Dear Reviewer,

After carefully reading both reviewers' comments, we conclude that they did not find any major weaknesses or flaws with our manuscript. Our analysis of the comments can be summarized as:

(i) adding four more years of data to the time series (R1) – this is the most significant change suggested, and was only a suggestion for us to consider. We respond to this below.

(ii) restructuring the m/s and further clarify some aspects of the methods (R2) – this is straightforward for us to do, and we are happy to do this.

In response to (i) from R1. We agree that a longer, more complete, record is always desired. However, we explained in our response why it is not a simple matter, as it involves many steps and careful integration of models. We feel that the request is reasonable but should not be considered as a condition for publication. We feel it is appropriate to point out that this paper has now been through a few rounds of revision (with other journals before this), every one of them being fairly slow. We believe that this is why the data now seem dated. Regardless, we believe the dataset in its present form is of high value to the community and will be well received upon publication.

We also must provide you with some context to explain the conditions under which we are working. The lead author Fernando Paolo left academic research in 2020 and does not have the time nor the funding to do additional data analysis. We note that our dataset represents a significant improvement over the only other time-dependent dataset of ice shelf basal melt rates (spanning a similar time interval) currently available to the community (Adusumilli et al. 2020), and that the dataset presented here is already being used in large modeling initiatives (e.g. Estimating the Circulation and Climate of the Ocean – ECCO, see below) and published research (Nakayama et al. 2001, GRL; Greene et al. 2022, Nature).

The melt rates presented here have been used in producing ECCO's latest estimate, Version 4 Release 5, available at https://ecco.jpl.nasa.gov/drive/files/Version4/Release5

REVIEWER #1 COMMENTS

Review of Paolo et al. 'Widespread slowdown in thinning rates of West Antarctic Ice Shelves'

Summary

This study presents a new dataset of ice shelf thickness change derived from satellite radar altimetry from 1993 to 2017. The authors use this dataset to investigate the temporal evolution of ice shelf thickness patterns in the Amundsen and Bellingshausen Sea sectors over the course of this 26 year record showing that thinning rates have recently abated.

This paper confirms previous findings that thinning of ice shelves in the Amundsen Sea sector has slowed down since 2008 (e.g Adusumilli et al., 2020), and allows for further investigation of temporal fluctuations in ice shelves thinning and basal melt rates owing to methodological improvements leading to a higher temporal resolution. **This paper is well-written and the methodology is clearly explained**. However, I have some comments and suggestions that would need to be addressed before this paper can be published.

Thank you so much for taking the time to review our paper. We appreciate the insightful comments and suggestions you provided. Your constructive criticism is highly valued. We also appreciate that you consider the manuscript to be well written, as we took a lot of time to ensure this was the case.

Main comments

- This study covers the years 1993 to 2017 but it might be worth considering extending this record further in time to cover the years 2018 to 2021 using the most recent CryoSat-2 baseline product (now in baseline E instead of baseline C), especially since Adusumilli et al. dataset (2020) covers the years 1994 to 2018. Adding more recent data would be a great addition to this paper and would add some interesting discussion on more recent changes in ice shelf thickness not published elsewhere. In addition, having an up-to-date dataset would be helpful to the scientific community.

We first note that the only other published dataset of basal melt rates is composed of a temporally-static (i.e. time averaged) map at 500 m resolution for the CryoSat-2 period only, accompanied by a low-resolution (10 km) time series, published by Adusumilli et al. (2020). The high-resolution map is a great dataset but does not provide information on the year-2-year variability. Our dataset is the first, and only, 26-year-long quarterly dataset published at 3 km grid posting (with an effective resolution between 3 and 5 km). This makes our dataset unprecedented relative to the current state of the art. We include a figure at the end of this document that shows the capability of our time evolving product.

That said, we fully agree with the reviewer that extending the ice shelf melt record would be a great and logical next step. The challenge is that it is not just a simple matter of tagging on a few more data points; there are many ancillary data and models that we also need to run to extend the time series, including: SMB, firn and surface velocities. This would mean new model runs, blending velocity data sets with inconsistent time spans and spatial coverage, etc. For the new Cryosat-2 data we would need to recompute the surface scattering correction and assess any differences compared to the previous data. We would also need to re-estimate the spatial covariances for the optimal interpolation. All this would require significant work that is in the pipe for the next iteration of the dataset. All of this is sensible to do, however we should be required to do this for the paper being presented. Given that the lead author is no-longer working in academic research, such an effort would likely delay important publication and sharing of this work by a year or more.

- **The methodological improvements implemented in this study are clearly explained in the manuscript**. However there is no quantitative statements in the paper describing how those improvements have led to a better/more robust dataset compared to previous work. For instance, does the surface scattering correction effectively removes the height changes induced solely by changes in the scattering properties? What are the improvements afforded by the modified plane fitting procedure implemented here?

The altimetry processing innovations we present are not the main focus of this paper, but they do represent a major methodological step change that makes previously invisible glaciological processes visible.

In the Quality Assessment section, we compare our results to Adusumilli et al. (2020), the only other existing large-scale time-variable (at low spatial resolution) melt rate product. We used a control-volume approach (entirely independent from the approach used in our analysis) to compare every ice-shelf estimate from both products. Our product shows significantly better statistics, with a variance of -0.2 ± 5.1 Gt/yr versus 1.4 ± 32.2 Gr/yr from Adusumilli et al. (2020), a 7-fold improvement. This is shown in Figure 10 in the manuscript, and we also include it at the end of this document.

We demonstrate the effect of our backscatter correction to the height records over Lake Vostok (Figure 1 in the manuscript), where GPS measurements are available confirming that it is a stable surface. Figure 1 shows clearly that our approach is successfully able to remove almost all backscatter-induced changes (compare with, for example, Zwally et al.'s (2015) Figure 7 [see below figure], where the authors of that paper were unable to fully correct for this effect over Lake Vostok). This is arguably the main limitation of radar altimetry over ice surfaces. As Paolo et al. (2016) showed, this effect can account for up to 80% of the height change signal over ice shelves. Here again we note that some state-of-the-art ice-shelf studies (e.g. Shepherd et al., 2018, Nature; Wouters et al. 2015, Science; Konrad et al. 2017, GRL) provide little to no information on how they have addressed this key problem over the ice shelves.

Our study

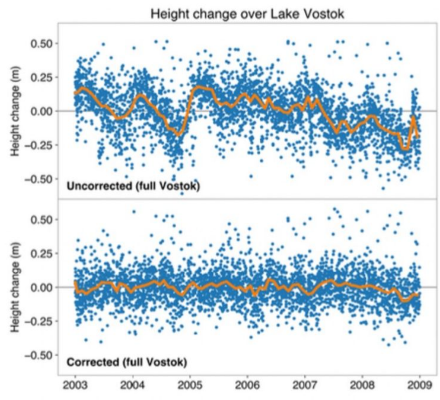

Figure 1: Multi-parameter radar scattering correction. (top) The different waveform parameters used to characterize the radar echo (where A is amplitude, N is the noise floor, and 'Range bins' are the discrete samples of the return signal). (bottom) Time series of individual point high measurements before and after applying the scattering correction. The example shows Lake Vostok where GPS records show no significant trend or variability in surface height.

Zwally et al, 2015

Zwally and others: Mass gains of the Antarctic ice sheet

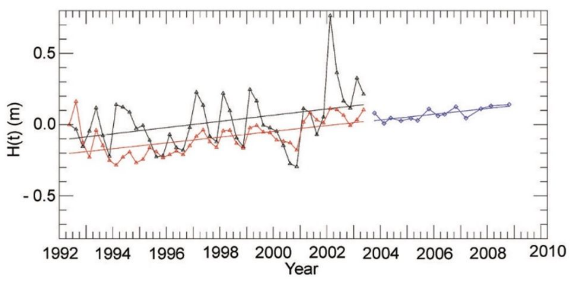

Fig. 7. *H*(*t*) time series on Vostok Subglacial Lake. From ERS 1992–2003 with trend of +2.03 cm a^{-1} after backscatter correction (red) and +2.18 cm a^{-1} before backscatter correction (black). From ICESat 2003–08 with trend of +2.02 cm a^{-1} (blue). The backscatter correction significantly reduces the amplitude of the seasonal variability in the ERS signal.

We also demonstrate that (a) there are clear spatial correlation scales for each quantity to be estimated (height, trend and acceleration; Figure 5 in the manuscript), and (b) there is an along-track pattern (artifacts) that originates from interpolating satellite data collected along tracks (Figure 6 in the manuscript). We show in Figure 6 a comparison for Ross Ice Shelf between neglecting and accounting for these correlation lengths in the data fusion approach. We feel strongly that the result speaks for itself. If, for example, we zoom in on the Adusumilli et al. (2020) melt product, we will notice these artifacts.

- The authors use the GEMB model to correct for firn air content. While the model is clearly explained in the paper, there is no validation of the model outputs. Has this model been used before in similar studies? Figure 3 shows the FAC volume change and SMB time-series from GEMB, GSFC FDM and IMAU FDM but this does not give enough information to the reader on how GEMB performs. It would be interesting to add a map of spatial differences between the three models as previous studies (e.g. Mottram et al. 2021) have shown that there are significant spatial differences between SMB models in Antarctica and while different models might agree on the total SMB, there might be some important biases regionally.

This is a good point and we believe this can be satisfied by directing the reviewer to a soon to be published GEMB model description and validation paper. Since submission of our original manuscript, the GEMB team has written and submitted a paper to Geoscientific Model Development (https://egusphere.copernicus.org/preprints/2022/egusphere-2022-674/). The paper is all but accepted with the last status update being that "The referees are satisfied with your revised manuscript. They have left a range of minor comments and technical corrections. Once you have addressed these, please submit your revisions. I plan to review them (for oversight) but not to send your paper back out to the referees." The GEMB manuscript provides model algorithm details and an exhaustive comparison between GEMB and RACMO SMB and between GEMB and IMAU-FDM firn models. In addition GEMB is a publicly available module of the official Ice Sheet System Model (ISSM) release so others are welcome to use the model in their research or to investigate the code in further detail. We will heavily modify the description of the SMB and firn model accordingly (mostly by reducing text) and provide proper citation to the new GEMB manuscript in the revised manuscript.

- The simple ice-ocean modelling experiment doesn't seem to bring much to the paper as the aim of this experiment is not very clear. In the abstract it is stated that this experiment will help test the resolution capability of the ice shelf thickness and basal melt rates datasets, but this is not discussed in the paper and there are no comparisons of observations and model results.

We agree with the reviewer that our simplistic modeling exercise does not enhance the ice shelf thinning/melting results we present. Unfortunately, observations of ocean properties relevant to ice shelf processes are sparse, making any conclusions about changes in ocean forcing difficult to demonstrate. We have been careful not to come to any major conclusions based on sparse oceanographic data, and instead we have simply asked how melt rates are expected to change as the ice shelves of the Amundsen Sea Embayment thin themselves into cooler, shallower waters. So we deliberately used a simple "sandbox" experiment to help answer this important question. In addition, since we tailored our ice-shelf thickness and basal melt rate products to the modeling community (these data are already being incorporated into large modeling initiatives such as the NASA Estimating the Circulation and Climate of the Ocean – ECCO), we wanted to test the level of detail in modeled basal melt changes that was possible using our dataset.

Specific comments

The ten comments below are all details of the methods and we plan to include every one of these details in the new Methods section:

1. L79-80: How and at what stage of the processing chain do you bring the ascending/descending data points together?

   During the optimal interpolation. Ascending/Descending are treated as independent datasets until the end.

2. L83-84: How many points are required to perform the bilinear/biquadratic fit? When do you pick one of the fits over the other?

   biquadratic < 30pts < bilinear < 15 < mean value < 5 < NaN

3. L85: What range radii are you using?

   This is simply stating that this approach allows the use of different search radii if needed.

4. L95: Please specify the range of your inversion cells size.

   8-15 km

5. L100-104: Is your buffer size sufficient to account for grounding line migration in areas that have significantly evolved over the course of these 26 years?

   We did the best we could with the GL information we have available. The caveats with GL migration are stated in the manuscript.

6. L143-146: What is the magnitude of the correction based on correlations with the waveform parameters? Is there one of the waveform parameters that exhibits a higher correlation or do all three parameters need to be used together?

   The details of this can be found in the dedicated literature, e.g. Paolo et al. 2016, Nilsson et al. 2022 and 2016. A multivariate fit takes care of collinearity between the variables.

7. L208: What are the seven densification methods available in GEMB?

   We will now refer to the (soon-to-be-published) GEMB paper for the technical description of the model. See comment on GEMB.

8. L251: Why using 5-month intervals? (It’s stated later in the paper, but as it is first mentioned here, it’d be best to add this justification here)

   Correct. It’s stated later. We will add it here.

9. L259: What's the average proportion of ice shelf area covered at each epoch before interpolation? L260: How many random locations do you use to calculate the empirical covariances?

   Coverage is homogeneous across ice shelves and fixed in time. We will add ice shelf surveyed areas in the revised manuscript. In the latest iteration of the dataset we used the full Ross Ice Shelf area worth of data (about 1/3 of all Antarctic ice shelf area). We will clarify.

10. L271: 'improved' compared to?

   To previous work? (Figure 10 in the manuscript compares our results with previous work. We also add the figure at the end of this document)

L281: 'varying in time in the Amundsen Sea sector' and what about the Bellingshausen Sea sector? At L289, you construct a velocity product for both the Amundsen and the Bellingshausen Sea sectors so it's a bit confusing whether you are also using a time-variable dataset for the Bellingshausen Sea sector.

We will clarify that we use time-varying velocity in the Amundsen and the Bellingshausen Sea sectors.

L282-284: There have been significant changes in ice flow in some basins of East Antarctica and in the Getz region as well. What's the time resolution of the ice velocity data used in the Amundsen Sea Sector? In recent years, annual velocity maps have been generated for the whole of the continent, can you use those annual maps to create a time-varying dataset for the whole of Antarctica for recent years?

This is a totally reasonable question. We do not yet use time-varying velocity in any region other than the Amundsen and the Bellingshausen Sea sectors. That said, Gardner et al. (2018) show that, for the period with satellite data, observed changes in surface velocity outside of these two regions are very small. We do not expect that the inclusion of more velocity data would change the results presented. If anything, the noise introduced by reduced time-averaging of velocity observations in areas with little to no changes in velocity could introduce more noise into estimates of melt rates. For these reasons we did not include time-varying velocities for other regions.

L289-290: Why do you combine those two products? Are they complementary, do they use different satellite datasets or use a different methodology or cover different areas?

Exactly, we synthesize multiple datasets to provide the best possible estimate of glacier surface velocity in a highly dynamic region of the ice sheet. The dataset of Mouginot et al. provides a long-localized record for the period 1973 to 2013 while the ITS_LIVE dataset provides pan Antarctic coverage for the period 2014 to 2018 (at time of submission). We will include this in Methods.

L391-392/L412-413: I suggest stating at the start of this section what variables you are computing for your comparison to Adusumilli et al. (2020) results as it will improve the clarity of this section.

Good suggestion, we will include this.

L411-413: Can you give the total volume control that you use? I suggest also adding the total ice shelf extent area and number of ice shelves that your dataset covers earlier in the paper (these values are given in Table 3 but are worth adding the main text)?

Good point, we will make sure to do this in the revision.

L435-437: Can you quantify this 'good agreement'? This sub-section, while explaining how the different parameters have been calculated to allow a comparison to Adusumilli et al., is missing a paragraph on the differences/similarities found between the two datasets. For instance, remarking that accounting for thickness changes leads to a better match for this study would be an interesting point to make and needs to be expanded in the text.

Thanks for the suggestion, we will include this in the revision.

L509: How many kilometres from the grounding line?

Seems like a valuable thing to include. We will address this in the revision.

Figure comments

1. Figure 1: Can you add a reference to this statement on the GPS record in the caption? Figure 6: Specify from what area this map shows.

   Thank you for catching that. we will add that in our resubmission

2. Figure 7 (right panel): Can you label the ice shelves directly on the map rather than by order of magnitude given in the caption?

   Yes, that makes more sense. We will do this in the revision.

3. Figure 8: What does the black line represent on in the inset map?

   Thanks for noticing that, it's a relic from an earlier iteration of the paper. We will remove that in the revision.

4. Figure 9: What is the acquisition date of the grounding lines shown? Can you perhaps change the brightness of the green velocity vectors as they are a bit difficult to discern on the map?

   We will include the date of the grounding line and modify the vectors in the revision.

5. Figure 11: As the mean values are plotted inside the error circles, it looks like the values refer to the error values and not the mean values. I suggest either increasing the font size to the size of the full circle (not just to fit the size of the inner error circle) or adding a mention on the figure directly (not just in the caption).

   If we increase the font size the darker outer band will make it difficult to see the numbers (see WIL for example).. We feel the best solution is to mention on figure directly. We will do this in the revised manuscript.

6. Figure 17: Can you add the same map of basal melt rates from your observations? Do the patterns of basal melt rates from observations in 1993 and 2017 look similar? It would be worth expanding on this in the main text as well to integrate the ice-ocean modelling experiment better with the rest of the paper.

   We see your point regarding the observations but in this case that wouldn't make a lot of sense as the figure is showing a theoretical model experiment with fixed ocean condition and modified ice shelf geometry. Here we are simply trying to demonstrate that changes in ice shelf geometry alone result in changes in basal melt rates, even in the absence of changes in ocean state.

7. Table 2: Can you add a column with the corresponding ice shelf areas over which the calculations have been made?

   Good suggestion, we'll add this in the resubmission.

Technical comments

All five of these typos will be fixed, thank you for catching them.

1. L233: missing word 'as a function of C' L243: typo 'plateau'
2. L258: remove superscript '28'
3. L290: remove '(' at the end of the sentence L348: 'comprises'
4. L415: remove 'where' L483: 'reflects'
5. L506: '4.' Remove '.'

Additional References

Greene, C.A., Gardner, A.S., Schlegel, NJ. *et al.* Antarctic calving loss rivals ice-shelf thinning. *Nature* 609, 948–953 (2022). https://doi.org/10.1038/s41586-022-05037-w

Nakayama Y., C.A. Greene, F.S. Paolo, et al. (2021), Antarctic Slope Current Modulates Ocean Heat Intrusions Towards Totten Glacier, Geophysical Research Letters, https://doi.org/10.1029/2021GL094149

Nilsson, J., Gardner, A. S., and Paolo, F. S.: Elevation change of the Antarctic Ice Sheet: 1985 to 2020, Earth Syst. Sci. Data, 14, 3573–3598 (2022), https://doi.org/10.5194/essd-14-3573-2022

Nilsson, J., Gardner, A., Sandberg Sørensen, L., and Forsberg, R.: Improved retrieval of land ice topography from CryoSat-2 data and its impact for volume-change estimation of the Greenland Ice Sheet, The Cryosphere, 10, 2953–2969 (2016), https://doi.org/10.5194/tc-10-2953-2016

Holland, P. W. and Welsch, R. E.: Robust regression using iteratively reweighted least-squares, Commun. Stat. – Theory Methods, 6, 813–827 (1977), https://doi.org/10.1080/03610927708827533

Zwally, H., Li, J., Robbins, J., Saba, J., Yi, D., & Brenner, A. Mass gains of the Antarctic ice sheet exceed losses. Journal of Glaciology, 61, 1019-1036 (2015), http://doi.org/10.3189/2015JoG15J071

Wouters, Bert & Martín-Español, Alba & Helm, Veit & Flament, Thomas & Wessem, J. M. & Ligtenberg, Stefan & Van den Broeke, Michiel & Bamber, Jonathan, Dynamic thinning of glaciers on the Southern Antarctic Peninsula. Science. 348. 899-903 (2015), https://doi.org/10.1126/science.aaa5727

Konrad, H., L. Gilbert, S. L. Cornford, A. Payne, A. Hogg, A. Muir, and A. Shepherd (2017), Uneven onset and pace of ice-dynamical imbalance in the Amundsen Sea Embayment, West Antarctica, Geophys. Res. Lett., 44, 910–918 (2017), https://doi.org/10.1002/2016GL070733

Paolo, F.S., Fricker H.A., Padman L., Constructing improved decadal records of Antarctic ice shelf height change from multiple satellite radar altimeters, Remote Sensing of Environment, Volume 177, 192-205 (2016), https://doi.org/10.1016/j.rse.2016.01.026

Paolo, F.S., Padman, L., Fricker, H.A. et al. Response of Pacific-sector Antarctic ice shelves to the El Niño/Southern Oscillation. Nature Geosci 11, 121–126 (2018). https://doi.org/10.1038/s41561-017-0033-0

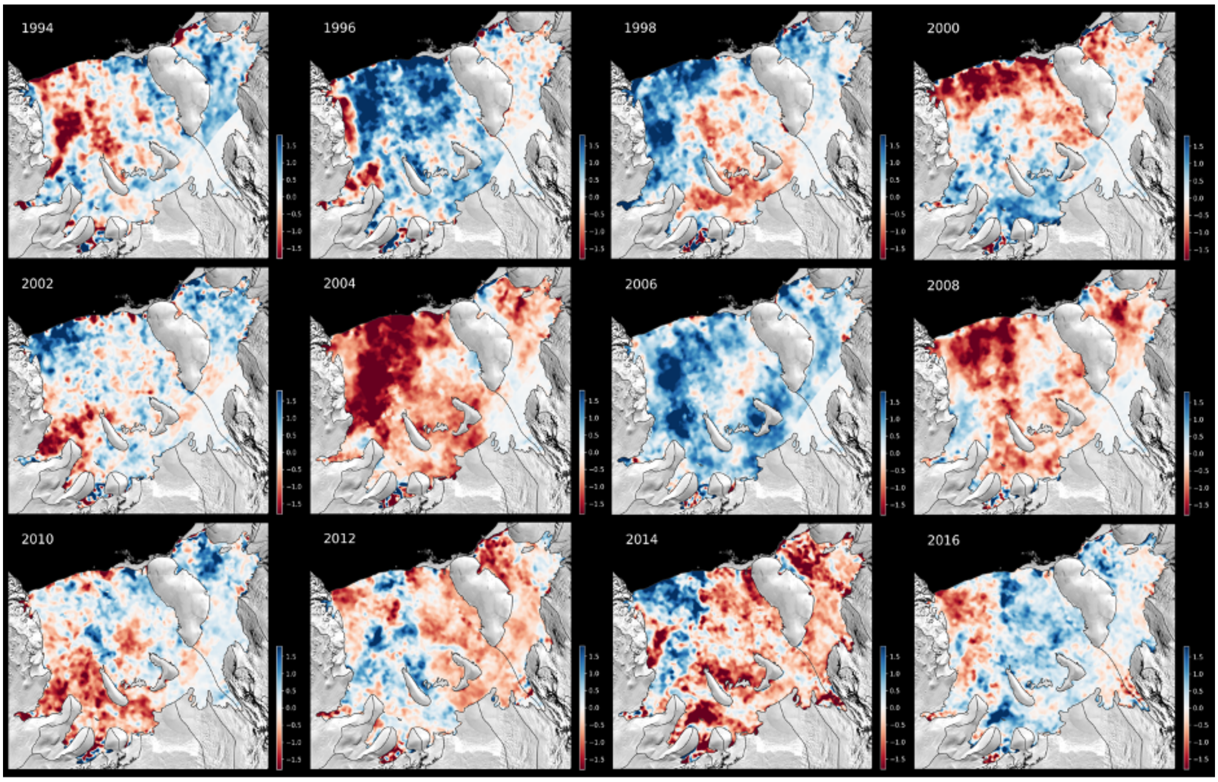

Figure 1: Example of our high-resolution time-variable basal melt rates. Melt anomalies (in meters of ice per year) with respect to the 26-year mean (1992-2017), where red is faster-than-normal melting and blue is slower-than-normal melting. Note the rapid change in basal melt patterns at interannual timescales. Also note that coherent melt structures form in different parts of the ice shelf at different epochs. Example is the Filchner-Ronne ice shelf in Antarctica. This temporal mapping of basal melt rates is only possible due to a consistent 3-km grid posting from 1992 to 2017 at 3-month timesteps. This is also what allowed us to estimate with high confidence the second derivative (acceleration/deceleration) of the thickness and melt records.

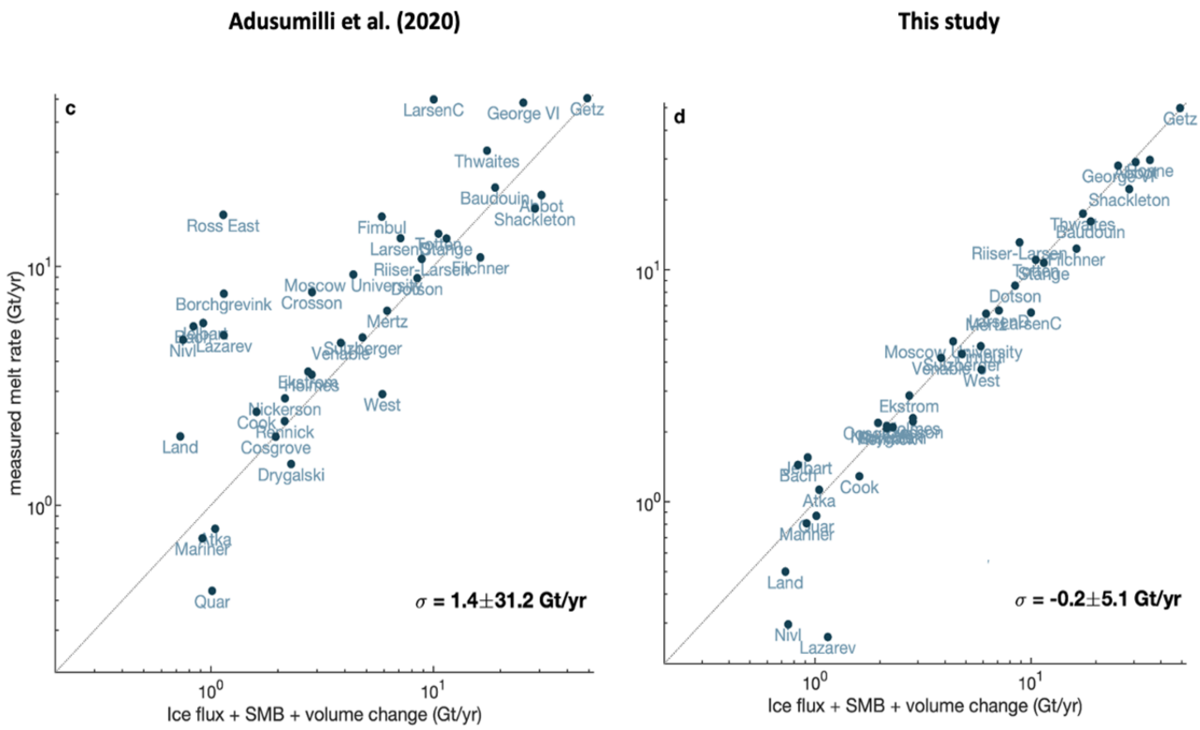

Figure 2: Comparison of melt estimates from this study with previous work. Comparison of (left) Adusumilli et al. (2020) and (right) this study's ice shelf basal melt estimates against a control-volume calculation of ice shelf mass change (gray line). The control volume is based on the input and output fluxes across the grounding line and ice front, i.e. ice loss due to anomalies in basal melt. For this comparison, we only considered grid cells that are at least 90% hydrostatically compensated (near fully floating).