. According to the error estimates and validation against ICESat-2 data, the DEM tilting has been effectively corrected.

Reference:

Shean, D. E., Alexandrov, O., Moratto, Z. M., Smith, B. E., Joughin, I. R., Porter, C., and Morin, P.: An automated, open-source pipeline for mass production of digital elevation models (DEMs) from very-high-resolution commercial stereo satellite imagery, ISPRS Journal of Photogrammetry and Remote Sensing, 116, 101-117, 10.1016/j.isprsjprs.2016.03.012, 2016.
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, 10.5194/tc-13-2633-2019, 2019.

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 (Table A1). 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. The combined 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, which can be used to analyze mélange elevation and volume changes.*"

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 the ZY-3 DEM (REMA sub-DEMs) and ICESat-2, these GCPs are further required to be on grounded features with a low velocity (< 10-20 m y^{-1}). 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.*"

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 (Section 2.1).

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 to “L150” above.

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:

The average differences are not very large. 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 Method 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).

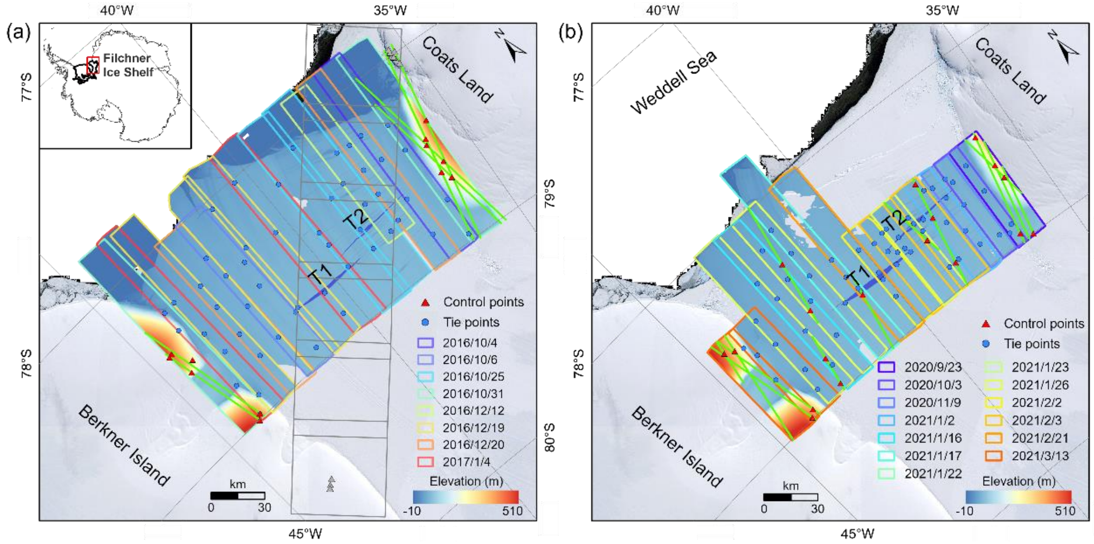


Figure 9: I would prefer to see these DEMs in 2D rather than 3D, as this 3D view does not allow for seeing the full depth of the rift. Secondly, I would consider adjusting the colorbar to make the ice shelf surface more visible without losing information from within the rift. Lastly, I miss a scale on 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:

Now we provide both 2D DEMs and 3D DEMs.

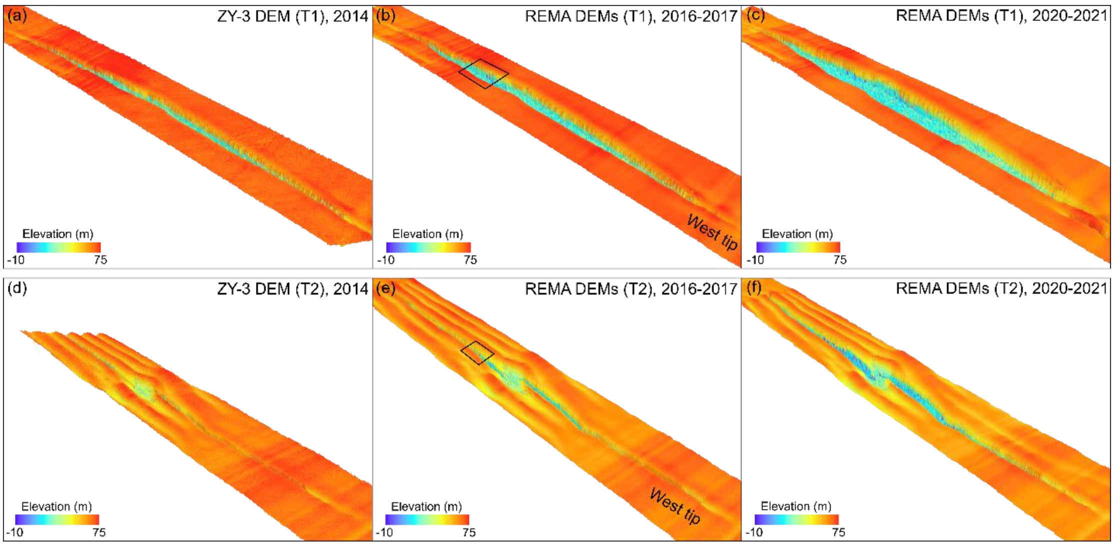


Figure 9. Multi-satellite DEM time series of two large rifts (T1 and T2) on Filchner Ice Shelf from 2014 to 2021 in 3D: (a) and (d) are reconstructed ZY-3 DEM of 2014, (b) and (e) are bias-corrected REMA DEMs of 2016-2017, and (c) and (f) are bias-corrected REMA DEMs of 2020-2021. The boxes in (b) and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

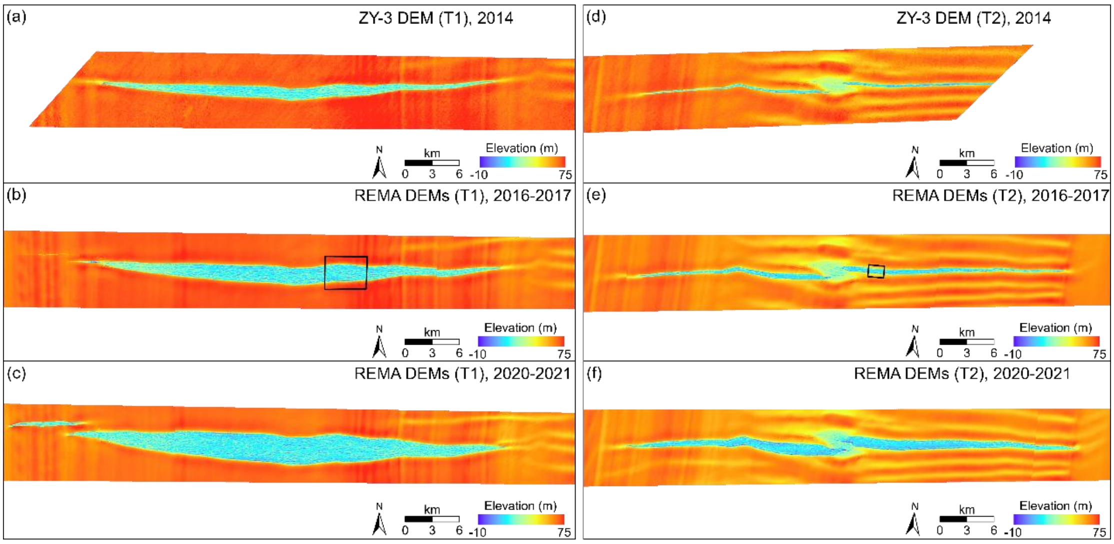
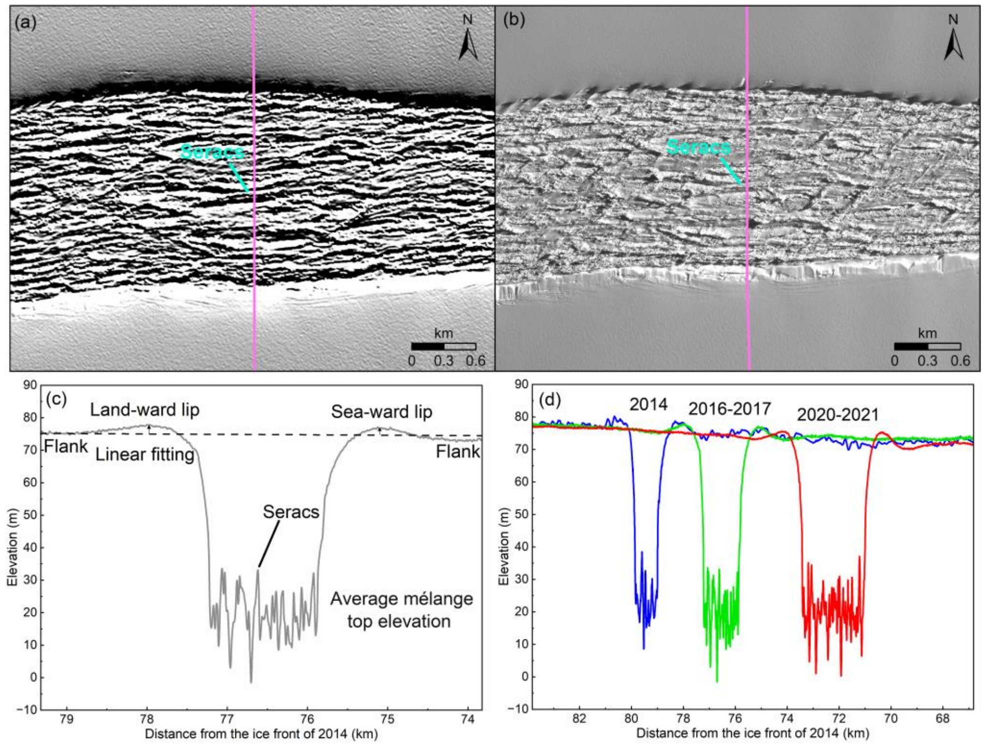


Figure A2. Multi-satellite DEM time series of the two large rifts (T1 and T2) on Filchner Ice Shelf from 2014 to 2021 in 2D: (a) and (d) are reconstructed ZY-3 DEM of 2014, (b) and (e) are bias-corrected REMA DEMs of 2016-2017, and (c) and (f) are bias-corrected REMA DEMs of 2020-2021. The boxes in (b) and (e) indicates two rift sections of the rift where details of 3D structure and mélange are presented in Fig. 10.

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.



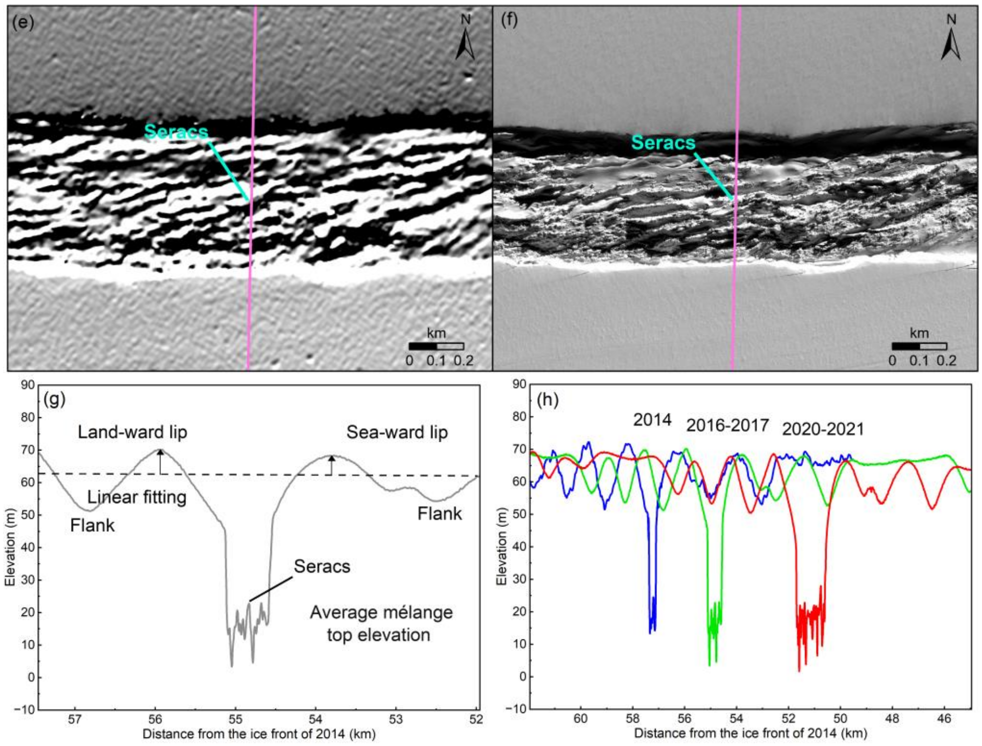


Figure 10. 3D sectional structure and mélange: (a) and (e) are sectional shaded relief maps of REMA DEMs of 2016-2017 (January 4, 2017 and October 25, 2016) indicated by the boxes in Fig. 9; (b) and (f) are WorldView images (0.5 m resolution) of February 25, 2016 and March 2, 2016; (c) and (g) are elevation profiles along the pink lines in (a) and (e), and 3D rift and mélange structure parameters; (d) and (h) are rift and mélange changes along the profiles from 2014 to 2021 (2014 in blue, 2016-2017 in green, and 2020-2021 in red). Elevation displayed in (a) and (e) are exaggerated by 10 times.

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.

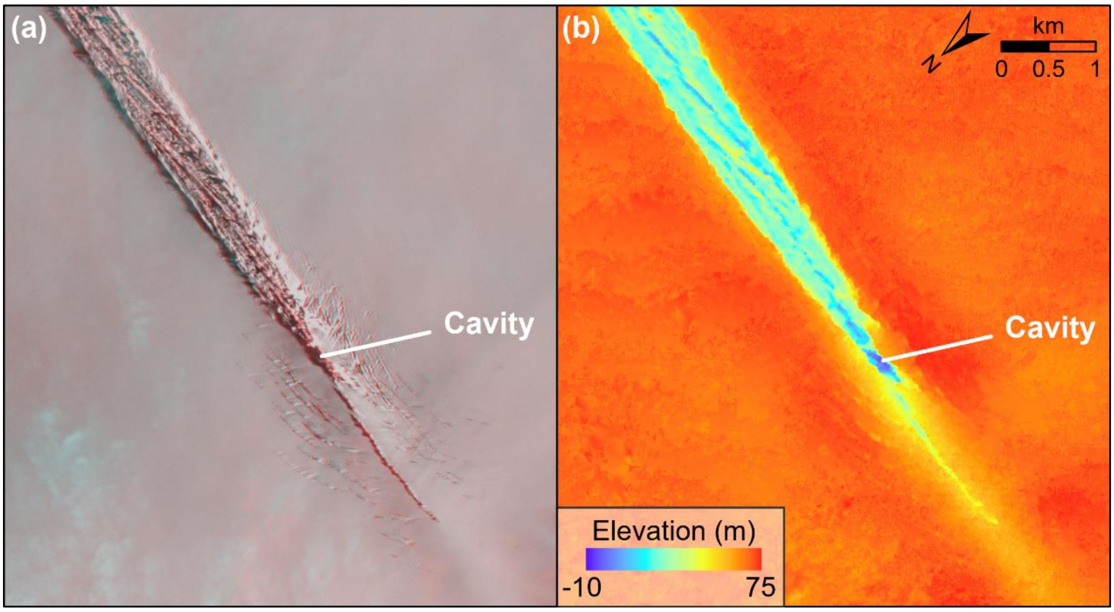


Figure A3. Anaglyph stereo pair of 2014 ZY-3 satellite images (a) and reconstructed ZY-3 DEM (b) showing cavities close to the west tip of rift T1.

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.

Referee #2

Dear Menglian Xia and co-authors,

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 Understanding variations in rift infill is crucial for assessing rift dynamics, which ultimately influence calving events. I commend the authors for their creative approach, thorough analysis, and well-designed, highly informative figures. Overall, I strongly believe this paper would be a valuable addition to the literature, and its scope and format make it well-suited for publication in The Cryosphere. Below, I provide a general comment along with more specific, line-by-line suggestions that I hope will further strengthen the manuscript.

GENERAL COMMENT:

I admit that DEM processing is not my direct area of expertise, but the logic of the technical part seems sound and appropriate for a reader, like me, who is not necessarily familiar with technicalities of DEM analysis. However, I believe this manuscript would benefit from a few improvements to enhance readability and impact. In some sections, the text becomes somewhat difficult to follow, partly due to the frequent use of acronyms and the listing of numbers with excessive significant figures. At times, this made it challenging to stay engaged with the flow of the manuscript. I recommend streamlining certain parts, as indicated in my line-by-line comments, to improve clarity and coherence.

Response:

Thanks for the suggestions. The manuscript is revised accordingly (see following responses).

More importantly, I find that this manuscript lacks a thorough discussion, a comparison with existing literature, and a clear background motivation. I was surprised to see that it does not include a dedicated discussion section, where I had expected to find these elements. To strengthen the manuscript's impact, I recommend contextualizing the observational results within the broader framework of rift monitoring and their implications for ice shelf and glacier dynamics, while also drawing comparisons with existing studies.

Response:

We addressed the issues in two parts.

1) We added substantial text in Introduction to give a clear background motivation, comparison with existing studies, and context to this study … (also see following responses)
2) We added a Discussion section to address the remaining points:

*"**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. We demonstrate the full 3D mapping capability of 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 and MacAyeal, 1998; Larour et al, 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 seawater 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 increase ice front calving and effect the ice shelf stability.

Although the iceberg calved from the shelf front in 1986 is mostly located inside the Passive Shelf Ice (PSI) 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. As warm water has recently been observed near Berkner Island (Davis et al., 2022), T1 *and T2 have the potential to trigger a larger calving beyond the PSI boundary, which may be caused by a destabilization mechanism like that proposed for the Larsen C Ice Shelf (Poinelli et al., 2023a and 2023b).”*

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:

We added the following text in the Discussion: “……*Although the iceberg calved from the shelf front in 1986 is mostly located inside the Passive Shelf Ice (PSI) 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. As warm water has recently been observed near Berkner Island (Davis et al., 2022), T1 and T2 have the potential to trigger a larger calving beyond the PSI boundary, which may be caused by a destabilization mechanism like that proposed for the Larsen C Ice Shelf (Poinelli et al., 2023a and 2023b).*” Also see the following figure.

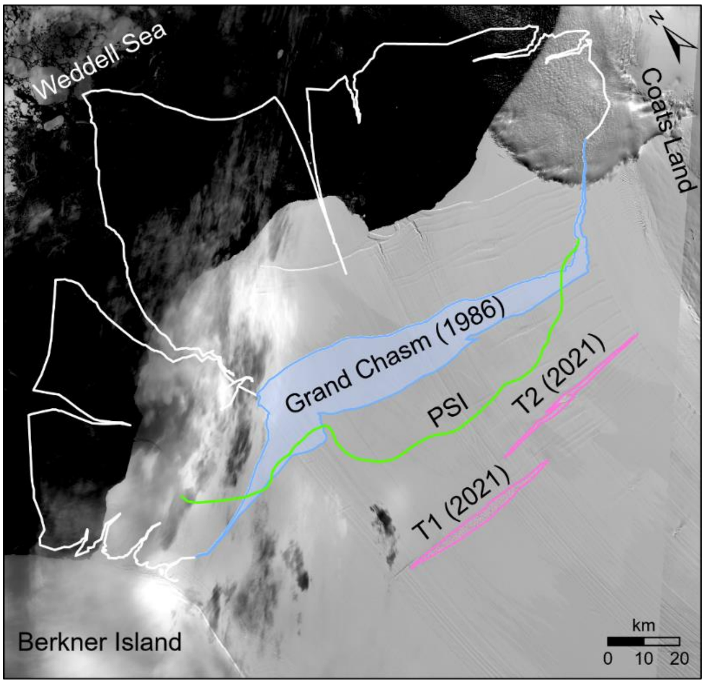


Figure A1. Rifts of T1 and T2 (pink) in 2021, Grand Chasm (blue) in 1986; PSI boundary (green) (Fürst et al., 2016); ice bergs calved in 1986 (white); background is a Landsat image of February 11, 2021.

This is, of course, a provocative question, and I fully agree with the authors that rifts play a critical role. 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 Larsen C and supported by theoretical work (Poinelli, 2023a,b). In the context of global warming, this is particularly relevant for FRIS, as warm water has recently been observed near Berkner Island (e.g., Davis, 2022). Such changes could ultimately lead to destabilization mechanisms like those proposed for Larsen C. I encourage the authors to incorporate these considerations to provide a stronger and more comprehensive discussion of their findings.

Response:

Thanks for suggestion. They are added into Discussion (see the response above).

In the introduction, there is a strong focus on technical studies related to altimetric and stereo mapping of rifts, but the broader scientific goal and the significance of this region of Antarctica seem underdeveloped. For a paper in The Cryosphere, I would expect a more robust scientific background that clearly establishes the relevance and utility of this work.

Response:

We added the following text in Introduction to address it.

"…… Furthermore, mélange (a mixture of shelf ice, snow, sea ice and water) changes related to ice shelf fracturing in Antarctica and glacier calving in Greenland are studied (Rignot and MacAyeal, 1998; Larour et al., 2004; Cassotto et al., 2021). Specifically, mélange thickness reduction is observed during rift widening on Amery Ice shelf, Ronne Ice Shelf and Larsen C Ice Shelf (Fricker et al., 2005; Walker et al., 2021; Larour et al., 2021). Modelling results indicate that mélange may have the capability of transmitting stresses across rift flanks and thus, influences rift propagation and shelf front calving (Larour et al., 2004 and 2021). However, there has been a lack of large-scale high-resolution observations of 3D rift structural changes and mélange dynamics in a sustained long period to support such a conclusion. This, in turn, hinders our understanding of the role of mélange in ice shelf retreating and the mechanism of ice shelf stability weakening."

"…… The validated MDAM is applied in the Filchner Ice Shelf to establish a cross-shelf DEM time series from 2014-2021. The Filchner Ice Shelf (Fig. 1a) is one of the dual ice shelves of Filchner-Ronne Ice Shelf that is the second largest in Antarctica. Berkner Island and Coats Land are located at western and eastern margins of the ice shelf, respectively. The largest calving event recorded for this ice shelf, with an area loss of 11500 km^2, occurred in 1986 due to a rapid propagation of a prominent rift known as "Grand Chasm" (Ferrigno and Gould, 1987), producing three giant icebergs that greatly impacted the circulation and hydrography in the nearby ice shelf-ocean system (Grosfeld et al., 2001) (Fig. A1). Recently, two large rifts, T1 and T2 (Fig. 3), are detected in a Landsat satellite image in 1996 and an ARGON satellite

image in 1963, respectively (Li et al., 2017a; Walker and Gardner, 2019; Lv et al., 2022). These rifts have a combined length of ~100 km and exhibit a similar propagation pattern as Grand Chasm……"

One crucial aspect that appears to be missing is the role of ice mélange variation in modulating rift dynamics. 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). This process is fundamental to understanding rift evolution and should be better integrated into the manuscript's scientific framing. I may have overlooked this point, and I apologize if it was addressed, but I encourage the authors to clarify and emphasize its importance.

Response:

We added this sentence in Introduction: "*Modelling results indicate that mélange may have the capability of transmitting stresses across rift flanks and thus, influences rift propagation and shelf front calving (Larour et al., 2004 and 2021).*"

We further added the following text specifically in Discussion, but also make a link to the "volume" change results from this study:

"

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 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 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 increase ice front calving and effect the ice shelf stability."

SPECIFIC COMMENTS

Line 13: The connection between calving and ice mélange is not clearly established in the manuscript. Why is the observed "significant gap" in mélange dynamics particularly relevant to calving processes? Ice mélange, when sufficiently thick, can bond rift flanks together, suppressing rift widening and propagation. Clarifying this link would strengthen the manuscript's argument and better highlight the importance of studying mélange dynamics in the context of ice shelf stability.

Response:

We added the following text in Introduction to clarify the link between mélange and calving: "*……Furthermore, mélange (a mixture of shelf ice, snow, sea ice and water) changes related to ice shelf fracturing in Antarctica and glacier calving in Greenland are studied (Rignot and MacAyeal, 1998; Larour et al., 2004; Cassotto et al., 2021). Specifically, mélange thickness reduction is observed during rift widening on Amery Ice shelf, Ronne Ice Shelf and Larsen C Ice Shelf (Fricker et al., 2005; Walker et al., 2021; Larour et al., 2021). Modelling results indicate that mélange may have the capability of transmitting stresses across rift flanks and thus, influences rift propagation and shelf front calving (Larour et al., 2004 and 2021). However, there has been a lack of large-scale high-resolution observations of 3D rift structural changes and mélange dynamics in a sustained long period to support such a conclusion. This, in turn, hinders our understanding of the role of mélange in ice shelf retreating and the mechanism of ice shelf stability weakening.*"

Line 20: Mélange volume expansion is directly correlated with rift widening, but its relevance in the context of ice sheet modeling is unclear. Can we speculate on causality—does mélange volume drive rift widening, or is it simply a byproduct? Since mélange volume necessarily increases as the rift widens due to greater exposure of open ocean to surface heat loss, a more informative parameter to monitor might be mélange thickness relative to ice shelf thickness. This ratio is crucial in determining how stress is transmitted between rift flanks (Larour, 2021).

Response:

Mélange thickness change is an important indicator. It is now reviewed in Introduction (see above response). We believe that volume is another important indicator that is related to both rift widening and supply of shelf ice to adjust the infill into the rift. We added how this process might occur in Discussion: "*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 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.*"

Line 29: This line is a bit confusing, mass discharge across the GL is the cause of sea level rise, but what does 'lost ice mass enters' mean?

Response:

We deleted the first half of the sentence. It is changed 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).*"

Line 39: Like my comment in the abstract, I don't fully see the link between calving and ice mélange? What does 'the importance … on studying mélange … are fully recognized' mean?

Response:

We changed this part of the section to strengthen the link: "*…… Furthermore, mélange (a mixture of shelf ice, snow, sea ice and water) changes related to ice shelf fracturing in Antarctica and glacier calving in Greenland are studied (Rignot and MacAyeal, 1998; Larour et al., 2004; Cassotto et al., 2021). Specifically, mélange thickness reduction is observed during rift widening on Amery Ice shelf, Ronne Ice Shelf and Larsen C Ice Shelf (Fricker et al., 2005; Walker et al., 2021; Larour et al., 2021). Modelling results indicate that mélange may have the capability of transmitting stresses across rift flanks and thus, influences rift propagation and shelf front calving (Larour et al., 2004 and 2021). However, there has been a lack of large-scale high-resolution observations of 3D rift structural changes and mélange dynamics in a sustained long period to support such a conclusion. This, in turn, hinders our understanding of the role of mélange in ice shelf retreating and the mechanism of ice shelf stability weakening.*"

Figure 1: Really nice figure.

Line 67: What do you mean with 'tie point'?

Response:

We added the text to refer it to the detailed TP description in Section 2.3: "*We introduce tie points (TPs, see detailed description in Section 2.3) ……*"

Line 76: This sentence is a bit confusing.

Response:

We revised the sentence to clarify the point: *"Finally, we demonstrate the observed mélange changes and estimated volumetric changes in relation to rift widening as the rifts advect toward the ice shelf front during the study period."*

Line 124: This is good example of the scientific motivation of this study. Perhaps this should be included in the introduction and not in methodology.

Response:

Yes, this part is now moved to Introduction.

Line 157,176: Acronyms in the title are hard to follow ad makes the reading experience confusing.

Response:

They are now spelled out in the titles.

Figure 8-9: Great figures! Congrats!

Line 264: I appreciate the precision in these values but is it necessary? This may be a question of personal preference, but I find it a bit confusing to follow these numbers. These details are also reported in Table A3 no? So why don't discuss the orders of magnitude of these changes?

Response:

We now keep the digits to meter for all numbers throughout the manuscript. We also give the orders of magnitude of these changes: "…… *we found that the rift T1 propagated consistently during the period, resulting in an accelerated widening by 647 m during 2014-2017 (44 %, 227 m* y^{-1}*) and 1,109 m during 2016-2021 (53 %, 268 m* y^{-1}*). Correspondingly, the rift has lengthened by 2,393 m during 2014-2017 (5%, 840 m* y^{-1}*), but only 1,082 m during 2016-2021 (2%, 262 m* y^{-1}*).*"

Here are data for both T1 and T2 and have been updated in the manuscript for T2:

	Time	Rift T1	Rift T2
Length (m)	2014	47132	48324
	2017	49525	50025
	2021	50608	51692
Lengthening (m & m/y)	2014-2017	2393 m (5%, 840 m/y)	1701 m (%4, 597 m/y)
	2016-2021	1083 m (2%, 262 m/y)	166 m (%3, 406 m/y)
Width (m)	2014	1457	1532
	2017	2103	1944
	2021	3212	2778
Widening (m & m/y)	2014-2017	647 m (44%, 226.95 m/y)	412 m (27%, 145 m/y)
	2016-2021	1109 m (53%, 268.36 m/y)	834 m (43%, 203 m/y)

Line 282: What is a 'cavity' in this context? Please specify.

Response:

We changed it to: "*……More specifically, we found cavities that are freshly opened during the fracturing process in the unmatured mélange section close to the west tip of T1 (Fig. 11a). These pre-mélange cavities are verified in ZY-3 stereo images and reconstructed ZY-3 DEM (Fig. A3) ……*"

Line 290: Volumetric change is a good parameter to monitor, but it would also be interesting to see an estimation of mélange thinning, which is relevant to ice sheet

modeling. The observed decreased in ice mélange elevation most likely means that this layer has thinned. This is extremely important as the stress propagation between flanks may be compromised (Larour 2004).

Response:

Here we added: "*The estimated change in mélange thickness H is relevant to ice sheet modeling. The observed mélange thinning may indicate that the stress propagation between flanks may be compromised (Larour et al., 2004).*"

Line 300: What do you mean with 'newly calved'? I may have missed this, but I thought the ice shelf has not calved during this period. Do you perhaps mean that the rift has widened due to partial collapse of its flanks? If so, can you speculate about what may have caused it? Mélange thinning may be the answer itself, and I agree that it is hard to point at a cause. Setting up a discussion on this would be very important.

Response:

We changed it to "…… *newly vacated space due to partial collapse of rift flank*".

We added a paragraph in Discussion to speculate its cause: "*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 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 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 increase ice front calving and effect the ice shelf stability.*"

Line 302: I was surprised to see that the manuscript does not include a discussion section. What are the strengths of this novel approach? How does this compare to previous studies that employed ICESat2? for example Walker 2021, Fricker 2005, …? Why is monitoring of these rifts important? Can you extend this novel processing techniques to other highly fractured areas of Antarctica (Larsen C, Totten, Brunt, Amery?)

Response:

We added a Discussion section to address these points:

*"**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. We demonstrate the full 3D mapping capability of 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 and MacAyeal, 1998; Larour et al., 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 seawater 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 increase ice front calving and effect the ice shelf stability.

Although the iceberg calved from the shelf front in 1986 is mostly located inside the Passive Shelf Ice (PSI) 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. As warm water has recently been observed near Berkner Island (Davis et al., 2022), T1 and T2 have the potential to trigger a larger calving beyond the PSI boundary, which may be caused by a destabilization mechanism like that proposed for the Larsen C Ice Shelf (Poinelli et al., 2023a and 2023b)."

Line 307: I may have missed it, but is there a similar analysis applicable to T2? The manuscript presents these rifts as a pair, yet the analysis appears to be restricted to T1, which seems inconsistent. To be clear, I am not suggesting additional analysis, but the rationale for focusing solely on T1 should be explicitly stated, even if it is due to data limitations.

Response:

As suggested also by Reviewer 1, we added corresponding analysis for T2 throughout the manuscript. The following are the revised figures and tables. The details have been revised in the manuscript.

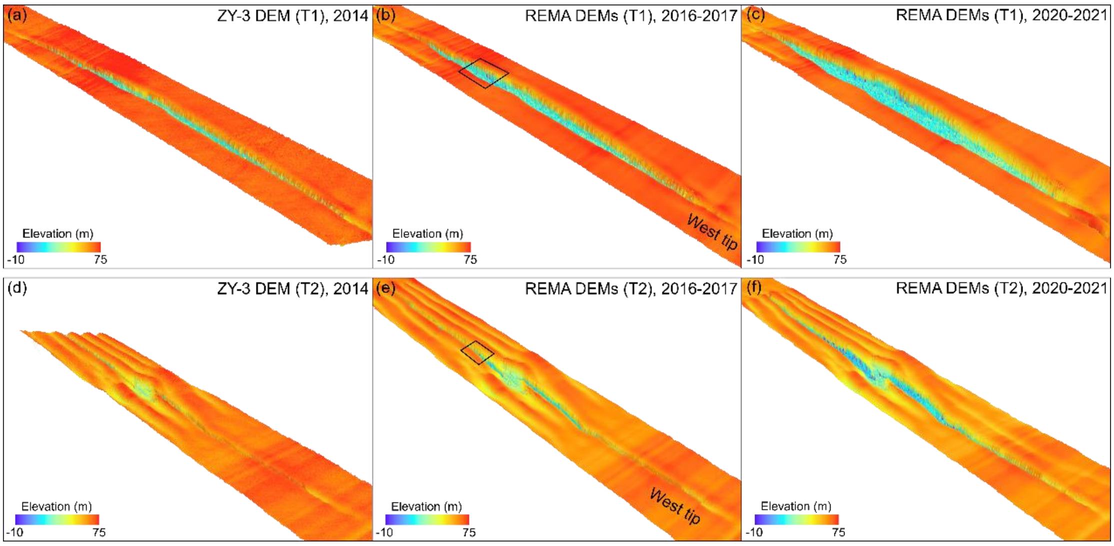
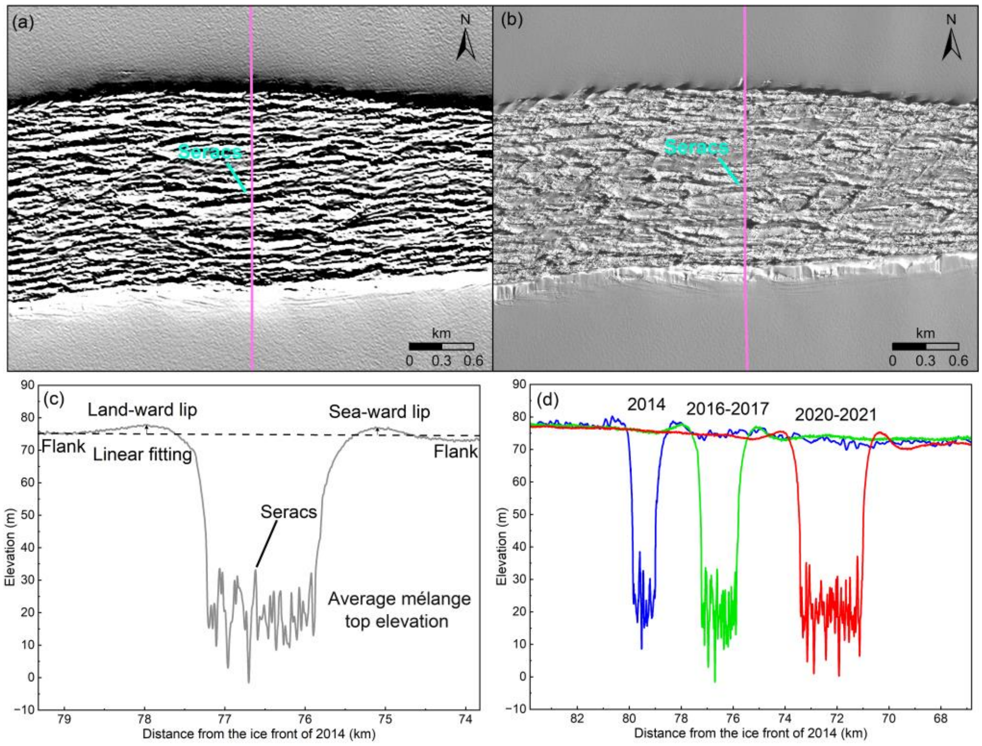


Figure 9. Multi-satellite DEM time series of the large rifts of T1 and T2 on Filchner Ice Shelf from 2014 to 2021: (a) and (d) reconstructed ZY-3 DEM of 2014, (b) and (e) bias-corrected REMA DEMs of 2016-2017, and (c) and (f) bias-corrected REMA DEMs of 2020-2021. The boxes in (b) and (e) indicate the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



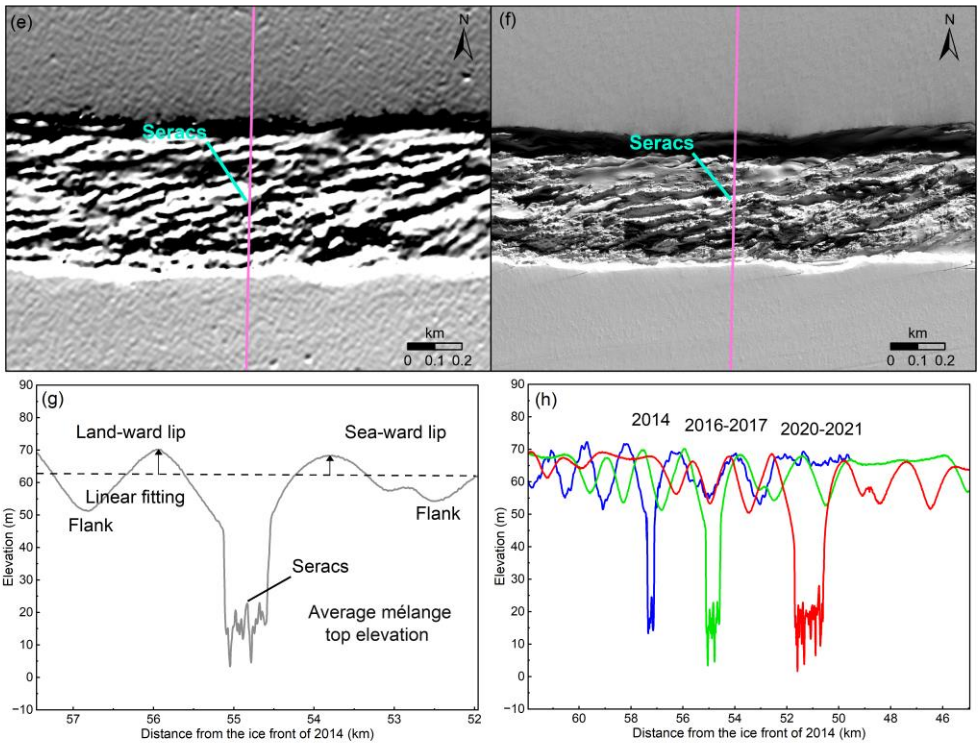


Figure 10. 3D sectional structure and mélange: (a) and (e) are sectional shaded relief maps of REMA DEMs of 2016-2017 (January 4, 2017 and October 25, 2016) indicated by the boxes in Fig. 9; (b) and (f) are WorldView images (0.5 m resolution) of February 25, 2016 and March 2, 2016; (c) and (g) are elevation profiles along the pink lines in (a) and (e), and 3D rift and mélange structure parameters; (d) and (h) are rift and mélange changes along the profiles from 2014 to 2021 (2014 in blue, 2016-2017 in green, and 2020-2021 in red). Elevation displayed in (a) and (e) are exaggerated by 10 times.

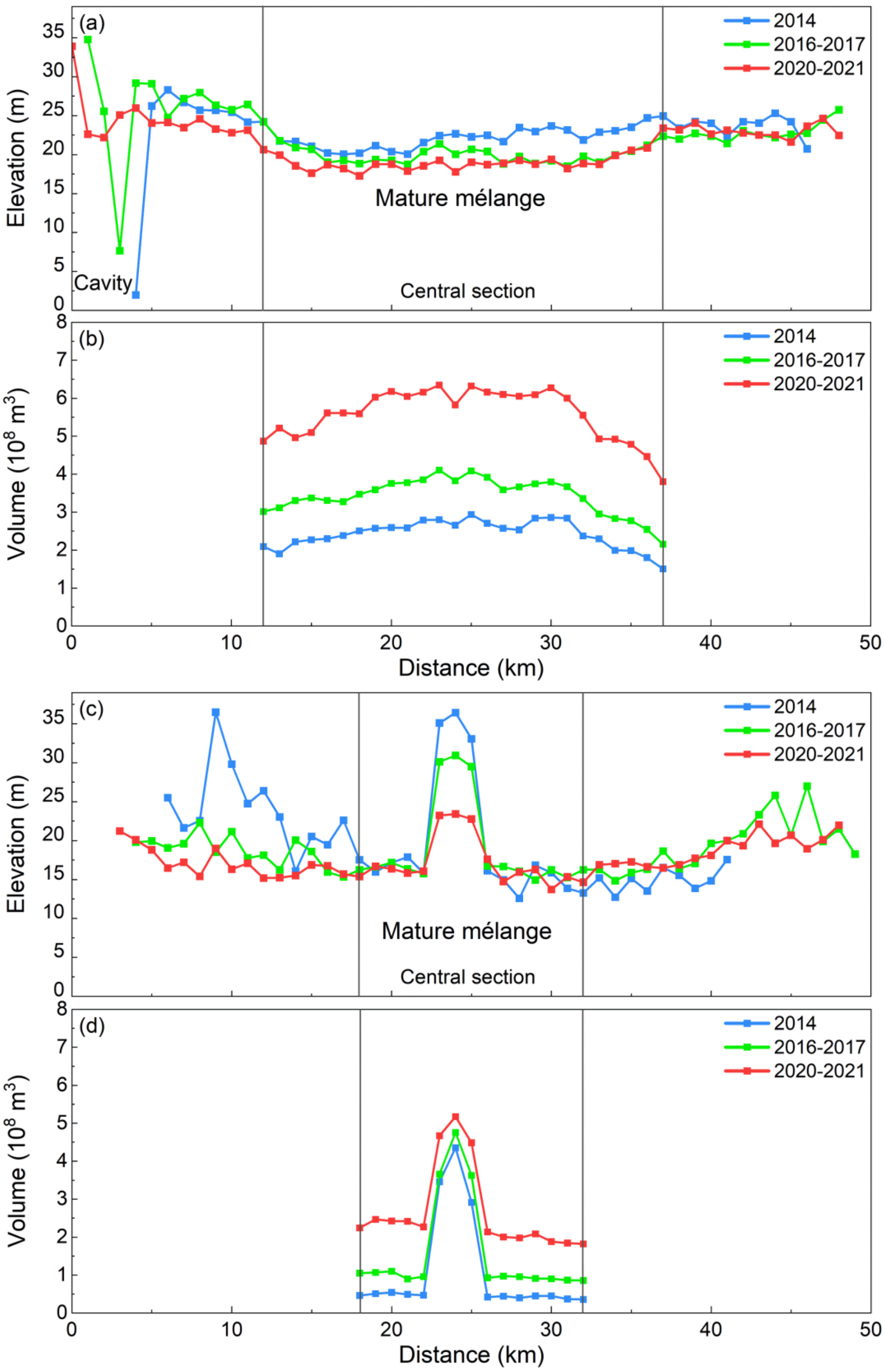


Figure 11. Thickness (a and c) and volume (b and d) of ice mélange inside the rifts T1 and T2, respectively, from the multi-satellite DEM series from 2014 to 2021. Average thickness and volume of each transect that are separated every 1 km along the rift centerlines are illustrated from west tip to east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

Table A3. Heights of rift lips measured on the land-ward (L) side and sea-ward (S) side, and their difference (S-L) at each transect along the centerlines of Rift T1 and T2 (REMA DEMs of 2016-2017).

Rift 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)
0	-1.7	0.5	2.2
1	3.6	4.5	1.0
2	2.7	4.7	2.0
3	0.8	1.7	0.9
4	4.4	1.5	-2.9
5	0.7	1.7	1.0
6	1.8	2.0	0.2
7	2.3	2.6	0.3
8	1.3	1.4	0.2
9	0.1	1.7	1.7
10	-1.6	1.8	3.4
11	-0.7	1.1	1.7
12	1.6	3.4	1.8
13	2.8	3.0	0.2
14	1.6	2.6	1.0
15	1.6	2.3	0.8
16	1.8	2.1	0.3
17	1.5	1.9	0.5
18	2.5	2.2	-0.3
19	1.6	1.9	0.2
20	1.9	1.8	-0.1
21	2.3	1.6	-0.7
22	2.0	1.4	-0.6
23	1.7	0.9	-0.7
24	1.7	1.0	-0.7
25	0.9	1.0	0.1
26	1.9	0.3	-1.6
27	1.0	0.1	-0.9
28	0.7	1.5	0.8
29	2.4	3.4	1.0
30	1.4	2.1	0.7
31	3.3	3.7	0.5
32	3.3	3.9	0.6
33	3.7	2.1	-1.6
34	3.7	4.8	1.1
35	2.0	1.9	0.0
36	0.4	1.2	0.8
37	-0.3	-2.3	-2.0

38	2.8	3.5	0.7
39	2.5	1.3	-1.2
40	2.4	1.7	-0.6
41	2.0	1.1	-0.9
42	0.8	1.5	0.7
43	2.6	2.6	0.0
44	4.6	4.2	-0.4
45	3.1	2.7	-0.5
46	-0.8	0.1	1.0
47	1.8	1.9	0.1
48	-1.4	-1.8	-0.4

Average lip height difference (s – l) within the section of mature mélange of T1: 0.1 m (max 1.8 m at 12 km from west tip).

Rift 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)
0	0.4	3.0	2.5
1	0.6	0.7	0.1
2	-0.1	1.6	1.7
3	2.1	3.0	0.9
4	4.5	4.9	0.4
5	2.3	2.9	0.7
6	2.0	0.8	-1.2
7	2.0	2.7	0.7
8	-2.2	-1.8	0.4
9	-2.6	-0.9	1.7
10	0.1	0.5	0.5
11	-0.7	0.1	0.8
12	0.9	1.2	0.3
13	0.3	-0.9	-1.3
14	-0.3	-3.2	-2.9
15	-0.3	-2.4	-2.2
16	0.3	-0.9	-1.3
17	0.2	1.2	0.9
18	0.1	3.2	3.0
19	-1.6	4.6	6.1
20	-11.5	1.4	-
21	-7.8	-11.5	-3.7
22	-2.8	3.0	5.9
23	0.6	2.7	2.2
24	1.2	3.6	2.5
25	0.7	-16.7	-

26	-18.6	-5.2	-
27	-0.3	-1.9	-1.6
28	2.5	0.0	-2.5
29	1.8	1.6	-0.1
30	1.1	1.1	0.1
31	1.2	1.1	-0.1
32	0.6	-0.1	-0.7
33	1.9	1.5	-0.4
34	3.3	2.1	-1.2
35	2.9	2.8	0.0
36	3.6	3.5	-0.1
37	4.7	4.4	-0.3
38	3.9	3.3	-0.6
39	4.3	3.5	-0.8
40	3.2	2.7	-0.6
41	3.0	2.0	-1.0
42	3.4	1.4	-2.0
43	3.6	1.7	-1.9
44	3.5	2.0	-1.5
45	3.5	1.7	-1.9
46	4.3	1.6	-2.7
47	5.3	1.7	-3.6
48	6.1	4.7	-1.4
49	5.0	6.2	1.2

Average lip height difference (s – l) within the section of mature mélange of T2: 0.2 m (max 5.9 m at 22 km from west tip).

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Response:

The above references are all cited in places, as suggested, in the manuscript.