Response to reviewer comments for the article "Antarctic Ice Sheet grounding line discharge from 1996 through 2023"

Overview of changes

We would like to thank the reviewers and editor for their time and effort in reviewing our manuscript.

In response to the comments, we have:

(1) Included an estimate of mass change using our discharge estimate and compared it to an independent time-series (IMBIE3; Otosaka et al., 2023).
(2) Compared our modified bed topography (FrankenBedAdj) to the existing bed products, to illustrate the pattern and magnitude of thickness changes required to reproduce observed rates of mass change.
(3) Modified our approach for accounting for SMB-induced mass changes between the gate and the grounding line.

In addition, we have made some additional improvements to the algorithm, detailed below, and updated the time-series through January 2024.

Below, we have reproduced the comments from both reviewers in black with our response in blue. We have also appended a copy of the manuscript with the proposed changes.

<u>Responses to comments from Reviewer #1</u>

Reviewer 1: This manuscript presents a 1996-present record of Antarctic-wide ice discharge at monthly resolution and finds that grounding line discharge increased by about 10% between 1996 and September 2023 (2205 Gt), mostly due to increasing flow speeds in West Antarctica. Several velocity and DEM products, at varying spatial and temporal coverage, are combined and iteratively gap-filled to create full reference maps. DEMs are differenced with multiple single (BedMap2, BedMachine v2) and hybridized ("FrankenBed") bathymetry datasets to compare the range of ice thickness estimates and net impact on ice discharge volume. In addition, a fourth reference bed, termed "FrankenBedAdj" represents the adjusted topography necessary to yield discharge volume changes compatible with altimetry-derived mass losses, when correcting for SMB. Grounding line discharge is calculated for a large variety of input variables, including bathymetry, as described above, multiple (2) firn compaction models, and flux gate location (16 equally spaced gate options plus the gate-average, for a total of 136 variations of ice discharge per drainage basin.

Overall, this is an interesting and both well written and executed study. The methods presented are robust and thorough – and the authors account for a variety of inputs and uncertainties to yield a comprehensive overview of grounding line discharge and its sensitivity to modeled + observational data and methods used. The manuscript will be valuable to the community and is thus deserving of publication in ESSD with minor revisions. However, I have also included suggestions for justification on several approaches, and a request to strongly consider a first order comparison to GRACE. Given the range in net discharge values discussed under various conditions in the manuscript, and regional discrepancies between these and previously published estimates, a comparison to gravimetry would provide valuable context for assessing sources of remaining error and uncertainty. My substantial comments are listed first, followed by minor comments and suggestions.

We would like to thank the reviewer for their detailed and constructive comments on the manuscript. It is refreshing to receive a review that clearly shows a thorough and careful reading of the submitted manuscript, where the language is collegial and the comments constructive. We have endeavoured to respond in kind to each of the reviewer's major and minor comments below.

Reviewer 1: I would encourage the authors to provide useful context by comparing large basin mass balance estimates to GRACE. Given that a multi-model SMB average has already been incorporated into the study, combining these data with discharge for a mass balance time series for comparison to GRACE seems feasible and important. Offsets between GRACE/Input-Output time series, and their differences with respect to mass loss magnitude, long term trends, and seasonality would be valuable for better understanding sources of uncertainty and uncertainty in bed topography.

On submitting the manuscript, it was our intention to produce a follow-up paper and dataset providing mass balance estimates using this discharge dataset along with comparisons to independent estimates of mass change. In the revised manuscript, we have included a time-series of mass balance using our inverse error-weighted mean discharge for each bed topography dataset for Antarctica, West Antarctica, East Antarctica and the Peninsula. We have included a new figure (Figure 14) summarising those mass change time-series, including a comparison to the latest IMBIE dataset (Otosaka et al., 2023). We have also revised our discussion section "implications for mass balance" accordingly, focusing more on the differences in implied mass change between bed products in each region, and how each mass budget approach is expected to perform in each region. We think that goes some way to (1) providing another means to evaluate the quality our discharge dataset; and (2) allows some initial speculation about the sources of uncertainty in mass change estimates, as discussed in the revised text. We maintain however, that a thorough evaluation of the performance of each mass budget approach and improvements to measurements of mass change, will require closer examination of the uncertainties in each approach at smaller spatial scales than considered here. We think that doing so would go far beyond what is reasonable to include in this paper and would require a full manuscript to achieve.

Otosaka, I. N., Shepherd, A., Ivins, E. R., Schlegel, N.-J., Amory, C., van den Broeke, M. R., Horwath, M., Joughin, I., King, M. D., Krinner, G., Nowicki, S., Payne, A. J., Rignot, E., Scambos, T., Simon, K. M., Smith, B. E., Sørensen, L. S., Velicogna, I., Whitehouse, P. L., A, G., Agosta, C., Ahlstrøm, A. P., Blazquez, A., Colgan, W., Engdahl, M. E., Fettweis, X., Forsberg, R., Gallée, H., Gardner, A., Gilbert, L., Gourmelen, N., Groh, A., Gunter, B. C., Harig, C., Helm, V., Khan, S. A., Kittel, C., Konrad, H., Langen, P. L., Lecavalier, B. S., Liang, C.-C., Loomis, B. D., McMillan, M., Melini, D., Mernild, S. H., Mottram, R., Mouginot, J., Nilsson, J., Noël, B., Pattle, M. E., Peltier, W. R., Pie, N., Roca, M., Sasgen, I., Save, H. V., Seo, K.-W., Scheuchl, B., Schrama, E. J. O., Schröder, L., Simonsen, S. B., Slater, T., Spada, G., Sutterley, T. C., Vishwakarma, B. D., van Wessem, J. M., Wiese, D., van der Wal, W., and Wouters, B.: Mass balance of the Greenland and Antarctic ice sheets from 1992 to 2020, Earth Syst. Sci. Data, 15, 1597–1616, https://doi.org/10.5194/essd-15-1597-2023, 2023.

Reviewer 1: Section 2.5: Thickness change between flux gates and grounding line.
Please add more detail on this section. For example, on line 180:

"For each gate pixel where ice flow is greater than 100 m/yr we calculate the number of years of ice flow between each flux gate pixel and the MEaSUREs grounding line (Mouginot et al., 2017c), to convert this rate of thickness change to a total thickness change."

Is the climatological SMB mean taken at the initial flux gate location, or an integrated average between the gate and MEaSUREs grounding line? Similarly, how is time of ice flow between gate and grounding line calculated? Lastly, is this correction applied to the mean gate, or each of the 16 gates?

I also struggle to understand the choice to compute the SMB-corrected ice thickness to better represent grounding line flux, but not also use the velocities at the grounding line. I may have misinterpreted the text, but the flux gates are placed three years of flow distance away from the grounding line, iterated every 0.1 years to account for variable velocity along the migration path. This implies that the velocity is different at the grounding line than at the most seaward flux gate. Why not use this velocity along with the corrected grounding line thickness to calculate grounding line discharge?

The last paragraph of the reviewer's comment made us question our choice here. On reflection, this was not the correct approach because, as the reviewer recognised, it produced something resembling the thickness at the grounding line but still used velocity from upstream. We have modified this approach so that we retain the thickness and velocity from upstream (after accounting for local changes in firn air content and ice surface elevation), but remove SMB-induced mass changes that occur between the gate and the grounding line. We do this by integrating RACMO2.3p2 SMB in the area between the gate and the grounding line for each basin. Since SMB is generally positive, this approach generally increases grounding line discharge. For Antarctica, it increases discharge by 64 Gt/yr on average compared to an approach that does not account for any SMB-induced mass change in that region. This approach also reduces the inter-gate differences between grounding line discharge to less than 1% for Antarctica as a whole (though this increases to at most 4.5 % at the highest elevation gates the Peninsula where the regional climate models struggle with the steep topography).

Reviewer 1: Figure 10. This figure is really interesting, and Line 328 of the manuscript notes that "The differences between flux gates primarily reflects the difficulty in conserving mass with imperfect ice thickness, velocity, and surface mass balance data, rather than algorithmic errors."

Do the values shown in Figure 10 reflect the location effect on discharge before or after the thickness adjustments (from surface processes, etc.) are applied? If the former, do these thickness adjustments account for the range in values seen across gates?

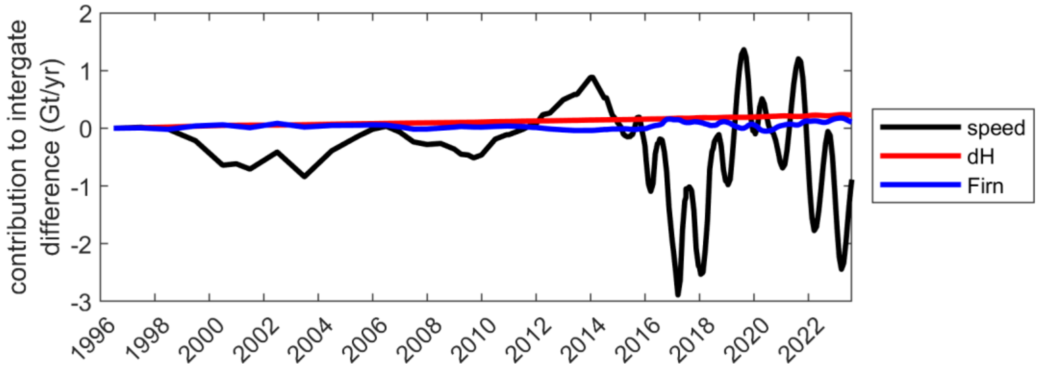
One recommendation is to apply the same methods discussed in Section 2.5 to the most inland gate, and compare to observed elevations at the downstream gate at the calculated between-gate flow time later. The difference between observed and calculated ice thickness change would provide uncertainty for the ice thickness adjustments discussed in Section 3.4.

Lastly, can you provide some discussion on the source of the seasonal "dimming" of inter-gate variability at the Peninsula (Figure 10, panel d). White patches reflecting similar discharge values across all gate locations seem to coincide with seasonal acceleration in ice flow (from Figure 9). However, the source of these patches prior to the availability of seasonally resolved dynamics (such as in 2006 through 2014) is unclear.

That description was quite brief and, somewhat embarrassingly, there clearly was an algorithmic error (or at least a poor choice of algorithm), which we have modified in the revised version. With this new approach to accounting for SMB, I don't think it would be informative to compare the thickness between gates – or at least we wouldn't expect them to match with this new algorithm.

The seasonal dimming in Figure 10 is an interesting observation. We looked at the individual components of inter-gate differences due to (1) changes in surface elevation, (2) changes in firn air content and, (3) changes in ice velocity. We have included a simple figure summarising that for the Antarctic Peninsula along one of the gates with large seasonality in the inter-gate difference (the most upstream gate). This shows (as expected) that changes in ice speed is the source of inter-gate differences in discharge. The integrate differences are generally greater in austral winter than in austral summer, within a hydrological year. We think this could reflect the greater reliance on interpolated, and therefore more stable velocities, in summer.

Regarding the apparent seasonality to the inter-gate differences in discharge prior to the availability of seasonal velocity data. This stemmed from the ~6-month offset between the annual measurements from ITS_LIVE and MEaSUREs, which differ slightly. In the revised manuscript, we have improved the alignment of velocity estimates, which reduces this apparent seasonality to the inter-gate differences in discharge.



Reviewer 1: On FrankenBedAdj. On deriving an adjusted bed topography by "proportionally adjust(ing) the pixel-based ice thickness based on the difference between our calculated basin"

First, if this is an iterative process, what is the precision or threshold value used to determine satisfactory agreement? Second, does "proportionally" imply that every pixel is adjusted by the same +/- %? In instances where ice streams rest on deep troughs, this type of correction would tend to increase the cross-flow gradient in bed slope. Does the type of cross-flow pattern in bed shape calculated from the FrankenBedAdj appear realistic, given available direct observations from ice penetrating radar? It would be useful to see how these adjustments (along with the other three bathymetry estimates) compare at several select sites where direct observations of the bed are available. If FrankenBedAdj performs poorly at these locations compared to the other models, that would suggest the error likely lies in SMB/firn models.

Thanks for pointing out the typo here. This is indeed an iterative process and we used a threshold of 0.1 % of the discharge implied from SMB and mass balance. Note that we now perform this adjustment on the scale of the MEaSUREs regional basins, rather than the MEaSUREs glacier basins, because some of the latter are small compared to the resolution of the elevation change and SMB datasets.

Regarding the proportional modification of each flux gate pixel: yes, each pixel within the basin is modified by the same percent as others within the basin and the reviewer is correct that in some places this increases the cross-flow gradient in bed slope. Equally, in places where the bed elevation needs to increase on average, it decreases the cross-flow gradient in bed slope.

In the revised manuscript, we have included some example profiles of the resulting bed topography, with comparison to BedMachine and BedMap2. Given that BedMachine passes through the observed bed topography and that FrankenBedAdj is not intended to reflect the true topography, we don't think it would be beneficial to compare it with radar flight line data. All it would show is that FrankenBedAdj is different from the observations where they were incorporated from BedMachine, and that FrankenBedAdj and BedMachine differ where there are no observations. It would be fruitful to compare BedMachine to new bed elevation observations that have been collected since it was created, but we think that is tangential to the purpose of this study and will likely be addressed in part by the release of the BedMap3 gridded dataset (which we hope to incorporate into this discharge dataset).

Reviewer 1 – minor comments

Line 159: "For gate pixels with no data at any time and more than 300 m from neighbouring finite pixels (after outlier removal), we use our reference ice velocity estimate which has no gaps by definition."

What percentage of flux gate pixels fall into this category?

Between 0.09 and 0.16 % of flux gate pixels in the latest update. The areas that typically require filling are in very slow-flowing parts of the Peninsula near the coast, that are either unresolved, masked out or have poor velocity retrieval due to contamination with sea-ice (for example), and in the southernmost parts of the Ross Ice Shelf, which aren't surveyed by Sentinel-1. I've included a figure below to highlight them (in red) for our most upstream flux gate.

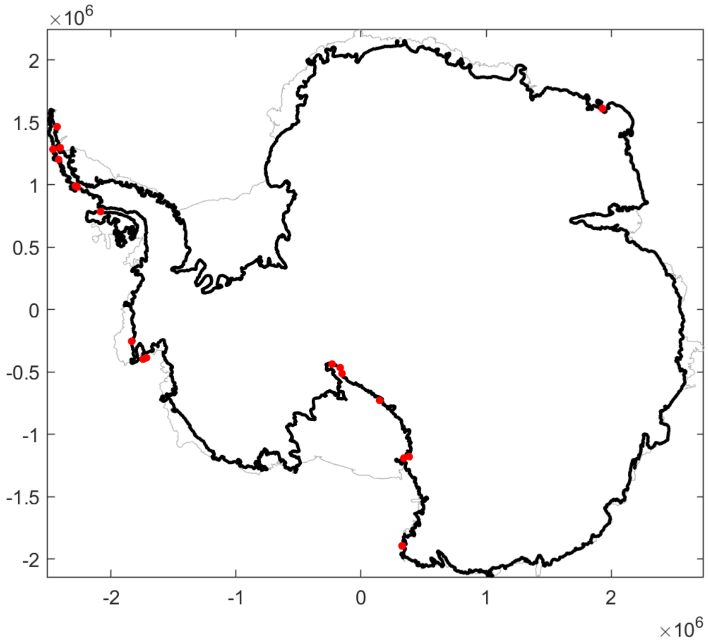


Figure 9. Consider using larger markers for FrankenBed for panel (b) to avoid other lines completely obscuring the time series. I am also confused by the caption text “Note that FrankenBed and BedMachine are identical for all displayed basins except West.” However, basin “Dryg” also indicates BedMachine (green) deviation from FrankenBed. How, if the beds are identical, do we see some divergence in the black and green time series in East Antarctica, panel c?

We have increased the size of the markers for FrankenBed in this figure as suggested. The note in the text is a mistake. Drygalski Glacier uses the Huss and Farinotti bed topography dataset in FrankenBed, so does differ from BedMachine here as the reviewer points out.

<u>Responses to comments from Reviewer #2</u>

Reviewer 2: The authors use a combination of datasets to estimate the grounding line discharge of Antarctica from 1996 to 2023. This is an extraordinarily complex problem because of the heterogeneities of the datasets, uncertainties in ice thickness, elevation changes, correction for thickness, location of flux gates, etc. and how error propagate to that chain, which means in practice that a blind approach to the problem is likely to fail to identify errors and/or their cause. Identifying local uncertainties is especially relevant to focus future observations.

Overall the study is well written, the details of the methodology are properly explained and relatively well thought through, including correction for polar stereo distance, but it is not clear that the mixing various models of unknown performance levels necessary yields a more reliable estimate of errors since model performance is not included in the weighting of the different inputs. The authors also offer no analysis of the changes in ice flux from their approach compared to other methods, so it is unclear where the differences are and what is their cause. As a general guideline for science, when updates of prior results are presented, it is a valuable exercise to compare with prior work, identify the differences, their impacts, and their sources. In this regard, the paper is lacking details. While I am not asking the authors to fill that void (that's their decision in the end), this gap will make it challenging to incorporate it in broader assessments which generally try hard to understand those details in order to generate further advances.

I have a few major comments and even fewer minor comments:

We are grateful to the reviewer for taking the time to review the manuscript. We are gratified that the reviewer found the manuscript well-written and the details of the methodology well-explained. We would like to state clearly here that we found it difficult to parse some of the reviewers concerns about the manuscript or to determine what change they would have liked to see in order to address their concerns. The reviewer appears to be concerned about our propagation of errors and the use of multiple datasets (or use of datasets that are themselves comprised of measurements from multiple types of sensor), but these concerns often make vague references to 'models' and 'errors' with providing any specific explanation of which aspects were unsatisfactory or made no recommendation for improvement. In these cases, we have attempted to determine the specific concern of the reviewer and have described in more detail the error components and their contribution to grounding line discharge, which in all cases were very small. Some of the reviewer's comments appear to reflect a misunderstanding of our methodology, so we have endeavoured to clarify the wording of our manuscript in those places. The reviewer also appears to be simultaneously concerned that we have not provided any comparison with prior work and that our comparison with prior work is too short. We have devoted a sub-section of the discussion to compare with every available Antarctic-wide grounding line discharge dataset that we are aware of and which we could access the data for (two of these were not downloadable and had to be digitised), which is substantially more comparison than any of those datasets provided. We think that comparison is thorough – there are comparisons for every basin provided by those other datasets, and clear quantification and visualisation of the spatial and temporal patterns to differences between those datasets and ours. Without access to the discharge components of the other datasets, we do not think that further comparisons would be fruitful.

Major comments

Reviewer 2: The Frankbed is essentially BedMachine v2 (BedMachine v3.7 is available, would be good to update the study with it). Huss and Farinotti (2014) is a (relatively old) model-based thickness, with unknown skills, because there are very few quality thickness data in the Peninsula other than at the GL based on flotation and precise surface elevation, so the error of Frankbed compared to BMv2 is unknown in the study.

We thank the reviewer for pointing out the new version of BedMachine, which we were not aware of. We have updated the dataset so that it uses BedMachine v3. We disagree with the reviewer's comment that "Frank[en]Bed is essentially BedMachine" – they are very different over the Peninsula and that difference creates a substantial change in discharge from Antarctica.

We are not sure what change the reviewer is recommending in the second part of their comment. We agree that there are very few thickness measurements on the Antarctic Peninsula, which is why the uncertainty in ice thickness is large here and why we think it is helpful to include a discharge estimate using each of BedMap2, BedMachine v3 and the Huss and Farinotti (2014) bed – we don't know which is closest to the true bed because we don't know the true bed. The use of the Huss and Farinotti (2014) dataset is further justified and perhaps even preferred over the other datasets because (1) the error in BedMachine and BedMap2 over the Peninsula is extremely high because there are so few thickness measurements; (2) in many places, the BedMachine and BedMap2 bed elevations are clearly unrealistic because they implies ice thicknesses of 10-20 m where the ice is flowing several hundred metres per year; (3) the Huss and Farinotti (2014) grid is derived from sound physical principles and, because of the regional scale of the dataset, was able to take advantage of high-resolution surface elevation data to inform the inversion. As such, the H&F grid produces much more reasonable ice thickness than does BedMachine v3 or BedMap2 given the observed ice speeds. We acknowledge that no one bed elevation dataset is perfect and that, without more measurements of the bed elevation, we can only use the errors provided in each product.

Reviewer 2: BMv2 already takes FC into account on the ice shelves, why remove FC again? What errors are introduced this way and is there a way the authors could evaluate their correction (or validate)?

This study only includes grounded ice. We assume FC means firn air content(?). The BedMachine v3 'surface' layer has the firn removed, but we make it clear in our methods that we use the BedMachine v3 bed and the REMA ice surface, which, to our knowledge, does not have firn removed. We do not remove the firn layer twice: we state clearly in our methods that we remove the climatological firn air content then remove anomalies in firn air content, so as to remove time-varying firn air content from the ice thickness estimates.

Regarding the evaluation of the firn correction, we already include a section in the manuscript titled "Effect of thickness adjustments" along with two figures, which clearly describe the effect of removing firn air content on grounding line discharge at different basins and throughout the time-series and with different firn models. We do this by calculating grounding line discharge both with and without the firn correction, so yes, there is a way we can evaluate the correction for firn air content, which we assume the reviewer's comment is concerned with.

Reviewer 2: SMB models have varying levels of performance in Antarctica, mixing their estimates could provide an indication of the uncertainty in SMB but does not really replace evaluating the skill of any of these models. RACMO2.3 is notoriously superior to other methods like MAR; and the HIRHAM is a notch below in Antarctica; but even various versions of RACMO2.3 disagree, especially in East Antarctica; and these differences are not discussed. There is also a specific version of RACMO2.3 for the Peninsula, but not sure the authors are aware.

Our aim is not to evaluate the skill of those regional climate models and we do not think that the reviewer's statement that "RACMO2.3 is notoriously superior to other methods [models?] like MAR" – one might be able to argue that the polar-optimized models (RACMO and MAR) better reproduce the limited SMB observations than HIRHAM, though often the differences are small or at least smaller than the uncertainties arising from the different spatial scales of in-situ SMB observations and regional climate model grids (see Mottram et al., 2021)

This study describes a dataset of grounding line discharge, for which an SMB correction is required to determine mass changes between the flux gate and the grounding line. Since we do not know the true SMB of Antarctica at the spatial and temporal scale, and at all points in time, required for this correction, we have to make recourse to regional climate models, which, partly because of the lack of observations, differ in their estimates and differ from the 'true' SMB by an unknown amount. We therefore think it is a reasonable approach to combine the SMB estimates from three RCMs to determine this correction. This correction contributes 64 Gt/yr on average to our discharge estimate for Antarctica compared to an approach that does not account for any SMB-induced mass change in that region, so it is an important component of this discharge estimate. However, the difference among the SMB models amounts to less than 1 % of our Antarctic-wide discharge, so the choice of SMB model here has almost no bearing on our grounding line discharge estimate. We are aware of the 5.5 km RACMO data over the Antarctic Peninsula.

Mottram, R., Hansen, N., Kittel, C., van Wessem, J. M., Agosta, C., Amory, C., Boberg, F., van de Berg, W. J., Fettweis, X., Gossart, A., van Lipzig, N. P. M., van Meijgaard, E., Orr, A., Phillips, T., Webster, S., Simonsen, S. B., and Souverijns, N.: What is the surface mass balance of Antarctica? An intercomparison of regional climate model estimates, The Cryosphere, 15, 3751–3784, https://doi.org/10.5194/tc-15-3751-2021, 2021.

Reviewer 2: FrankenBedabj includes corrections for match elevation changes over 1996-2014, which is a large source of uncertainty since altimetry over that time period mixes radar and laser instruments onboard various platforms, with varying level of performance, and surely low skills in steep areas, e.g. Peninsula. A comparison of this topography with actual data would help establish the actual performance level of this Frankenstein version of BedMachine. I could not find any element in the study that would convince me why this bed topography would be better than BMv2. It might very well be, but this has to be discussed more quantitatively.

We thank the reviewer for making a constructive suggestion to compare FrankenBedAdj to 'actual' data, by which we assume they mean measurements of bed elevation from, for example, radar surveys. In response to this and a similar comment from another reviewer, we now include a comparison between FrankenBedAdj, BedMachine v3 and BedMap2 in Figure 1 and Appendix A. Please see our detailed response to the first reviewer's comment for more information about this comparison.

Yes, there are uncertainties in mass change estimates from altimetry, especially in areas of steep topography, high accumulation and variable surface melt conditions. There are also uncertainties in snow and ice density estimates required for mass change estimates from elevation change observations, and uncertainties in the SMB estimates from regional climate models required for this inversion, which feed through into FrankenBedAdj. We are not sure how the reviewer has determined that the switch from radar to laser instruments in particular is a very large uncertainty in FrankenBedAdj – is the reviewer suggesting that time-averaged estimates of mass change during the radar-instrumented period and laser-instrumented period are accurate individually, but not in combination? In any case, we make it very clear in the manuscript that FrankenBedAdj is not a new bed topography dataset and should not be viewed as 'better' to the other datasets, it is simply the thickness required to reproduce the observed mass change. Indeed, in some places, that thickness seems unrealistic, which implies there are errors in the SMB or in the mass change estimate (assuming one is confident in the ice velocity data).

Reviewer 2: Later on, the authors correct REMA with altimetry 1992-2023, which introduces the same type of uncertainty at the surface, but they also correct for anomalies in SMB, but thickness is already corrected (twice if not once), so the entire picture is confusing. Would be nice to clarify.

This is one of the occasions where we think that the reviewer has misunderstood our algorithm. We shall clarify it here and we have revised the manuscript to try and clarify this, in order to reduce the risk of other readers making the same mistake.

We begin with an ice surface from REMA timestamped to May 2015 from which we remove the 30-year mean firn air content. We then remove time-varying anomalies (relative to the 30-year mean) in firn air content, which has the same effect as removing the firn air content through time. We then account for changes in ice surface elevation over time. We then remove SMB-induced mass changes between the flux gate and the grounding line – this final stage has changed in the revised manuscript and we have tried to clarify our description of the firn and surface elevation corrections, to avoid further confusion. The time-varying thickness changes have a very small impact on grounding line discharge (see Figure 11), so the reviewer's concern about the switch from radar to laser altimetry, which in itself is just one component of the error in the dH/dt time-series, will be a very small component of the discharge uncertainty.

Reviewer 2: The balance discharge from 3 x SMB models is problematic, especially in East Antarctica where RACMO2.3p2 has a lower performance than RACMO2.3p1, and in the Peninsula where only RACMO3.2 at 5.5 km has skills at reconstructing SMB. I do not have a sense of how these errors propagate in various estimates.

Please see our comment above about the various SMB estimates and, in general about uncertainties in mass change, ice thickness and SMB, and regarding the purpose of FrankenBedAdj, which is the only dataset affected by the balance discharge.

Reviewer 2 minor comments

Some comments seem arbitrary: "who manually selected different approaches to determine grounding line discharge and who modified ice thickness in a non-algorithmic manner in order to produce the required ice flux." Some specifics should be defined here rather than these blanket statements; not sure what "non-algorithmic manner" means, nor what is meant by "manual" approaches. This is a case where one would question: how do you know that your estimate is more precise than a prior one, and give us as many examples as possible for the most important basin. For instance, discussing uncertainties for Conger ice shelf is almost irrelevant. But discussing uncertainties for the Amundsen Sea Embayment sector of West Antarctica would seem to be a key priority.

We have modified this statement accordingly. We don't claim that FrankenBedAdj is more precise or better than any existing thickness dataset, it is simply the thickness required to reproduce the mass change derived from altimetry measurements, given the SMB from three RCMs. We highlighted basins and sectors in this discussion where there were large differences between discharge estimates and where they arose for different reasons – they are illustrative in order to provide the reader with an understanding of the differences between discharge estimates. In addition, Figures 9, 10 and 12 show the sensitivity of grounding line discharge in West Antarctica to the choice of bed topography dataset, gate location and firn model, which provide a lot of information to evaluate the impact of our choices on the dataset.

Line 125: It is unclear how the authors mix these velocity data from multiple sources into a cohesive dataset. How do the errors from these different products propagate? Monthly velocity maps at 100 m from velocity tracking seem almost impossible to achieve with S1. Why are they using ITS annual velocity maps but not the MEASURES annual velocity maps? Why is the multiyear map from 2020-2022 not used? Etc. The product quality varies significantly, so it is not clear what the aggregation of all of these estimates does to the analysis. An assessment should be made.:

1) 'Mixing' of velocity estimates from multiple sources: we clearly state that we assign each velocity measurement to a single time-stamp, align the different sources based on the mean difference of robust linear fits through each data source during their overlapping time-periods or, if the temporal resolution of each source is very different (annual or multiyear vs monthly, for example), then the average difference of the measurements themselves after temporal averaging of the monthly data.
2) How do the errors of each velocity product propagate? Again, we clearly state that we take the error from the respective datasets as provided. Where we have filled measurement gaps, we assume the error is 10% of the filled thickness. Since we never merge velocity measurements, there is no error propagation between measurements. We do propagate the individual velocity errors into our discharge error.
3) Monthly velocity maps at 100 m from Sentinel-1: the reviewer has not provided any argument or evidence to support this statement. The resolution of Sentinel-1 is nominally 2.3x14.1 m and we use a tracking window step size of approximately 100 m.
4) Use of ITSLIVE annual and MEaSUREs annual mosaics: this statement is incorrect – we do use annual velocity maps from MEaSUREs.
5) 2020-2022 MEaSUREs multi-year mosaic: we chose not to use this multi-year velocity mosaic because by that point we have monthly measurements with good coverage. Including a multi-year average velocity with lower resolution would create a velocity epoch that seemed much slower than the surrounding epochs, creating an apparent drop in discharge that would likely be erroneous.
6) The reviewer's final points are quite vague and the logic in the statement does not follow. As they did not provide any recommendation or suggestion of what such an assessment should look like or what even should be assessed, we are not sure how to respond to this. We already provide a value to indicate how the dataset alignment impacts Antarctic-wide grounding line discharge.

"Given that Antarctic Ice Sheet mass changes estimated from gravimetry and altimetry agree much more closely with each other than either do with the single available input-output mass change estimate (Otosaka et al., 2023)" ? This is not correct. Most of the disagreement is in East Antarctica. I would like to understand how the authors substantiate this comment.

This statement is based on Figure 3 of Otosaka et al. (2023). Yes, the differences between gravimetry and altimetry compared to input-output is greatest in East Antarctica.

Otosaka, I. N., Shepherd, A., Ivins, E. R., Schlegel, N.-J., Amory, C., van den Broeke, M. R., Horwath, M., Joughin, I., King, M. D., Krinner, G., Nowicki, S., Payne, A. J., Rignot, E., Scambos, T., Simon, K. M., Smith, B. E., Sørensen, L. S., Velicogna, I., Whitehouse, P. L., A, G., Agosta, C., Ahlstrøm, A. P., Blazquez, A., Colgan, W., Engdahl, M. E., Fettweis, X., Forsberg, R., Gallée, H., Gardner, A., Gilbert, L., Gourmelen, N., Groh, A., Gunter, B. C., Harig, C., Helm, V., Khan, S. A., Kittel, C., Konrad, H., Langen, P. L., Lecavalier, B. S., Liang, C.-C., Loomis, B. D., McMillan, M., Melini, D., Mernild, S. H., Mottram, R., Mouginot, J., Nilsson, J., Noël, B., Pattle, M. E., Peltier, W. R., Pie, N., Roca, M., Sasgen, I., Save, H. V., Seo, K.-W., Scheuchl, B., Schrama, E. J. O., Schröder, L., Simonsen, S. B., Slater, T., Spada, G., Sutterley, T. C., Vishwakarma, B. D., van Wessem, J. M., Wiese, D., van der Wal, W., and Wouters, B.: Mass balance of the Greenland and Antarctic ice sheets from 1992 to 2020, Earth Syst. Sci. Data, 15, 1597–1616, https://doi.org/10.5194/essd-15-1597-2023, 2023.

Reviewer 2 conclusions: Overall, the paper has value but glosses over the performance level of the various components used in the analysis to offer a holistic approach with little insights about differences, uncertainties, and causes. The comparison with prior estimates is too brief. Thickness ought to be a major one but the mixing of various velocity estimates could be another one, esp. given the large uncertainty of ITS-Live coarse feature tracking. For major basins in West Antarctica and East Antarctica, the authors ought to compare their results with prior studies, identify the differences and explain them, but the results are very important to the ice sheet mass balance estimates. It would help justify why the current estimates are qualified by the authors to be “the best”, which is amusing and unjustified.

We are disappointed that the reviewer thinks that we “glossed over the performance level of various components” of the dataset. We do not think that is a fair comment: we provide summary statistics, detailed description, discussion and figures to illustrate the impact on grounding line discharge of the choice of bed topography, firn air content, gate location and surface elevation change. We provide bulk estimates of the impact of velocity data source alignment on our grounding line discharge. We have provided an extensive comparison with several other grounding line discharge datasets. We also estimate the approximate changes in bed topography required to produce the observed mass changes, which provides important insights into the locations of uncertain bed topography, SMB and mass change, which are discussed in the manuscript (expanded on in the revised manuscript).

We are not sure what the reviewer means by ITSLIVE “coarse” feature tracking. As far as we are aware, ITS_LIVE use a similar window size to MEaSUREs and the ITS_LIVE mosaics are posted at 240x240 m, compared to 1x1 km for the MEaSUREs annual mosaics. So we are not sure what is meant by “coarse” feature tracking here and do not see a reason to exclude the ITS_LIVE data from our analysis.

The reviewer simultaneously claims that we have not compared our results with previous studies and that our comparison with previous studies is too brief. We provide a substantial figure and subsection devoted to comparing our dataset with other estimates. We have tried to be very transparent about our approach and the differences between our discharge estimates and those from other papers. We have provided illustrative examples of where the datasets differ and have explained why those differences occur.

By “the best” we meant that ours is the highest temporal resolution dataset and is the first to resolve changes in discharge on individual Antarctic Peninsula glaciers at monthly resolution, which we think is a real improvement over previous Antarctic-wide datasets (which often provided just one or two snapshots in time, or were at annual temporal resolution, and did not include as many basins, particularly on the Peninsula. We have modified the wording accordingly. We think our dataset offers potential for new discovery that would not be possible with those other datasets.

Antarctic Ice Sheet grounding line discharge from 1996 through 2023

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Abstract. Grounding line discharge is a key component of the mass balance of the Antarctic Ice Sheet. Here we present an estimate of Antarctic Ice Sheet grounding line discharge from 1996 through to ~~last month~~January 2024. We calculate ice flux at up-~~-~~to ~~1~~00 m resolution through 16 algorithmically-generated flux gates, which are continuous around Antarctica. We draw on a range of ice velocity and thickness data to estimate grounding line discharge. For ice thickness, we use four bed topography datasets, two firn models and a ~~temporally~~ time-varying ice surface. For the ice velocity, we utilise a range of publicly-available ice velocity maps at resolutions ranging from 240 x 240 m to 1000 x 1000 m, as well as new, 100 x 100 m monthly velocity mosaics derived from intensity-tracking of Sentinel-1 image pairs, available since October 2014. The pixel-based ice fluxes and ice flux errors are integrated within all available Antarctic ice stream, ice shelf and glacier basins. Our dataset also includes the contributions to discharge from changes in ice thickness due to surface lowering, time-varying firn air content and surface mass change between the flux gates and grounding line. We find that Antarctic Ice Sheet grounding line discharge increased from ~~1,990 ± 23~~2,140 ± 189 Gt yr^{-1} to ~~2,205 ± 18~~2,283 ± 207 Gt yr^{-1} between 1996 and 202~~3~~4, much of which was due to acceleration of ice streams in West Antarctica but with substantial contributions from ice streams in East Antarctica and glaciers on the Antarctic Peninsula. The uncertainties in our discharge dataset primarily result from uncertain bed elevation and flux gate location, which account for much of difference between our results and previous studies. It is our intention to update this discharge dataset each month, subject to continued Sentinel-1 acquisitions and funding availability. The dataset~~s~~ ~~are~~ is freely available at ~~https://zenodo.org/records/10183327~~ https://zenodo.org/records/10700903 (Davison et al., 2023a).

1 Introduction

The Antarctic Ice Sheet is losing mass at an accelerating rate (Diener et al., 2021; Otosaka et al., 2023; Shepherd et al., 2019; Slater et al., 2021). Much of this mass loss originates in West Antarctica, where ice streams draining into the Amundsen Sea Embayment have accelerated dramatically during the satellite era (Konrad et al., 2017; Mouginot et al., 2014). As such, the majority of mass loss from the Antarctic Ice Sheet is attribut~~able~~ed to increases in grounding line discharge – the flux of ice into ice shelves or directly into the Southern Ocean from the grounded Antarctic Ice Sheet (henceforth 'discharge'). Grounding line discharge is therefore a key component for quantifying the 'health' of the

Antarctic Ice Sheet, particularly when combined with surface mass balance (SMB) estimates to determine overall ice sheet mass change (Rignot et al., 2019; Sutterley et al., 2014). This 'mass budget' or 'input-output' approach to measuring ice sheet mass change compliments other ice sheet mass change measurements derived from altimetry measurements (Shepherd et al., 2019; Smith et al., 2020) or gravimetric approaches (Diener et al., 2021; Sutterley et al., 2020; Velicogna et al., 2020). The principle benefits of the input-output method are two-fold. Firstly, it permits direct partitioning of mass change between SMB and discharge, which provides insight into the processes driving ice sheet mass change. Secondly, discharge is derived from ice velocity and thickness datasets, which can now be generated through continuous satellite-based monitoring at relatively frequent (~monthly) intervals at the continent scale. These data are available at higher spatial resolution than the other mass change measurement approaches, making the input-output method particularly useful in smaller drainage basins and in mountainous terrain, where it is limited only by SMB model performance. Despite their utility, grounding line discharge measurements for Antarctica are relatively sparse (Depoorter et al., 2013; Gardner et al., 2018; Miles et al., 2022; Rignot et al., 2019) resulting in only one estimate of ice sheet mass change using the input-output method (Otosaka et al., 2023; Rignot et al., 2019; Shepherd et al., 2018), which means that independent verification of ice sheet mass balance using this method is lacking. Furthermore, the limited available discharge estimates feeding into those mass change calculations disagree in some regions and basins (for example, the Antarctic Peninsula) such that opposing conclusions regarding basin-scale mass change must be reached for those basins (Hansen et al., 2021).

Here, we present a new grounding line discharge dataset for the Antarctic ~~I~~Ice Sheet. We draw on several bed topography products and velocity measurements from 1996 through to January 2024~~last month~~, and we use time-varying rates of ice surface elevation change and firn air content. The velocity measurements range in spatial resolution from 1 x 1 km annually to 100 x 100 m every month since October 2014, thereby increasing the detail and frequency of continent-wide discharge estimates over time. We provide these discharge estimates integrated over every published basin definition available for Antarctica – ranging in scale from the whole ice sheet down to 1 km-wide glaciers on the Antarctic Peninsula. It is our intention to update this discharge dataset each month, subject to continued Sentinel-1 acquisitions and funding availability. In addition, we will endeavour to provide irregular updates following the release of new bed topography datasets, grounding lines and if any bugs are identified.

2 Data and Methods

2.1 Bed topography, ice surface and ice thickness

We estimate grounding line discharge using multiple bed elevation datasets. Our primary estimates of bed elevation and bed elevation error draw predominantly on BedMachine v3~~2~~ (Morlighem, 2020; Morlighem et al., 2020), but we replace the BedMachine bed and bed error with ~~a more recent regional~~

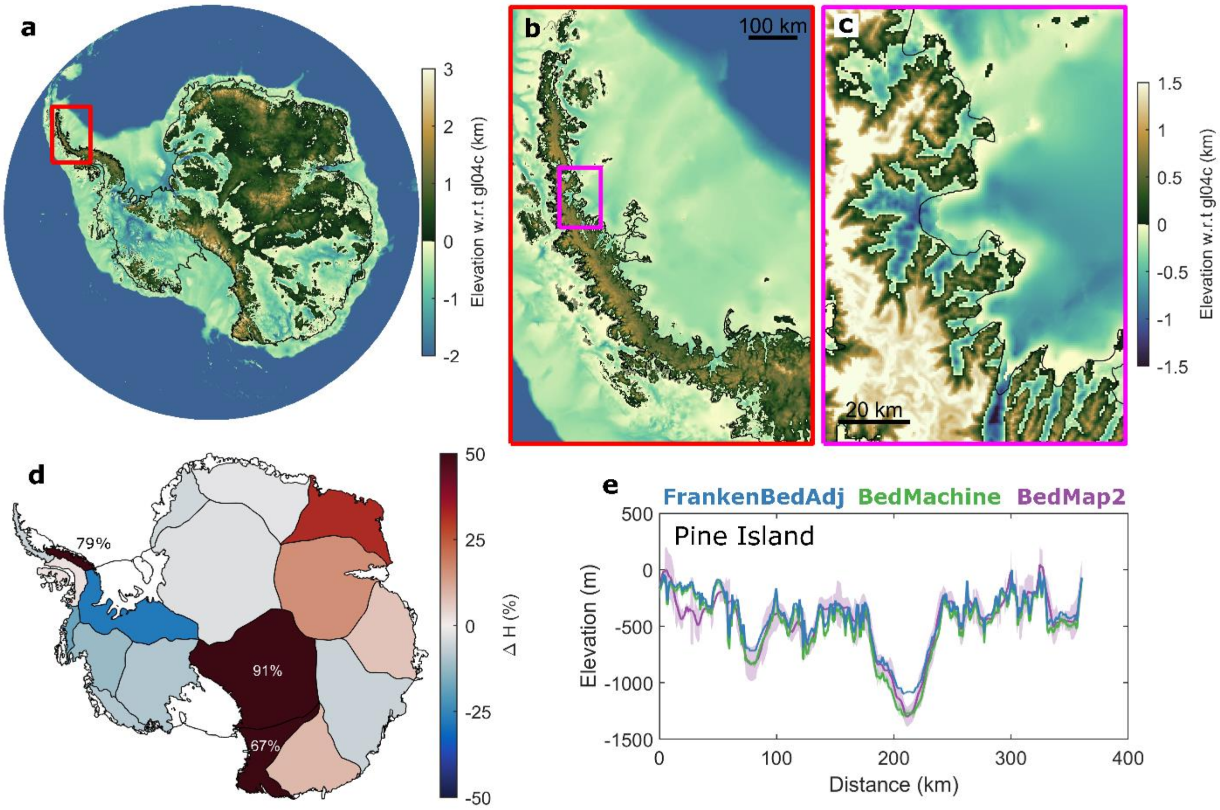

Figure 1. Antarctic Ice Sheet bed topography overview. (a) Overview of BedMachine v3. Also shown are overviews of **(b)** the Antarctic Peninsula (Huss and Farinotti, 2014) and **(c)** the Larsen-B Embayment with FrankenBed. **(d)** The change in ice thickness in each MEaSUREs regional basin in FrankenBedAdj compared to FrankenBed, where positive values indicate an increase in ice thickness. **(e)** A comparison of bed elevation in BedMachine, FrankenBedAdj and BedMap2 for Pine Island Glacier at our most seaward flux gate. The coastline and grounding line in panels (a) to (d) are also shown as black lines.

~~estimate in Princess Elizabeth Land (Cui et al., 2020) and with~~ a dedicated bed topography dataset over the Antarctic Peninsula (Huss and Farinotti, 2014), after conversion to a common geoid (GL04c). We use the MATLAB tool wgs2gl04c to perform this conversion (Greene et al., 2019). Henceforth, we refer to this merged bed topography dataset as 'FrankenBed' (Fig. 1). We also provide discharge estimates using the bed topography data and associated error from an unmodified version of BedMachine v3~~2~~ and using BedMap2 (Fretwell et al., 2013).

For each of these bed products, we calculate ice thickness using the Reference Elevation Model of Antarctica (REMA) Digital Elevation Model (DEM), posted at 100 x 100 m and timestamped to 9th May 2015 (Howat et al., 2019). Before calculating ice thickness, we reference the REMA DEM elevations to the GL04c geoid and remove the climatological mean (1979-2008) firn air content (Veldhuijsen, Sanne et al., 2022) (Section 2.4). Henceforth, we refer to this firn-corrected ice surface as our reference ice surface, which we assume has a spatially uniform 1 m error (Howat et al., 2019). For the thickness grid calculated using FrankenBed, we fill exterior gaps through extrapolation along ice flowlines using the same method applied to the reference velocity map described in Section 2.3. The purpose of the extrapolation is to ensure that ice thickness estimates are available at each flux gate pixel

(Section 2.4). We chose to extrapolate along flowlines rather than using a more conventional nearest-neighbour interpolation because the latter can lead to erroneous or poorly-targeted sampling near shear margins.

Even though we draw on the best available bed topography and ice surface datasets to construct FrankenBed, some ice remains unrealistically thin given the observed ice flow speeds and the resulting discharge is, in places, lower than that implied by the observed rates of surface elevation change and surface mass balance (Figs. A1 & A2). We therefore generate a final bed elevation estimate at each of our flux gates (Section 2.4) ~~for~~ at which we adjust the bed elevation such that the average 1996-2021~~14~~ discharge across each flux gate matches that required to reproduce observed basin-integrated rates of elevation change over the same time period, after accounting for surface mass balance anomalies obtained from three regional climate models. This method is described further in Appendix A and we refer to the resulting dataset as 'FrankenBedAdj' (Fig. A2). In summary, we use four ice thickness estimates derived from a reference ice surface and four bed elevation datasets (Fig. 1) – BedMap2, BedMachine v3~~2~~, FrankenBed and FrankenBedAdj.

To generate an ice thickness time-series from each of these baseline thickness estimates, we modify the REMA DEM using observed changes in ice surface elevation from 1992 to 2023 (Fig. A1) derived from satellite radar altimetry following the methods of Shepherd et al. (2019). Because satellite altimetry~~er~~ ~~time series~~measurements do not fully ~~sample~~ observe the ice sheet margins at monthly intervals~~, either due to their orbit patterns or occasional failure in tracking challenging terrain~~, we estimate monthly time series of ice surface elevation change by fitting time-dependent quadratic polynomials (Fig. A1) to the observed surface elevation changes posted on a 5 x 5 km grid at quarterly intervals, which we linearly interpolate to our gate pixels and evaluate at each velocity epoch (Section 2.3). We apply these modelled time-series of elevation change to each reference ice thickness estimate to form time-series of ice thickness at each gate pixel. We quantify the errors in the elevation change by calculating upper and lower bounds to the quadratic fit from the 95 % confidence interval on each of the model coefficients (Section 2.7.3). South of 81.5°, where elevation change measurements are only available since the launch of CryoSat-2 in 2010, we assume static ice thickness rather than extrapolate the historical thinning rates from those observed between 2010 and 2023. Given that the flux gate pixels south of 81.5° only contribute 6~~7~~ % to the pan-Antarctic discharge and that the applied thickness changes elsewhere around the continent only modify the total discharge by 0.7~~6~~ %, this choice has little impact on our pan-Antarctic discharge estimate. We then account for temporal variations in firn air content by adjusting the climatological firn air content correction in each flux gate pixel using time-series of firn air content anomalies from two firn models (Section 2.2) at each velocity epoch. For discharge estimates after the last available output from each firn model, we use the monthly firn air content climatology (1979-2008), in order to capture seasonal changes in firn air content. For discharge estimates after January 2023, when our thickness change observations end, we continue to use the quadratic fit. We

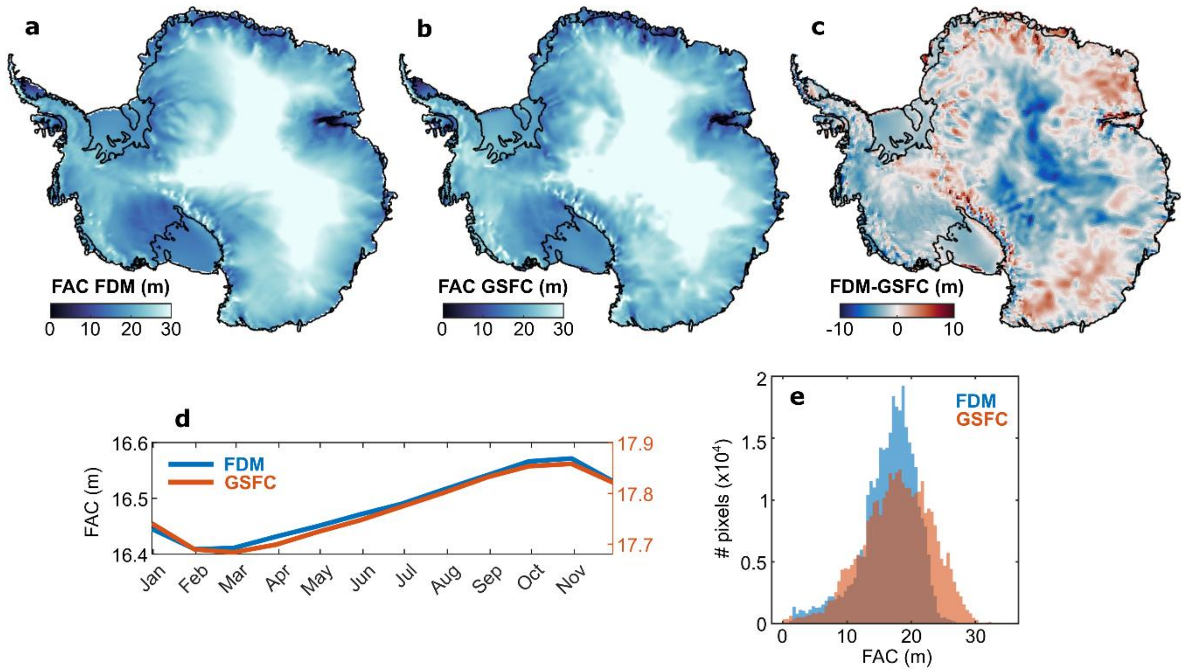

Figure 2. Overview of firn air content models. Overviews of (a) the IMAU FDM, (b) the GSFC-FDMv1.2 and (c) the difference between the two models. (d) The climatological seasonal cycle of firn air content (FAC) in each firn model. Note that in panel (d) the IMAU FDM and the GSFC-FDMv1.2 are plotted on separate y-axes to facilitate comparison of their seasonal variability; their units are the same. (e) The frequency distribution of FAC at every flux gate pixel in each model.

also assume no changes in bed elevation due to erosion of the substrate or changes in ice thickness due to changes in subglacial melt rates, both of which are expected to be negligible.

2.2 Firn air content

We use two firn models (Fig. 2) to remove firn air content from our ice thickness estimates, to determine the ice equivalent thickness at each flux gate and to permit the use of a single ice density value in the discharge calculation (Section 2.7). These are the Institute for Marine and Atmospheric Research Utrecht Firn Densification Model (IMAU FDM) (Veldhuijsen, Sanne et al., 2022) and the Goddard Space Flight Center FDM (GSFC-FDMv1.2), which draws on the Community Firn Model framework and is forced by the Modern-ERA Retrospective analysis for Research and Applications, Version 2 (MERRA-2) climate forcing (Medley et al., 2022b, 2022a). The resolution of the IMAU FDM is 27 x 27 km and the GSFC-FDMv1.2 is 12.5 x 12.5 km. Both models provide daily firn air content for all of Antarctica and span the periods January 1979 to December 2021 for the IMAU FDM and January 1980 to July 2022 for GSFC-FDMv1.2. We use both solutions independently and provide a discharge estimate using each.

2.3 Ice velocity

We generate a reference velocity dataset by combining two velocity products. First, we use a 100 x 100 m multi-year velocity mosaic derived from feature tracking of Sentinel-1 imagery between January 2017 and September 2021 (Davison et al., 2023b). Sentinel-1 imagery are only continuously acquired around the Antarctic Ice Sheet margin, with sparser measurements further inland acquired in 2016. To fill the pole hole, we use the 450 x 450 m MEaSUREs reference velocity product (Rignot et al., 2017), which is linearly interpolated to the grid of the Sentinel-1 product. We fill interior gaps in this mosaic using the regionfill algorithm in MATLAB, which smoothly interpolates inward from the known pixel values on the outer boundary of each empty region by computing the discrete Laplacian over each region and solving the Dirichlet boundary value problem. This interior gap-filling has no bearing on our discharge estimate, but it allows for easier filling of external gaps. We then fill exterior gaps through extrapolation along flowlines following the method of Greene et al. (2022), where the observed velocity is multiplied by the observed thickness mosaic (described in Section 2.1), before extrapolating along the hypothetical direction of flow and inpainting between flowlines. We multiply the ice velocity by the reference ice thickness before extrapolating and inpainting, so as to give appropriate weight to flow directions of thicker ice that contribute more to ice flux. As with the reference thickness map, we choose to extrapolate along flowlines to avoid erroneous sampling of ice velocity, especially near shear margins. This produces a gapless ice velocity map of Antarctica (Fig. 3), broadly representing the average velocity of the ice sheet from 2015 to 2021. We emphasise that the purpose of the gap filling is only to ensure that a velocity estimate is available at every flux gate pixel. As such, the velocity in the ice sheet interior and the extrapolated velocity seaward of the flux gates in this reference map have no bearing on our discharge estimate.

For our time-series product, we compile multiple velocity sources:

1. The 1 x 1 km MEaSUREs annual velocity mosaics (Mouginot et al., 2017b, 2017a) for the year 2000 and from 2005 to 2016
2. Monthly 100 x 100 m velocity mosaics derived from intensity tracking of Sentinel-1 image pairs (described in Appendix B), available from October 2014 to January 2024 (Davison et al., 2023c, 2023b).

~~2.~~3. Monthly 200 x 200 m velocity mosaics derived from intensity and coherence tracking of Sentinel-1 image pairs, available from October 2014 to December 2021 (Nagler et al., 2015).

~~3.~~4. In the Amundsen Sea Embayment in 1996, we also use a combination of 450 x 450 m MEaSUREs InSAR-based velocities derived from 1-day repeat ERS-1 imagery (Rignot et al., 2014), which covers the region spanning Cosgrove to Kohler Glacier, and 200 x 200 m velocities from ERS-1 offset tracking over the Getz basin (https://cryoportal.enveo.at/data/). The latter have been filled using an optimisation procedure supported by the BISICLES ice sheet model (Selley et al., 2021).

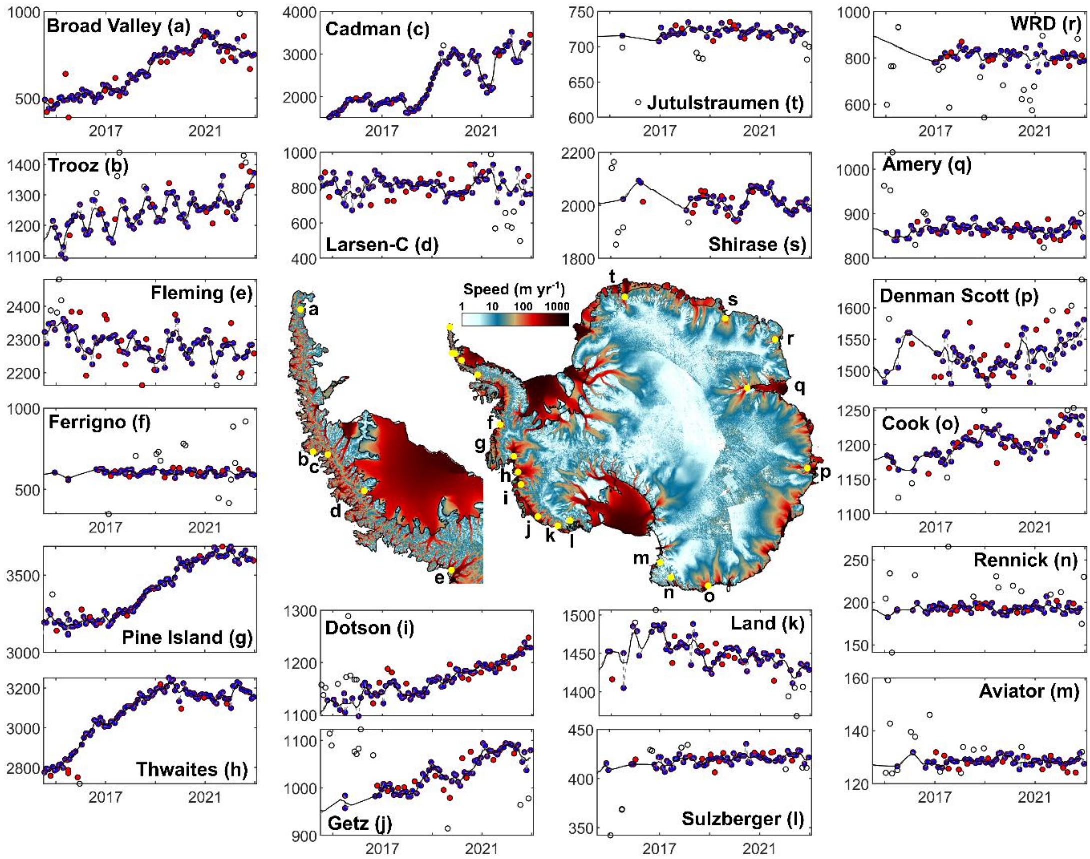

Figure 3. Reference ice velocity map and time-series outlier removal. The central plot shows the reference ice velocity map (with extrapolated velocities masked to aid visualisation). Panels (a) to (t) show example time-series of cross-gate velocity (in m yr^{-1}) extracted from single flux gate pixels. The black dots show points removed by the global outlier filters, and the red dots show points removed by the local outlier filters are shown. The unsmoothed filled time-series is shown as a grey-dashed line and the smoothed time-series is shown as a black line. WRD is Wilma Robert Downer.

~~4.~~5. The 240 x 240 m ITS_LIVE annual mosaics (Gardner et al., 2019) during 1996-2018~~05~~.

~~5.~~6. ~~Three~~ Two 450 x 450 m MEaSUREs multi-year velocity mosaics, which incorporate velocity estimates in the periods 1995-2001 and~~,~~ 2007-2009 ~~and 2014-2017~~ (Rignot et al., 2022).

~~6.~~7. In the Amundsen Sea Embayment, gap-filled 240 x 240 m ITS_LIVE annual mosaics, from 1996 to 2018 (Gardner, 2023; Paolo et al., 2023)

~~7.~~8. Over Pine Island Glacier, 500 x 500 m mosaics of ice velocity derived from speckle-tracking of TerraSAR-X and TanDEM-X imagery, averaged over 2 to 5 month periods from 2009 to 2015 (Joughin et al., 2021).

Each of these velocity products spans a time period; following Mankoff et al. (2019, 2020), we treat each product as an instantaneous measurement with the timestamp given by the central date in the estimate.

From these data, we generate discharge-ready, gapless velocity time-series at each gate pixel as follows. We linearly interpolate the easting and northing velocities, and their respective errors, from each product to each flux gate pixel. There are consistent differences between velocity data sources that we assume are related to differences in offset tracking parameter choices, digital elevation models used in the tracking, image co-registration procedures, outlier removal routines and final dataset ~~resolution~~ posting.~~–~~ Generally, the datasets posted at a higher resolution, ~~datasets~~ such as the 100 x 100 m Sentinel-1 mosaics and the 240 x 240 ITS_LIVE mosaics, typically ~~provide~~ indicate higher velocities than the coarser datasets, especially on narrow outlet glaciers. Treating each gate pixel as a time-series, we first remove extreme outliers defined as those more than two-times or less than half of the reference velocity. W~~w~~e then align each data source based on a robust linear fit through their overlapping time-periods, and apply the difference between the means of each fit as a scalar shift to the coarser velocity datasets. This shift increases our pan-Antarctic discharge estimate by ~~89~~116 Gt yr^{-1} compared to the case where we align the higher resolution datasets down to the coarser datasets.

Treating each flux gate pixel as a time-series, we remove outliers in two stages. Firstly, we remove global time-series outliers after detrending using two passes of a scaled median absolute deviation filter with thresholds of five then ~~two~~three. This global filter is only applied to time-series with more than 30 % of non-nan measurements. Secondly, we remove local outliers using two passes of a moving median filter with a threshold of two median absolute deviations and window sizes of four months then three months. We fill gaps in each of our flux gate velocity time-series in three stages. Firstly, we linearly interpolate across short temporal gaps (two months or less). Secondly, we linearly interpolate across short spatial gaps (~~300 metres~~three gate pixels or less). Thirdly, we fill remaining temporal gaps using linear interpolation, ~~again~~ then back- and forward-filling at the ends of each time-series. For gate pixels with no data at any time and more than three gate pixels~~300 m~~ from neighbouring finite pixels (after outlier removal), we use our reference ice velocity estimate which has no gaps by definition. This final step affects just 0.05 to 0.15 % of flux gate pixels. After infilling, we smooth each pixel-based time-series with two passes of a moving mean ~~(or boxcar)~~ filter, with window sizes of three months then four months. Where we have removed outliers then infilled the time-series, we set the easting and northing error to be |10 %| of the interpolated and smoothed easting and northing velocity components, respectively, at the gate pixel and velocity epoch in question. As in previous studies (Mankoff et al., 2019, 2020; Mouginot et al., 2014), we assume the depth-averaged velocity is the same as the measured surface velocity. Examples of this outlier removal and infilling are shown in Fig. 3.

2.4 Flux gates

We algorithmically generate 16 flux gates close to the Antarctic Ice Sheet grounding line (Fig. 4). Each flux gate is continuous around the Antarctic Ice Sheet and Wilkins Island; other Antarctic islands are not included in this analysis. The seaward grounding line is placed 3-years of ice flow upstream of the MEaSUREs grounding line (Mouginot et al., 2017c). The ice velocity for this migration is taken from the reference velocity dataset (described in Section 2.3) and the migration is performed in increments of 0.1 years to account for variations in ice velocity along the migration path. Gate pixels are spaced

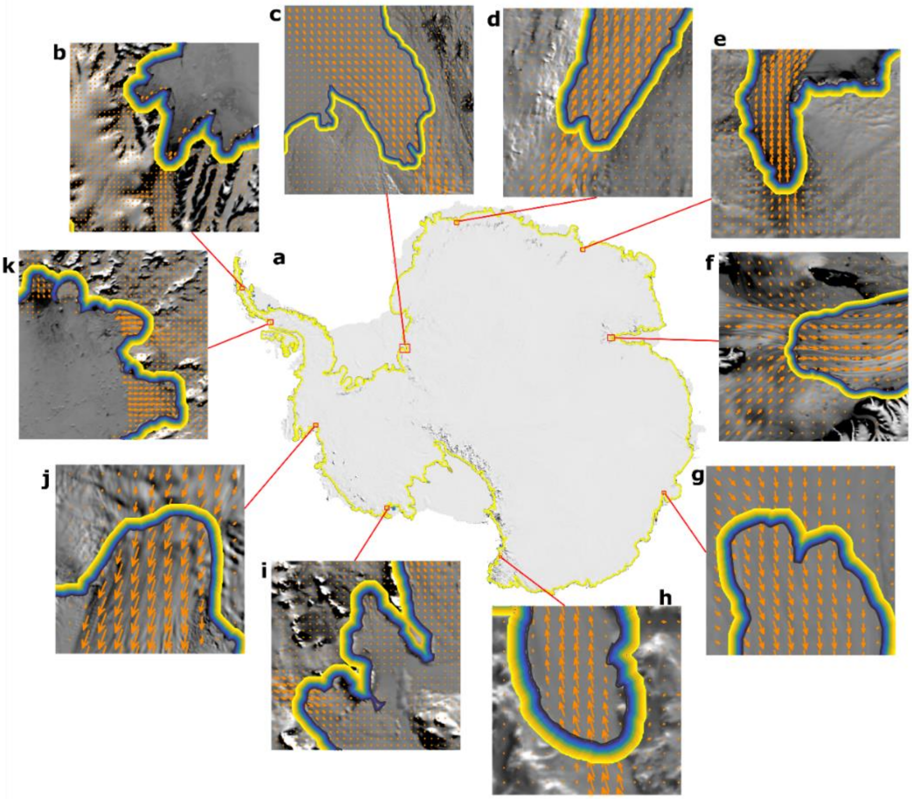

Figure 4. Flux gate overview. (a) Overview of Antarctica with flux gates plotted, where yellow lines represent the most inland gate and the blue lines represent the most seaward flux gate. Panels (b) to (k) show zoomed in examples of the 16 flux gates in small regions around Antarctica, with ice velocity vectors overlain (orange arrows). The background image is the MODIS Mosaic of Antarctica (Haran et al., 2018).

every 100 m for ice flowing faster than 100 m yr^{-1} and 200 m for slower ice, defined on a Polar Stereographic grid (EPSG 3031) and accounting for distance distortions introduced by that projection. 15 additional gates are generated at 200 m increments further upstream of the first gate, such that the most upstream gate is 3 km upstream of the first gate. We provide discharge and error estimates for each of these flux gates and for the mean of all of the gates, weighted by the reciprocal of the error at each gate.

2.5 ~~Thickness~~ Mass change between flux gates and grounding line

~~Ice thickness~~Mass changes ~~can~~ occur between ~~the~~ each flux gate and the grounding line due to surface processes and due to subglacial melting. Here, we estimate ~~thickness~~ mass changes due to surface processes only. We estimate this ~~thickness~~ mass change for each drainage basin (Section 2.6) ~~using~~ by integrating the climatological (1979-2008) surface mass balance from three regional climate models: RACMO2.3p2 (van Wessem et al., 2018), MAR (Agosta et al., 2019; Kittel et al., 2018) and HIRHAM5 (Hansen et al., 2021) in the area enclosed between each flux gate and ~~. For each gate pixel where ice flow is greater than 100 m yr^{-1}, we calculate the number of years of ice flow between each flux gate pixel and~~ the MEaSUREs grounding line (Mouginot et al., 2017c)~~, to convert this rate of thickness change to a total thickness change~~. This mass correction is applied at each velocity epoch~~We use this~~

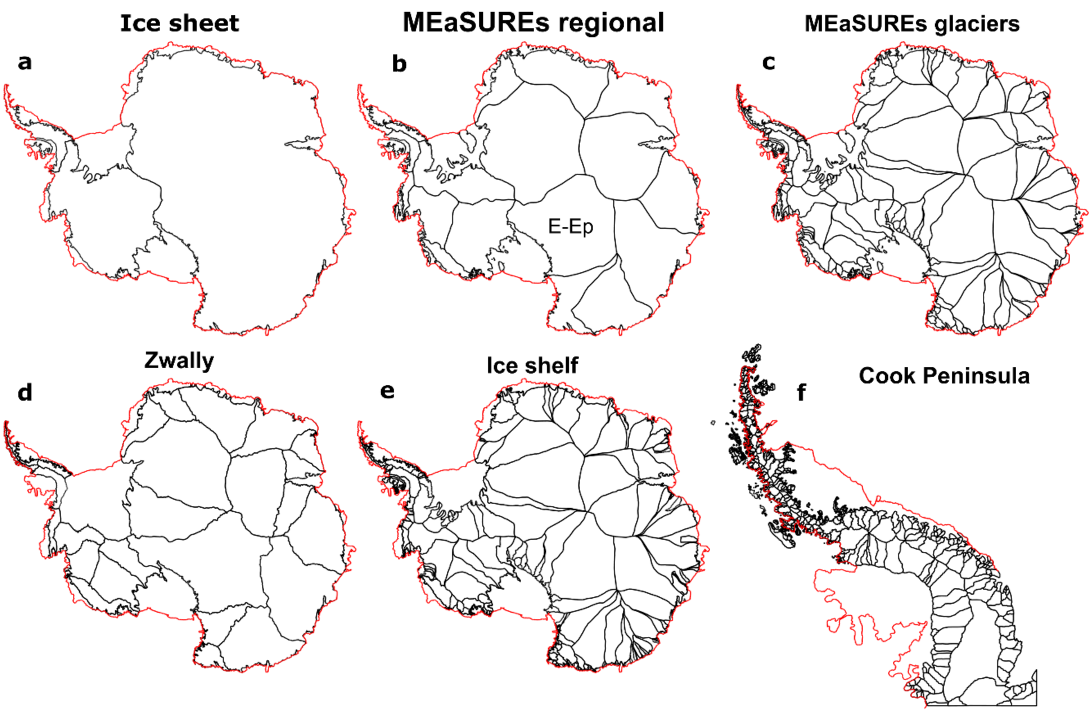

Figure 5. Overview of Antarctic Ice Sheet drainage basins. (a) Main ice sheet basins – East Antarctica, West Antarctica and the Antarctic Peninsula. Also shown are smaller drainage basin definitions, including (b) the MEaSUREs regional basins, (c) the MEaSUREs glacier basins, (d) the Zwally basins, (e) ice shelf basins and (f) the Peninsula glacier basins. The coastline is shown in red.

~~static thickness correction at each velocity epoch. We do not perform this correction for ice flowing slower than 100 m yr^{-1}, so as to avoid unrealistic modifications to the initial ice thickness~~. Since surface mass balance is generally positive downstream of the flux gates, this correction increases our Antarctic-wide grounding line discharge by 64 Gt yr^{-1} on average.

2.6 Drainage basins

We provide a discharge estimate for all available Antarctic Ice Sheet basins (Fig. 5). This includes the MEaSUREs regional basins and MEaSUREs glacier basins (Mouginot et al., 2017c), Zwally basins (Zwally et al., 2012), ice shelf basins (Davison et al., 2023b), and Antarctic Peninsula basins (Cook et al., 2014). In total, there are 998~~66~~ basins used in this study. For each basin, we provide the discharge through each of the 16 flux gates and the average of all flux gates (weighted by the reciprocal of their respective errors) along with their errors. These metrics are provided using each of the four bed topography estimates and with two firn models. In total, therefore, we provide 136 discharge time-series for each basin. In addition, we provide the impact of the ~~three~~ two ice thickness corrections – (1) IMAU FDM firn air content and~~;~~ (2) ice surface elevation changes – as well as the impact of downstream surface mass balance~~, and; (3) ice surface elevation changes –~~ on each basin-integrated discharge estimate for each flux gate.

2.7 Grounding line discharge

2.7.1 Balance discharge

We define the balance discharge as the discharge required to maintain the mass of a given ice sheet basin on ‘long’ time-scales (decades). In order to maintain the mass of a basin, the hypothetical balance discharge would therefore need to equal the basin-integrated SMB input on average. Accordingly, we estimate the balance discharge of each basin by integrating the 1979-2008 SMB from the mean of three regional climate ~~three~~ models (RACMO2.3p2, MAR and HIRHAM5) within each of the above basins. We estimate the balance discharge error in each basin as the standard deviation of 10 realizations of 20-year climatologies from 1979 to 2008 (i.e. 1979-1999, 1980-2000, etc.). Note that only RACMO2.3p2 is available in 1979.

2.7.2 Discharge

We estimate grounding line discharge, D, across each flux gate pixel as:

$$D = VHw\rho, \tag{4}$$

where V is the gate-normal ice velocity, H is the ice equivalent thickness, w is the pixel width and ρ is ice density (917 kg m^{-3}).

The gate-normal ice velocity is given by:

$$V = sin(\theta)V_x - cos(\theta)V_y, \tag{5}$$

where V_x and V_y are the easting and northing components of the horizontal ice velocity, as defined by the South Polar Stereographic grid (EPSG3031), respectively, and θ is the angle of the flux gate relative to the same grid. To calculate the total discharge from each basin at each velocity measurement epoch, we simply sum the discharge through each flux gate pixel contained within the basin.

2.7.3 Discharge error

We define our discharge error in each flux gate pixel, D_σ, as:

$$D_\sigma = \sqrt[2]{\cancel{V}D_{vel\_\sigma}^2 + D\cancel{H}_{H\_\sigma}^2}, \tag{6}$$

where D_{vel_σ} ~~V_σ~~ is the velocity-induced discharge error and D_{H_σ} ~~H_σ~~ is the thickness-induced discharge error. Both sources of discharge error are timestamped and calculated at each flux gate pixel. We calculate ~~the velocity-induced discharge error as~~both the velocity- and thickness-induced discharge errors in a Monte-Carlo approach with 100 iterations. In each iteration, the time-stamped cross-gate velocity and thickness in each pixel are separately modified using uniformly-distributed random numbers generated from the time-stamped and pixel-based cross-gate velocity and thickness errors. The standard deviation of resulting time-stamped, pixel-based discharge estimates amongst the 100 iterations is taken as the discharge error owing to uncertainties in thickness and cross-gate velocity.~~:~~

$$\cancel{V_\sigma = ((D_{ref} - D_{Vmin}) + (D_{Vmax} - D_{ref}))/2,} \qquad \cancel{(7)}$$

~~where D_{ref} is the reference discharge estimate at each epoch. D_{Vmin} and D_{Vmax} are the discharges derived using lower and upper bounds on the gate-normal velocity, V, given by the velocity error, V_σ. The minimum and maximum gate-normal velocities, V_{min} and V_{max}, are determined from the error in the gate-normal velocity, which in turn~~ The uncertainty in the cross-gate velocity at each pixel and epoch, V_σ, is calculated from the errors in the easting and northing velocity components:

$$V_{xmax} = sin(\theta)V_{xmax} - cos(\theta)V_y,$$

$$V_{xmin} = sin(\theta)V_{xmin} - cos(\theta)V_y,$$

$$V_{ymax} = sin(\theta)V_x - cos(\theta)V_{ymax},$$

$$V_{ymin} = sin(\theta)V_x - cos(\theta)V_{ymin},$$

$$V_\sigma = \sqrt[2]{(V - V_{xmax})^2 + (V - V_{xmin})^2 + (V - V_{ymax})^2 + (V - V_{ymin})^2},$$

$$\cancel{V_{min} = V - V_\sigma,}$$

$$\cancel{V_{max} = V + V_\sigma,} \qquad (7\cancel{8})$$

~~Similarly, we calculate the thickness-induced discharge error as:~~

$$\cancel{D_\sigma = ((D_{ref} - D_{Hmin}) + (D_{Hmax} - D_{ref}))/2,} \qquad \cancel{(9)}$$

~~where D_{Hmin} and D_{Hmax} are the discharges derived using lower and upper bounds on the local ice thickness given by the thickness error.~~ The thickness error at each measurement epoch and gate pixel, H_σ, is calculated as:

$$H_\sigma = \sqrt[2]{(B_\sigma + 1)^2 + F_\sigma^2 + \Delta H_\sigma^2}, \qquad (10)$$

where B_σ is the bed elevation error taken from the respective bed elevation products, to which we add 1 meter of ice surface elevation error (Howat et al., 2019). F_σ is the error in the firn air content correction, which we assume is 10 % of the correction. ΔH_σ is the error in the applied surface elevation change timeseries, which we calculate as:

$$\Delta H_{max} = t(a + a_\sigma)^2 + t(b + b_\sigma) + (c + c_\sigma),$$

$$\Delta H_{min} = t(a - a_\sigma)^2 + t(b - b_\sigma) + (c - c_\sigma),$$

$$\Delta H_\sigma = \left(\frac{\lambda_1}{\lambda_0}\right)\left(\frac{(\Delta H_{max} - \Delta H) + (\Delta H - \Delta H_{min})}{2}\right). \tag{11}$$

Here, *a*, *b* and *c* are the quadratic, linear and intercept coefficients of the quadratic fit to the ice surface elevation change data. a_σ, b_σ and c_σ provide the bounds on the 95 % confidence interval for each coefficient. λ_0 and λ_1 are the sampling frequency of the fit (monthly) and the original observations (every 140 days) on which the fit is based, which together provide a scaling factor that prevents the uncertainty in ΔH scaling with the observational frequency. The total pixel-based errors are typically 10 to 30 % of the pixel-based discharge estimates.

We calculate the basin-integrated error in two ways. Firstly, we ~~use the root-sum-square of the discharge error at each flux gate pixel contained within the basin~~follow Mankoff et al. (2019, 2020) and set the basin-integrated discharge error as the average difference between the minimum and maximum possible discharge implied by the thickness and velocity errors described above and the central discharge estimate. These errors are typically 7 to 13 % of the basin-integrated discharge and, because they accumulate the error in every pixel, they represent an upper-bound on the discharge error. ~~This root-sum-square approach assumes the errors of neighbouring flux gate pixels are independent and reduces the basin-integrated errors to around 1 % of the basin-integrated discharge. As such, it represents a lower bound on the error in the discharge dataset.~~ Secondly, we also provide the 95 % confidence interval of the gate-mean discharge based on the standard error of the discharge estimates through each of the 16 flux gates. The latter approach provides a measure of the uncertainty in the discharge estimate associated with the gate location, which in turn reflects the errors in the underlying ice velocity and ice thickness datasets, and are typically less than 5 % of the basin-integrated discharge. In the following, all ~~plots and~~ statistics use the former, upper bound estimate of discharge error, whilst plots use the ~~second~~latter estimate, to facilitate visualisation of discharge changes.

3 Results

3.1 Grounding line discharge

We provide grounding line discharge estimates through 16 flux gates using four bed topography products and two firn models for 998~~66~~ drainage basins. In the following, we primarily present values from the mean of all flux gates (weighted by the reciprocal of their errors) using our favoured bed topography dataset (FrankenBed) and the IMAU FDM. We also present comparisons across gates, bed topography datasets and firn models in turn.

Our primary discharge dataset (Fig. 6) gives a total Antarctic grounding line discharge of 2,140 ± 189 ~~1,990 ± 23~~ Gt yr^{-1} in July 1996, rising to 2,283 ± 207~~2,205 ± 18~~ Gt yr^{-1} in ~~September~~ January 2024~~3~~. On average, Antarctic discharge has increased at a rate of ~~6.5~~4.9 Gt yr^{-2} or 0.2~~3~~ % yr^{-1}~~^{2}~~ over the study period from 1996. Our dataset shows that Antarctic grounding line discharge has ~~fluctuated slightly through~~not risen steadily during our ~~time~~ study period. Discharge increased steadily from 1998 to 2012 and since 2018. These periods of rising discharge were interrupted by ~~a slight decline in~~a period of steady discharge ~~from 2012 to 2014 and relatively steady discharge from 2014 to 2018~~.

Our dataset also provides grounding line discharge measurements for distinct Antarctic regions (Fig. 6). Grounding line discharge from West Antarctica increased from ~~790 ± 8~~841 ± 72 Gt yr^{-1} in July 1996 to ~~943 ± 7~~946 ± 81 Gt yr^{-1} in ~~September~~ January 2024~~3~~, with a trend of ~~5~~3.8 Gt yr^{-2} or 0.4~~6~~ % yr$^{-1\cancel{2}}$ and following a similar pattern of temporal variability described above. West Antarctica therefore currently accounts for approximately 41~~3~~ % of all Antarctic grounding line discharge and 73~~0~~ % of the total Antarctic increase in discharge from 1996 through~~o~~ 2023. Discharge from East Antarctica ~~has~~ also increased, from ~~945 ± 13~~1,000 ± 87 Gt yr^{-1} in 1996 to ~~977 ± 9~~1,021 ± 94 Gt yr^{-1} in ~~June 2023~~January 2024, with a statistically significant trend of 0.55~~1.3~~ Gt yr^{-2}. However, East Antarctic discharge is the most uncertain of any region and fluctuated on approximately 10-year time-scales with an amplitude of approximately 20 Gt yr^{-1}. This relative large uncertainty and temporal variability means that East Antarctic grounding line discharge during 2011 to 2015~~in 2015~~ was not significantly different from that ~~in 2002~~ during 2002 to 2008, and may explain previous reports of unchanging East Antarctic grounding

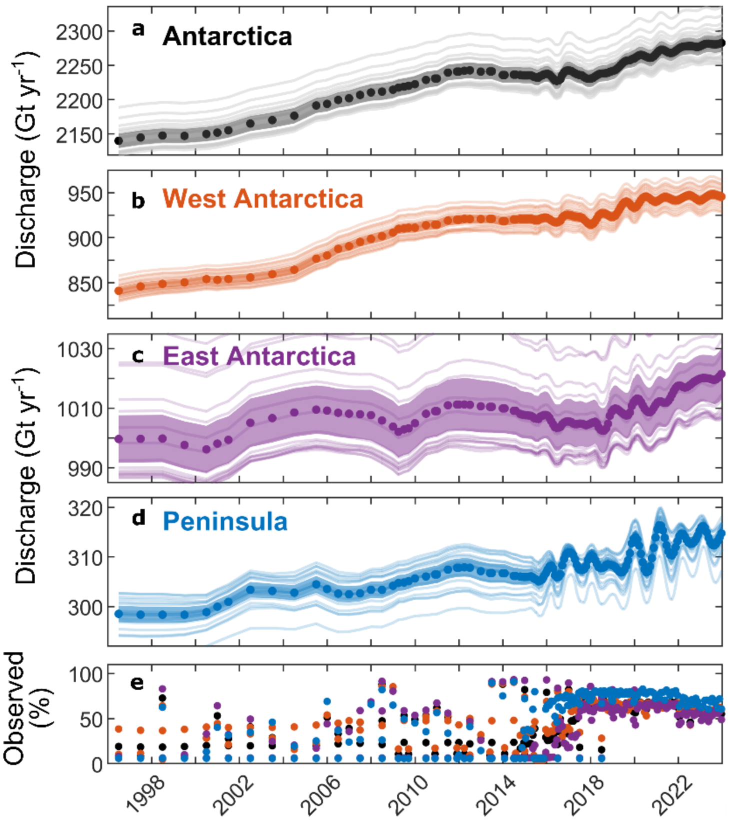

Figure 6. Antarctic Ice Sheet grounding line discharge. Discharge time-series for (a) Antarctica, (b) West Antarctica, (c) East Antarctica and (d) the Antarctic Peninsula. In each panel, the dots show the central discharge estimate with 95 % confidence bounds (shading) and the discharge through each individual flux gate (faint lines). (e) The proportion of discharge that is observed, as opposed to infilled, shown for the whole Antarctic Ice Sheet (black dots), West Antarctica (orange dots), East Antarctica (purple dots) and the Antarctic Peninsula (blue dots).

line discharge that were based on comparisons between two epochs during those periods (Gardner et al., 2018). Grounding line discharge from the Antarctic Peninsula was ~~261 ± 2~~299 ± 29 Gt yr^{-1} in 1996, increasing to ~~292 ± 6~~313 ± 32 Gt yr^{-1} on average during April to September 2023, with a significant trend of 0.6~~1.4~~ Gt yr^{-2} or 0.2~~5~~ % yr^{-1}~~2~~. Our monthly discharge estimates since 2015 contain pronounced seasonal variations in discharge on the Antarctic Peninsula as a whole and on many of its outlet glaciers, as shown by two other studies to date (Boxall et al., 2022; Wallis et al., 2023). The seasonal cycles across the whole Peninsula have an amplitude of approximately ~~10-15~~5-10 Gt yr^{-1} but with substantial variability between years~~.~~ (Fig. 6).

Within the above regions, we provide discharge time-series for individual glacier, ice stream and ice shelf basins. A selection of these basins, spanning discharges from less than 0.1~~3~~ Gt yr^{-1} to over 100 Gt yr^{-1}, are shown in Fig. 7. The top five contributors to Antarctic-wide grounding line discharge, on average since 2016, are Pine Island Glacier (~~144 ± 9~~146 ± 4 Gt yr^{-1}), Thwaites Glacier (~~136 ± 10~~ 137 ± 2 Gt yr^{-1}), Getz drainage basin (~~104 ± 4~~ 109 ± 2 Gt yr^{-1}), Totten Glacier (~~85 ± 1~~ 84 ± 0.3 Gt yr^{-1}) and

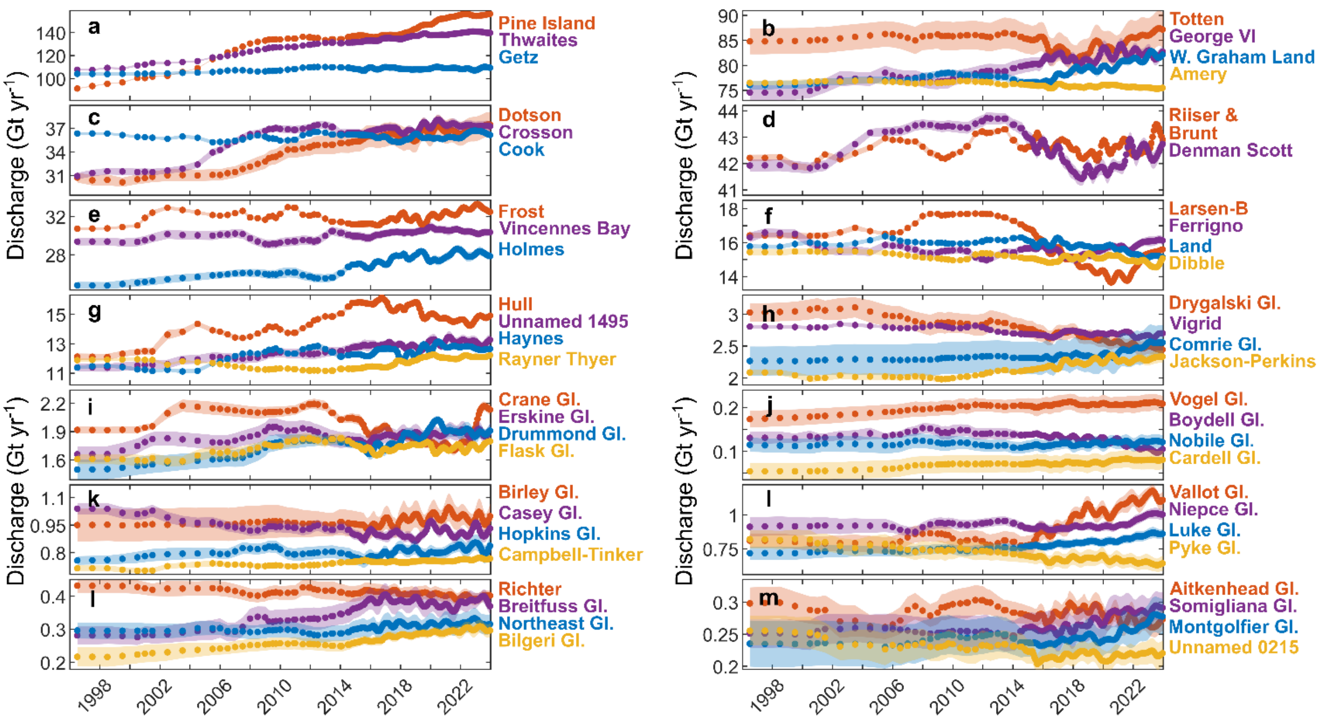

Figure 7. Basin-scale grounding line discharge examples. Grounding line discharge for selected basins from 1996 through 2023. The points show the gate-average discharge estimate and the shading shows the discharge uncertainty (95 % confidence limits). Glacier locations in Figure 8.

George VI (~~72 ± 4~~77 ± 1 Gt yr^{-1}). Discharge from Pine Island Glacier increased from ~~89 ± 0.2~~91 ± 7 Gt yr^{-1} to ~~153 ± 0.6~~156 ± 13 Gt yr^{-1} from 1996 to January 2024~~September 2023~~, but this increase was interrupted by relatively steady discharge from 2009 to 2017 and ~~from late-2021 to 2023~~since 2022 (Fig. 7a). Our dataset also includes other well-known changes in grounding line discharge around Antarctica, including increases at Thwaites Glacier, Crosson and Dotson ice shelves (Fig. 7a,b), and ~~decreases at Drygalski Glacier particularly since 2010~~a progressive deceleration of the Larsen-B tributary glaciers until their recent acceleration in 2022 (Fig. 7f; ~~(~~Ochwat et al., 2023; Surawy-Stepney et al., 2023)~~)~~ and ~~Kamb~~ Whillans Ice Stream (Fig. 8; ~~(~~Joughin et al., 2005)~~)~~. Our dataset also reveals substantial changes in discharge at ~~some~~ many glaciers and ice shelves that are less well-known. These~~,~~ includ~~eing~~, for example, increases in discharge from Cook Ice Shelf basin (Miles et al., 2022), Muller Ice Shelf, Denman Scott Glacier, Holmes, Vincennes Bay (primarily from Vanderford Glacier), Frost Ice Shelf, Ferrigno Ice Shelf, as well as numerous glaciers on the Antarctic Peninsula (Fig. 7). Other basins, such as Richter, Dibble and Boydell Glacier, show declining discharge, whilst many others, such as Rayner Thyer, undergo large multi-year fluctuations in discharge (Fig. 7).

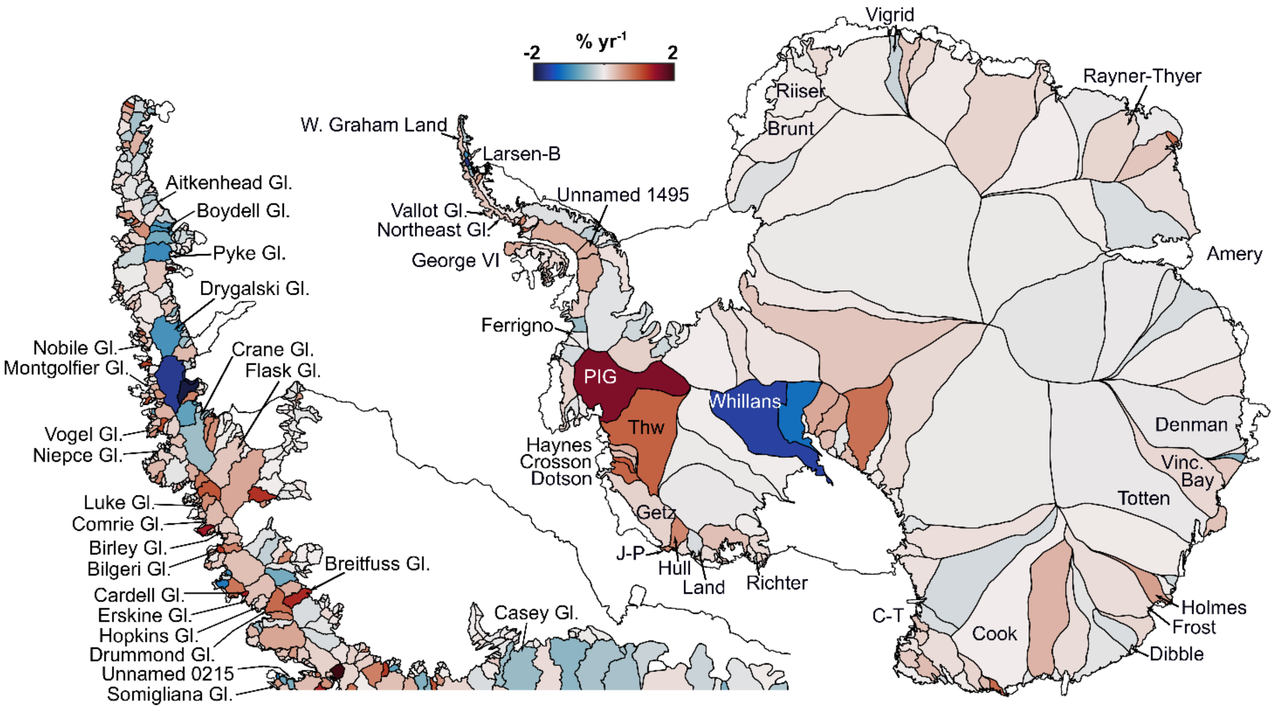

Figure 8. Basin-scale grounding line discharge trends from 1996 to 2023. Overview of grounding line discharge trends from 1996 through 2023, as a percentage of the median discharge in each drainage basin. Basins mentioned in the main text and Figure 7 are labelled. Some basin names have been shortened for display purposes: "Vinc. Bay" is Vincennes Bay; "PIG" is Pine Island Glacier; "Thw" is Thwaites; "Riiser" is Riiser-Larsen; "C-T" is Campbell-Tinker; and "J-P" is Jackson-Perkins.

Fig. 8 provides an overview of 1996 to 2024~~3~~ trends in grounding line discharge from individual glacier and ice stream basins around Antarctica. This overview highlights ~~increasing~~ the rapid increase in grounding line discharge ~~in much~~from the Amundsen Sea Embayment of West Antarctica, ~~especially along the Amundsen Sea coastline~~as well as weaker increases ~~, many basins in the~~in the Bellingshausen Sea, the west coast of the Antarctica Peninsula and across the Indian Ocean-facing sector of Antarctica. It also ~~highlights decreasing~~shows declines in grounding line discharge from ~~many glaciers and ice streams~~Whillans Ice Stream~~ feeding the Ross Ice Shelf~~, from ~~glaciers draining Oates Land~~numerous basins around Amery Ice Shelf in East Antarctica, and from many glaciers ~~(for example, Boydell Glacier) surrounding Longing Peninsula~~ on the east coast of the Antarctic Peninsula (Fig. 8). This broad spatial pattern of grounding line discharge change is consistent with, but adds more detail to, changes in ice sheet surface elevation over a similar time period (Shepherd et al., 2019).

3.2 Effect of bed topography dataset on discharge

Excluding FrankenBedAdj, the choice of bed topography dataset affects the Antarctic-wide discharge estimate by 55 Gt yr^{-1} on average (Fig. 9). At the continent scale, FrankenBed produces the highest discharge and BedMachine and BedMap2 respectively produce discharge 3.0~~9~~ % and 4.2~~3.4~~ % lower

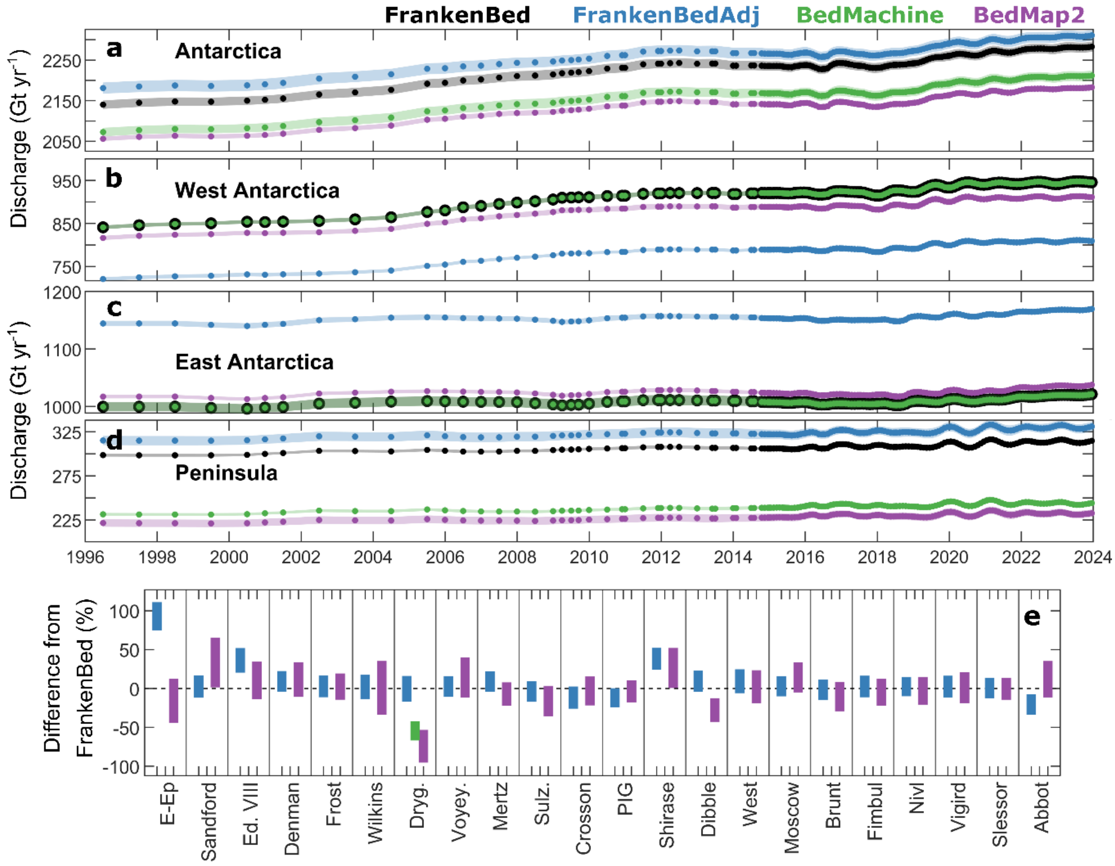

Figure 9. Impact of bed topography dataset on grounding line discharge. Grounding line discharge time-series averaged across all flux gates for (a) Antarctica, (b) West Antarctica, (c) East Antarctica and (d) the Antarctic Peninsula. Panel (e) shows the percentage difference in grounding line discharge produced using FrankenBedAdj, BedMachine and BedMap2 compared to FrankenBed, for a range of drainage basins. The vertical extent of each bar represents the potential spread in the differences between bed products owing to error in each discharge estimate. Note that FrankenBed and BedMachine are identical for all displayed basins except Drygalski Glacier. Some basins have been shortened for display purposes: "Ed. VIII" is Edward VIII, "Dryg." is Drygalski Glacier, "Voyey." is Voyeykov Ice Shelf and "Sulz." is Sulzberger Ice Shelf.

than with FrankenBed. BedMap2 gives discharge that is 3.5 % lower than FrankenBed in West Antarctica, 1.6 % greater in East Antarctica and 26 % lower on the Antarctic Peninsula. BedMachine and FrankenBed are identical in West Antarctica and East Antarctica, but BedMachine gives discharge 22 % lower than FrankenBed on the Peninsula.~~In West Antarctica, the difference between FrankenBed and BedMachine is negligible and the difference with BedMap2 is 3 %. In East Antarctica, BedMachine produces 0.4 % less discharge than FrankenBed, whilst BedMap2 produces 2.3 % more than FrankenBed. The bed datasets differ most on the Antarctic Peninsula, where BedMachine and BedMap2 give 29 % and 26 % less discharge than FrankenBed (Fig. 9),. which we attribute to the overly-shallow topography and therefore implausibly thin ice given by those datasets on the Peninsula.~~ Within individual MEaSUREs glacier basins, BedMachine typically causes either positive or negative discharge changes of 2.5 % or less compared to FrankenBed and the discharge implied by BedMap2 is typically ~~underestimates~~ lower than from FrankenBed by discharge by ~~2.5-7.5~~1 to 5 % ~~relative to FrankenBed~~ (Fig. 9~~f~~). The impact can be much larger for some individual basins, especially those on the Antarctic Peninsula; for example, the discharge from ~~Hektoria~~ Drygalski Glacier is ~~90~~ over 40 % lower using BedMachine and BedMap2 than it is with FrankenBed. ~~and the differences are typically greater than 75 % for individual glaciers on the Peninsula.~~ The standard error of discharge across our 16 flux gates is similar between FrankenBed, BedMachine and BedMap2, despite the increase in bed topographic observations and improvements in interpolation and assimilation methods since BedMap2 was developed.

Our grounding line discharge estimate derived using FrankenBedAdj differs substantially from that using the other bed products in the majority of basins ~~, with the largest differences between FrankenBedAdj and FrankenBed are in East Antarctica and the Peninsula~~ (Fig. 9). FrankenBedAdj increases our pan-Antarctic discharge estimate by 1.4 %, but has opposing and roughly equal effects in East and West Antarctica; decreasing West Antarctic discharge by 14 % whilst increasing East Antarctic discharge by 14.5 %. It increases discharge from the Peninsula by 5 %. For some basins, the impact of FrankenBedAdj is dramatic, for example ~~In~~ discharge from basin E-Ep in East Antarctica (location in Fig. 5), ~~FrankenBedAdj produces a discharge more than~~is over 80 % greater using FrankenBedAdj than that ~~using~~ with FrankenBed (Fig. 9) ~~(Fig. 9)~~. ~~On the Peninsula, FrankenBedAdj produces a discharge estimate almost 20 % greater than that derived from FrankenBed (Fig. 9).~~ Some of the differences between FrankenBedAdj and the other bed topography products will be due to uncertainties in mass balance estimates and unknown uncertainties in SMB modelling, particularly in ~~Victoria Land~~and around basin E-Ep, and in mountainous areas like the Antarctic Peninsula, –where radar-derived elevation change measurements have lower performance and SMB models disagree substantially (Mottram et al., 2021). Nevertheless, basins in which the discharge from FrankenBedAdj differ substantially from FrankenBed (Fig. A2) could be useful areas to target future bed topographic mapping campaigns. We reiterate that the derivation of FrankenBedAdj assumes that ice thickness is the only contributor to differences between mass balance estimates derived from the input-output method and altimetry measurements (Appendix A), so we consider these discharge differences upper bounds on that owing to uncertainties in bed topography.

3.3 Effect of gate location

Antarctic-wide grounding line discharge varies by 41~~99~~ Gt yr^{-1} (1.8~~4.5~~ %) on average ~~from 1996 througho 2023~~ between our most upstream and downstream flux gates, and individual gates are generally less than 2 % different from the gate-average discharge (Fig. 10). East Antarctic has the largest relative change in discharge between flux gates: discharge from the most seaward gate is 3.7 % greater than the most upstream gate and 2.5 % from the gate-mean discharge. The Antarctic Peninsula ~~is the area with the largest relative differences between flux gates, where the most upstream and downstream gates differ from each other by 6 %~~exhibits some seasonality in the inter-gate discharge differences (Fig. 10), likely reflecting seasonal changes in velocity retrieval in summer and winter. The differences

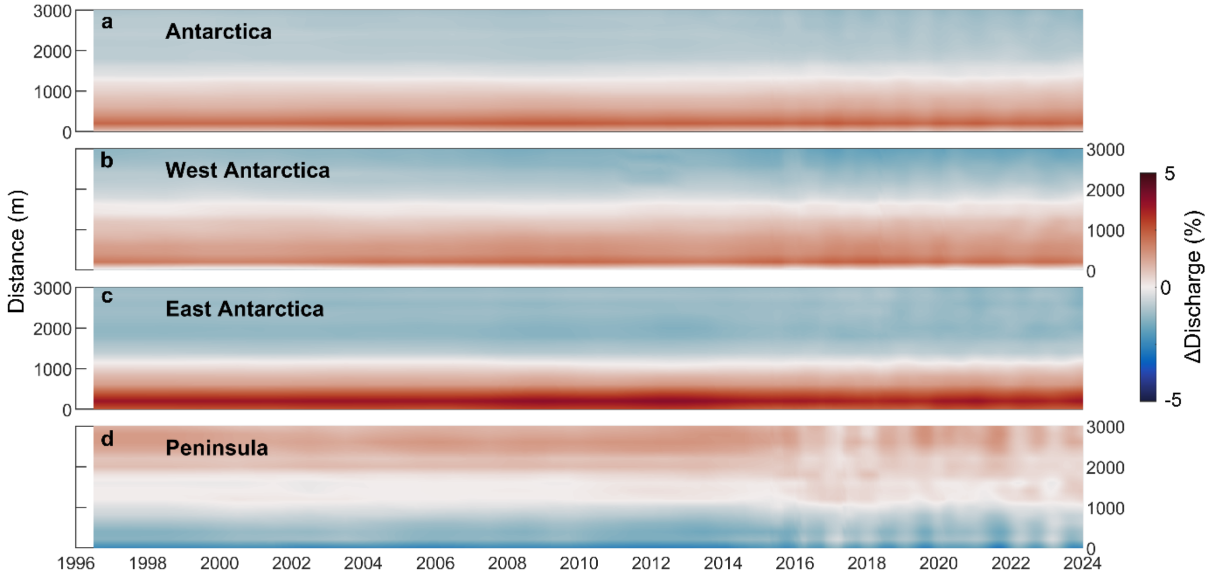

Figure 10. Impact of flux gate location on grounding line discharge. Time-series of the percentage difference in grounding line discharge from the inverse error-weighted mean discharge across all flux gates for (a) Antarctica, (b) West Antarctica, (c) East Antarctica and (d) the Antarctic Peninsula. The y-axes correspond to the distance upstream of the first flux gate.

between flux gates primarily reflects the difficulty in conserving mass with imperfect ice thickness, velocity and surface mass balance data, rather than algorithmic errors. Reflective of this, the location of the flux gate makes a small difference for basins where the bed is well surveyed. For example, at Pine Island Glacier, the maximum discharge difference between any flux gate and the gate-average is just 2.1~~1.7~~ Gt yr^{-1} (1.~~3~~5 %). Some studies (Davison et al., 2023c; Gardner et al., 2018) have minimised the impact of uncertain bed topography by placing their flux gates directly over bed topographic observations (primarily from radar flight lines). We opt instead to use the inverse error-weighted average of all gates, which has the advantage of permitting algorithmic gate generation and will prioritise gates positioned closer to bed elevation observations since the error in the bed products is primarily determined by the distance to the nearest bed elevation observation.

3.4 Effect of thickness adjustments

We apply ~~three~~ two modifications to the reference ice thickness extracted at each flux gate. These are (1) applying observed rates of surface elevation change based on a quadratic fit to elevation change observations from 1992 to 2023 to obtain a time-series of ice thickness at each flux gate pixel, and; (2) the removal of firn air content using a time-series of firn air content from two firn models.~~, and; (3)~~ We also correct the basin-integrated discharge ~~a correction for any changes in ice thickness that occur between the flux gate and the grounding line due to surface processes~~to account for surface mass balance changes between each flux gate and the grounding line. Antarctic-wide, the overall impact of these modifications is to ~~reduce~~ increase grounding line discharge by 23~~7~~ Gt yr^{-1} in 1996 and reduce it by 10~~58~~ Gt yr^{-1} in January 2024~~3~~ (Fig. 11). The individual corrections for firn air content and surface

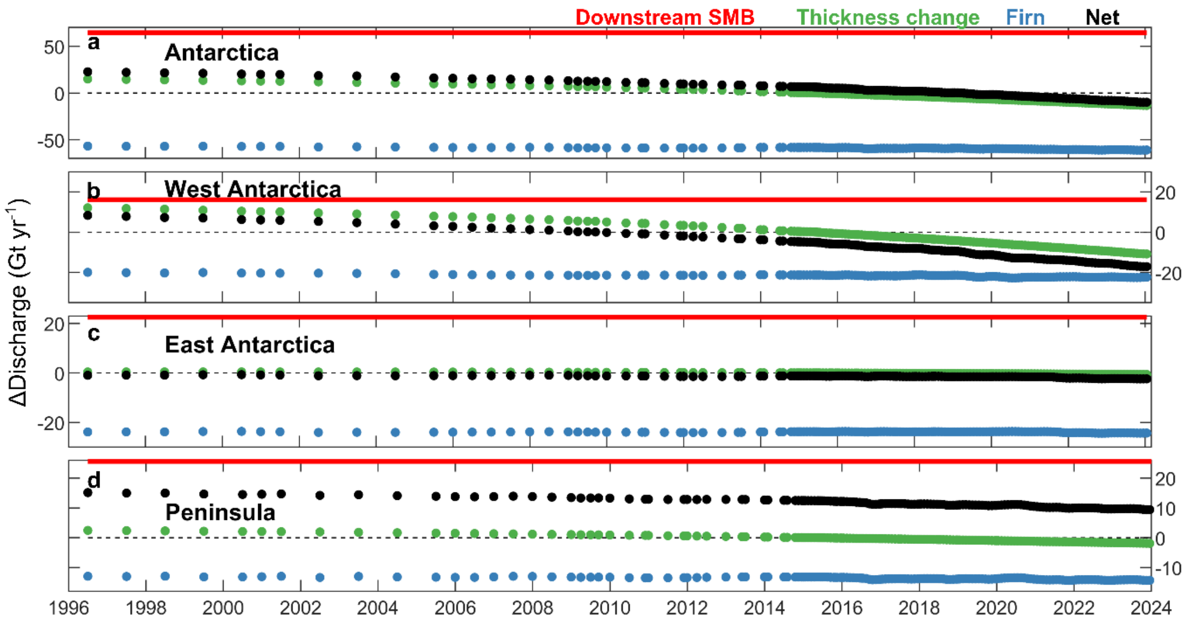

Figure 11. Timeseries of ice thickness and surface mass balance (SMB) corrections. The impact of SMB changes downstream of the flux gate (red dots), altimetry-derived thickness change (green dots) and removal of firn air content (blue dots) (described in text) on the derived grounding line discharge from (a) Antarctica, (b) West Antarctica, (c) East Antarctica and (d) the Antarctic Peninsula. The sum of the three corrections is also shown (black dots). Note that surface elevation changes are applied to our reference Antarctic Ice Sheet surface, which is timestamped to 9th May 2015.

mass balance impacts are larger (over 50 Gt yr^{-1}) but opposing and change little over time. ~~The majority of the reduction in discharge from these modifications is due to the removal of firn air content, which reduces Antarctic grounding line discharge by 59 Gt yr^{-1} on average, with a standard deviation of 2 Gt yr^{-1}, when using the IMAU FDM.~~ The majority of the change in the impact of these modifications from 1996 through~~o~~ 2024~~3~~ is due to changes in ice surface elevation during that period, which cause an overall decrease in discharge of 28~~6~~ Gt yr^{-1} from 1996 through~~o~~ 2023 (Fig. 11). The impact of surface elevation changes on grounding line discharge is greatest in West Antarctica, where thinning rates are highest (Fig. 11; Fig. A1). The impact of firn air content removal is comparable in East and West Antarctica (approximately 22 Gt yr^{-1} or 2 % discharge reductions each, on average) and is greatest in relative terms on the Peninsula (14 Gt yr^{-1} or 4~~5~~ %). The effect of gate-to-grounding line ~~thickness changes from SMB~~SMB changes is to increase Antarctic grounding line discharge by ~~14 17~~21 Gt yr^{-1} at the most seaward flux gate, increasing to 105 Gt yr^{-1} at the most upstream gate (Fig. 11).

The choice of firn densification model has a negligible (0.4 %) impact on Antarctic-wide grounding line discharge (Fig. 12), regardless of which flux gate is used. The IMAU-FDM gives consistently lower firn air content (Fig. 2d) so produces slightly higher discharge values than the GSFC-FDMv1.2. The differences between the firn models are generally greatest (~1 % discharge equivalent) on the Peninsula, which we interpret to be primarily due the ability of each model to resolve the impact of steep topography on surface processes, owing to their different spatial resolutions (12.5 x 12.5 km for the GSFC-FDMv1.2 and 27 x 27 km for the IMAU FDM). In some basins, the choice of firn model makes

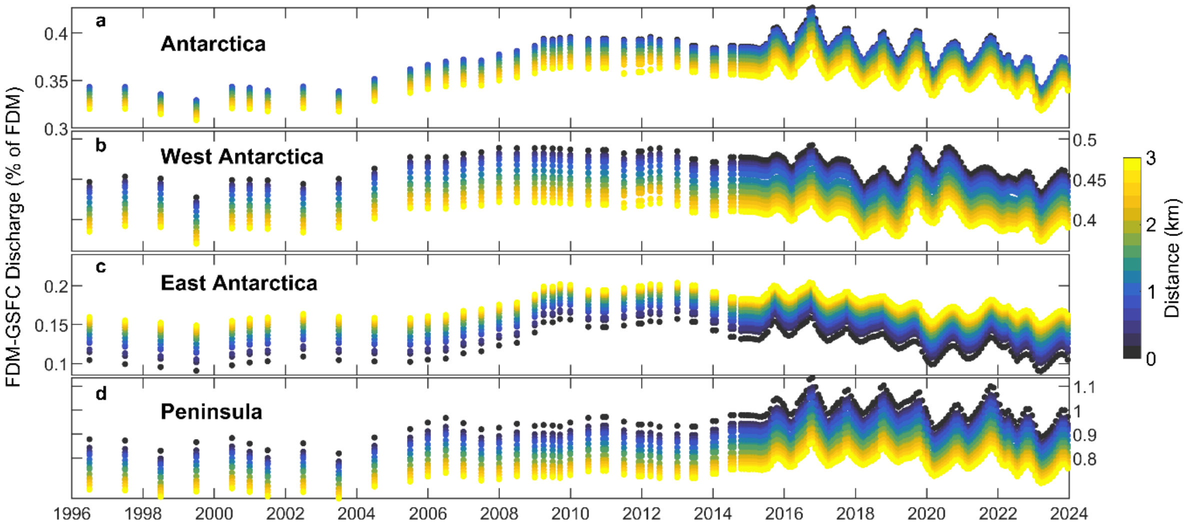

Figure 12. Impact of firn model choice on Antarctic grounding line discharge. Time-series of the difference in grounding line discharge when using the IMAU FDM compared to the GSFC-FDMv1.2 from (a) Antarctica, (b) West Antarctica, (c) East Antarctica and (d) the Antarctica Peninsula. Point are coloured according to their distance in kilometres from the most downstream flux gate (blue) compared to the most inland flux gate (yellow).

an appreciable difference – for example, at Moser Glacier, the IMAU-FDM decreases grounding line discharge by 4 % relative to the GSFC-FDMv1.2 on average. Basins with large relative differences are generally very small – with widths much less than the resolution of either firn model – so contribute little to total Antarctic discharge and require extraction from a single firn model pixel that will in many cases not resolve the glacier geometry. Overall then, the use of a firn model has a large enough impact on grounding line discharge to be relevant to glacier mass balance, but the choice of firn model seems to have little impact on Antarctic discharge, at least for the two firn models examined here.

4 Discussion

4.1 Comparison to previous estimates

Surprisingly few estimates of Antarctic grounding line discharge have been published and made freely available, so we hope that the community will benefit from the release of the dataset described in this study. We focus our comparison on previous estimates that encompass the majority or all of the Antarctic Ice Sheet (Depoorter et al., 2013; Gardner et al., 2018; Miles et al., 2022; Rignot et al., 2019). We note that the '2008' discharge estimates from Gardner et al. (2018) and Depoorter et al. (2013) were estimated using a velocity mosaic (Rignot et al., 2017) compiled from images acquired during the 1996 to 2009 period, but the majority of those images were acquired between 2007 and 2009. To compare our discharge time-series to those data, we use our average discharge from January 2007 to December 2009. Rignot et al. (2019) used a range of methods to estimate grounding line discharge; we restrict our comparison to basins for which discharge was estimated using a comparable method (i.e. using both measured ice velocity and ice thickness).

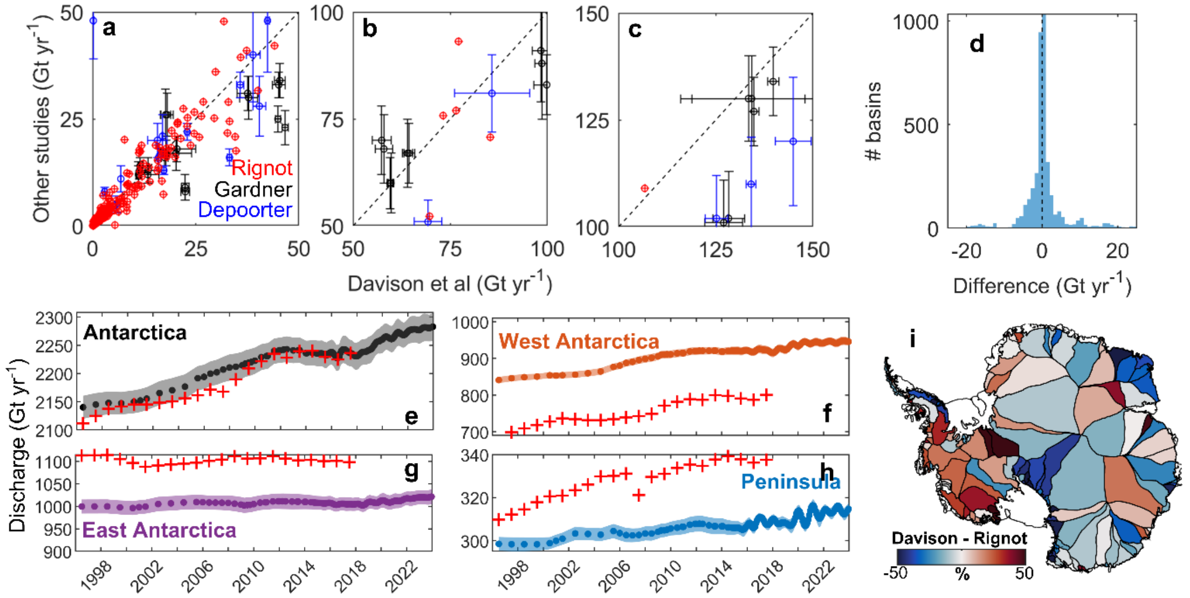

Figure 13. Comparison to existing grounding line discharge estimates. Panels (a) to (c) show comparisons with Rignot et al. (2019), Gardner et al. (2018) and Depoorter et al. (2013) for equivalent basins and during overlapping time-periods. Each point shows the discharge for a single basin, with errors provided where available. (d) Histogram of the discharge residuals from panels (a) to (c). Panels (e) to (h) show time-series of our primary discharge estimate (using FrankenBed) compared to estimates from Rignot et al. (2019) (red crosses). (i) Basin-scale comparison of discharge between this study and Rignot et al. (2019) during their overlapping time periods, as a percentage of the Rignot discharge.

There are substantial differences between our discharge estimates and other published estimates for some basins and for Antarctica, East Antarctica, West Antarctica and the Antarctic Peninsula as a whole (Fig. 13). For Antarctica as a whole, our new dataset compares favourably to that of Rignot et al. (2019) but our dataset gives discharge on average 133 Gt yr^{-1} greater in West Antarctica, 97 Gt yr^{-1} lower in East Antarctica and 13 Gt yr^{-1} lower on the Antarctic Peninsula than estimates from Rignot et al. (2019). ~~The average absolute difference between our discharge estimates and the available alternative estimates is 5 Gt yr~~$^{-1}$~~.~~ In some basins, the differences among estimates are ~~much~~ large~~r~~ relative to our estimates dicharge. For example, Depoorter et al. (2013) estimate the discharge from Filchner-Ronne to be 72~~69~~ Gt yr^{-1} (24~~3~~ %) lower than in this study, the discharge from Brunt and Riiser-Larsen to be 5.6~~9~~ Gt (13~~23~~ %) greater, the discharge from Pine Island to be 24~~17~~ Gt yr^{-1} (18~~13~~ %) lower, and the discharge from Sulzberger to be 4~~5.6~~ Gt (24~~37~~ %) greater than in this study. Depoorter et al. (2013) use a combination of ice thickness estimates based on the assumption of hydrostatic equilibrium and from ice penetrating radar measurements, whereas we draw on gridded bed topography products – the differences between these thickness datasets accumulate across long flux gates like that at Filchner-Ronne, Brunt, Riiser-Larsen and Sulzberger. Depoorter et al. (2013) also use different flux gate positions than used here, which could plausibly account for much of the difference in flux estimates. To illustrate, we find a 27~~39~~ Gt yr^{-1} difference between our most upstream and downstream flux gates at Filchner-Ronne. Some small basins with little grounding line discharge have very large proportional differences between estimates. For example, our discharge into Conger Glenzer Ice Shelf is 0.8~~1~~ Gt yr^{-1}, or ~~less than~~

~~half~~about 60 % of that in Rignot et al. (2019). In these cases, the absolute differences are comparable to the error in the estimate and may due to the resolution of the flux gate used, as well as the choice of bed topography and ice surface dataset.

4.2 Implications for mass budget estimates

At present, only one input-output estimate of Antarctic Ice Sheet mass balance is available (Rignot et al., 2019). This sparsity of input-output data limits the otherwise comprehensive scope of ice sheet mass balance inter-comparison exercises (Otosaka et al., 2023) and limits insights conferred by mass budget partitioning attempts. Here, we briefly examine the mass balance implied by our grounding line discharge and the mean of three regional climate models (Fig. 14), in comparison to a reconciled mass balance estimate (Otosaka et al., 2023). ~~By providing discharge estimates derived using a range of bed topography datasets, we hope that the community will take advantage of the full range of available SMB datasets to compute Antarctic Ice Sheet mass change for any basin of interest, so as to enable deeper investigations into uncertainties and drivers of Antarctic Ice Sheet mass change.~~The mass balance of Antarctica and each ice sheet region implied by our discharge estimates using FrankenBedAdj are, perhaps unsurprisingly, very similar to those presented in the latest IMBIE assessment (Fig. 14). FrankenBed compares well to the IMBIE estimate for Antarctica as a whole and on the Peninsula, but overestimates mass loss in West Antarctica and implies large mass gain in East Antarctica, rather than negligible mass change. It is our hope that the community will take advantage this discharge dataset and the full range of available SMB datasets to compute Antarctic Ice Sheet mass change for any basin of interest, so as to enable deeper investigations into uncertainties and drivers of Antarctic Ice Sheet mass change.

There ~~is currently~~remains significant uncertainty in mass change estimates of some basins as calculated using the input-output method. In some basins, the differences between available discharge estimates, including our own, can lead to opposing conclusions regarding the overall mass change of the basin. For example, Hansen et al. (2021) found opposing mass change trends on the Antarctic Peninsula when using two different discharge datasets and a single SMB dataset. This is also apparent in our dataset when comparing the mass balance of the Peninsula computed using different bed topography datasets (Fig. 14). The mass change sensitivity to the choice of discharge dataset will be particularly severe in basins from which the grounding line discharge is consistently above or below the integrated SMB by an amount comparable to the error in the discharge estimates.

Whilst we think that our grounding line discharge estimate ~~is the best that can currently be achieved using existing ice velocity, ice thickness and firn air content estimates~~offers many improvements in terms of spatial and temporal resolution, combination of ice velocity datasets, time period surveyed and processes included (firn air content, surface elevation change and surface mass changes), several uncertainties still hinder input-output mass balance estimates~~we do not expect it to entirely resolve these~~

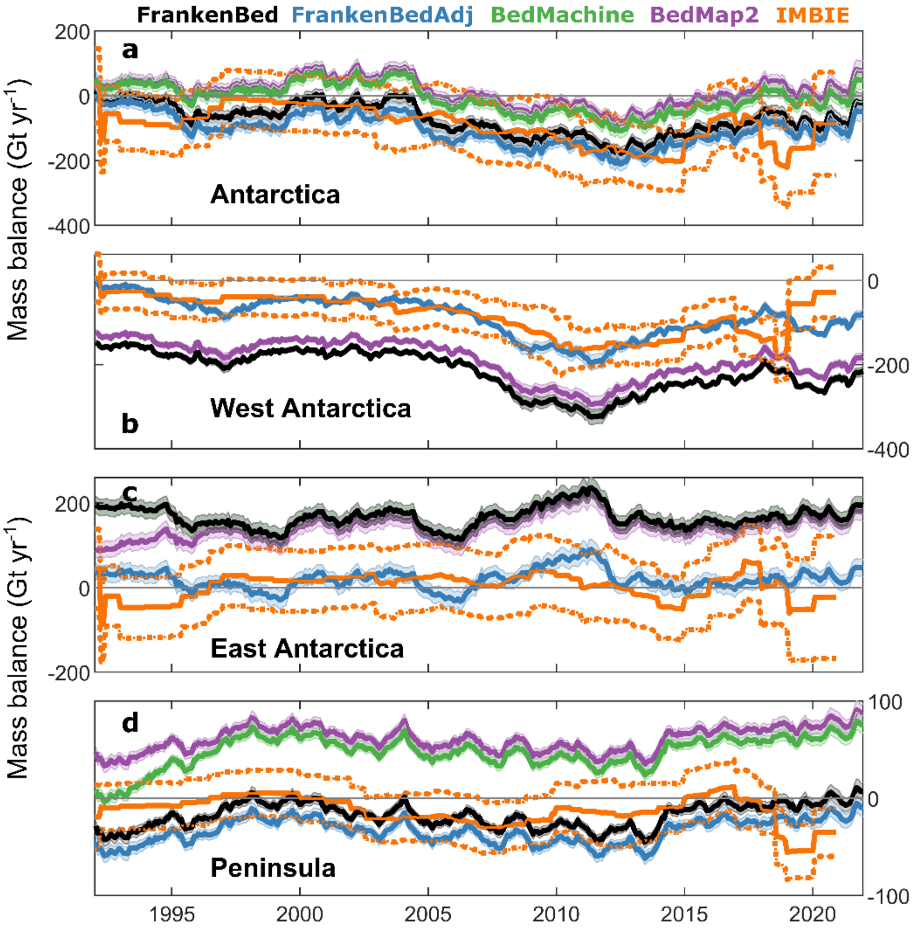

Figure 14. Antarctic Ice Sheet mass balance. Mass balance time-series for (a) Antarctica, (b) West Antarctica, (c) East Antarctica and (d) the Antarctic Peninsula, compared to the third IMBIE assessment in orange (Otosaka et al., 2023). Mass balance is calculated using the mean of the three regional climate models described in the main text.

~~challenges~~. We still find substantial differences in some basins between (i) our primary discharge estimates from FrankenBed compared to those provided by FrankenBedAdj (which we tuned to match independent mass loss observations) and (ii) the discharge estimates provided by Rignot et al. (2019), who manually selected different approaches to determine grounding line discharge~~ and who modified ice thickness in a non-algorithmic manner in order to produce the required ice flux~~. ~~In general, our FrankenBed discharge is lower than from FrankenBedAdj and lower than in Rignot et al. (2019), implying less mass loss~~In West Antarctica, our FrankenBed discharge is greater than that in Rignot et al. (2019) and that from FrankenBedAdj. In East Antarctica, the opposite is true: FrankenBed implies lower discharge than in Rignot et al. (2019) and FrankenBedAdj. There are only three plausible explanations for these deviations. (1) ~~The ice thickness used here is an underestimate of the true ice thickness in places where our ice flux is too low, thereby leading us to underestimate grounding line discharge~~Uncertainties in ice thickness cause us to overestimate grounding line discharge in West Antarctica and underestimate it in East Antarctica and on the Peninsula. This is likely to be true on the Peninsula, where the bed is poorly surveyed and the balance thickness used here (Huss and Farinotti,

2014) was calculated using low-resolution SMB estimates that give lower SMB than statistically-downscaled equivalents (Noël et al., 2023). (2) ~~Basin-scale S~~surface mass balance ~~provided~~ from ~~by~~ the mean of RACMO2.3p2, MAR and HIRHAM ~~are~~ is too high in East Antarctica and too low in West Antarctica, ~~leading~~ resulting in apparent input-output mass ~~balance~~ gain in East Antarctica and mass loss in West Antarctica, ~~to underestimate mass balance~~ even where the grounding line discharge with FrankenBed is correct. This could be the case in West Antarctica and in the Amundsen Sea Embayment, where the bed is well-surveyed. (3) The mass loss estimates from gravimetric and altimetric approaches are too great, possibly because of uncertainties in rates of glacial isostatic adjustment, which gravimetric approaches are sensitive to, or uncertainties in the density of snow and ice contributing to the observed changes in surface elevation. This could be the case especially in East Antarctica, where small uncertainties accumulate over large integration areas, and on the Peninsula where altimetry measurements are compromised by heavy snowfall and rapid surface melting as well as steep ice surface slopes.

It is probable that all of these factors contribute to differences between mass budget estimates and that basin-scale comparisons between mass budget approaches will offer deeper insights into their respective uncertainties. Given that Antarctic Ice Sheet mass changes estimated from gravimetry and altimetry agree much more closely with each other than either do with the single available input-output mass change estimate, especially in East Antarctica (Otosaka et al., 2023), it seems unlikely that (3) is the dominant contributor to ~~the challenges facing the input-output method~~differences between input-output mass balance estimates and reconciled estimates at the spatial scale considered in this comparison (Fig. 14). If (1) were the sole contributor, then our thickness adjustments in FrankenBedAdj provide an ~~rough~~ approximate indication of the magnitude and location of poorly-constrained thickness in existing bed products and could be used to guide future bed topographic mapping efforts. Given that the magnitude of the thickness adjustments in FrankenBedAdj exceed 50 % in some places, and that these are typically in locations where SMB and firn air content estimates from different regional climate models disagree the most (such as basin E-Ep in East Antarctica), we think that factors (1) and (2) likely contribute ~~to~~ the majority of differences between mass budget approaches at the scale considered here. It is our hope that synergistic use of each mass budget approach, with due consideration for the location-specific uncertainties in each method, will lead to increased confidence regarding the direction and magnitude of mass change around Antarctica, as well as improved understanding of the drivers of that mass change.

5 Data availability

The ice sheet basins, balance discharge and grounding line discharge estimates are, for the purposes of review, available at: ~~https://zenodo.org/records/10183327~~ https://zenodo.org/records/10700903 (Davison et al., 2023a).

6 Conclusions

We present a new grounding line discharge product for Antarctica and all of its drainage basins available from 1996 through to ~~last month~~January 2024. The temporal resolution and coverage increases from annual and <25 % respectively in the early years of our dataset to monthly and over 50 % respectively in the latter years of our dataset. We show that grounding line discharge from Antarctica increased from 2,140 ± 189 ~~1,990 ± 23~~ Gt yr^{-1} in 1996, rising to 2,283 ± 207~~2,205 ± 18~~ Gt yr^{-1} in ~~September~~ January 2024~~3, with slight fluctuations superimposed on this longer term increase~~. Much of this grounding line discharge change is due to increasing flow speeds of West Antarctic ice streams, but we also observe large increases in discharge at some basins in East Antarctica, including ~~Totten Glacier,~~Holmes, Vanderford Glacier, Denman Scott and Cook Ice Shelf. The high spatial resolution of our ice velocity mosaics since October 2014 allow us to measure substantial seasonal variability and pronounced multi-year trends in discharge even on small ~1 km-wide glaciers draining the Antarctic Peninsula.

Our results broadly agree with other published discharge estimates; however, t~~T~~here are substantial differences in some basins. ~~between our results and previous estimates during their overlapping time periods (Rignot et al., 2019; Gardner et al., 2018; Depoorter et al., 2013).~~ Broadly, our discharge estimate is greater in West Antarctica and lower in East Antarctica and on the Peninsula than other estimates. These differences generally arise due to uncertainties in bed topography, which can accumulate across long flux gates or which represent a substantial proportion of the discharge across very short flux gates, and due to differences in ice velocity resolution and flux gate position. For some basins, the differences between existing discharge datasets, including our own, is significant enough to have bearing on the mass change of those basins when using the input-output method, particularly in basins which remain close to balance but which are persistently above or below balance. This is particularly acute on the Antarctic Peninsula and in ~~parts of~~ East Antarctica, where deriving estimates of ice thickness, ice velocity, firn air content and surface mass balance are fraught with difficulties owing to the steep topography, narrow glaciers, high snowfall and (in places) intense summertime surface melting.

We find that bed topography remains a potentially large uncertainty in grounding line discharge estimates and therefore has the potential to severely limit the utility of attempts to calculate basin-scale ice mass change using the input-output method. In order to reproduce observed rates of mass loss, we have to modify the bed topography by over 50 % in some basins. This may be realistic in some places where the bed is poorly surveyed; however, uncertainties in SMB and uncertainties in independent estimates of mass change ~~will also contribute~~should not be ignored. The progressive increase in ice thickness measurements around Antarctica (Frémand et al., 2023) and the improvements in assimilation and interpolation methods (Ji Leong and Joseph Horgan, 2020; Morlighem et al., 2020) will lead to improved estimates of ice thickness around Antarctica – our workflow is designed to facilitate the addition of new bed topography datasets as they become available and we aim to do so. We have provided this dataset for the scientific community so as to ensure that accurate measurements of Antarctic grounding line discharge remain available routinely for researchers everywhere.

Appendix A: Making FrankenBedAdj bed topography

Here we describe the method used to adjust the FrankenBed elevations such that the corresponding discharge estimate produces the observed change in ice surface elevation.

The mass balance, *M*, of an ice sheet or ice sheet basin is given by:

$$M = S - D, \tag{A1}$$

where *S* is the surface mass balance and *D* is the grounding line discharge. For each of the MEaSUREs ~~glacier~~ regional basins, we estimate the 1996 to 2021~~14~~ average mass balance by integrating ice equivalent surface elevation change measurements over each basin (Shepherd et al., 2019). The rates of elevation change from 1992 to 2023 are shown in Fig. A1. Using this rate of mass change, we estimate the average discharge required to produce that mass change (Fig. A2), given the surface mass balance anomalies from three regional climate models including RACMO2.3p2, MAR and HIRHAM5. We refer to this as our altimetry-derived discharge.

For each basin, we proportionally adjust the pixel-based ice thickness based on the difference between our calculated basin-scale discharge and the altimetry-derived discharge. This is akin to rearranging Eq. (4) to:

$$H = D/Vw\rho, \tag{A2}$$

Where *V* is the 1996 to 2021~~14~~ average velocity normal to the flux gate in each pixel, ~~and~~ D is the altimetry-derived discharge~~.~~ and ~~In~~ *w* is the total length of the gate in each basin. In practice, this is an iterative process because we modify the pixel-based ice thickness to solve for the basin-scale altimetry-derived discharge. The effect of these thickness adjustments are shown in Fig. 2 of the main text and Fig. A2.

This approach forces our 1996 to 2021~~14~~ mean discharge derived from FrankenBedAdj to match the 1996 to 2021~~14~~ mean discharge inferred from ice sheet surface elevation change measurements and regional climate model output. As such, the FrankenBedAdj discharge dataset is not fully independent of one altimetry-derived mass change estimate; therefore, we recommend caution if using that subset of the dataset in inter-comparison exercises such as IMBIE. The FrankenBedAdj estimate does, however, provide an indicator of which regions of existing Antarctic bed topography datasets may be under- or over-estimating the bed elevation on average, especially in drainage basins where there is confidence in the velocity measurements and SMB products.

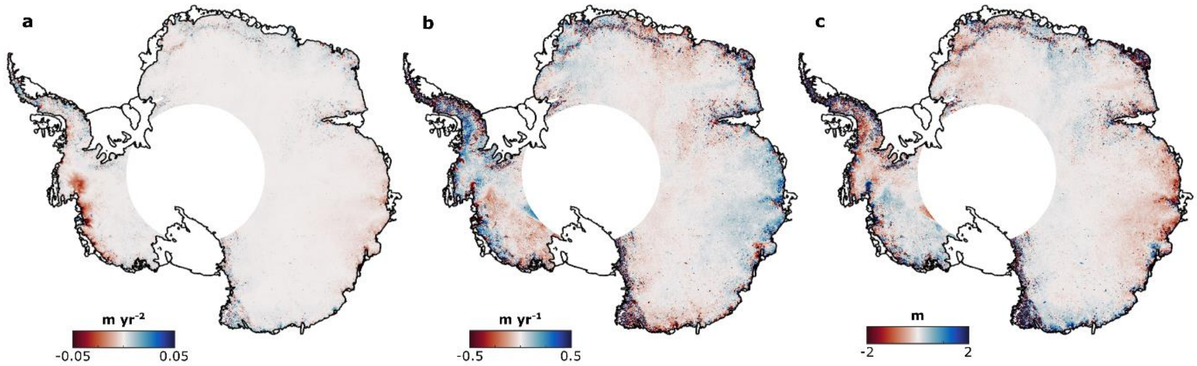

Figure A1. Coefficients from a time-dependent quadratic polynomial fitted to surface elevation change observations. The (a) acceleration, (b) linear and (c) intercept coefficients of the quadratic fit to observed surface elevation changes from 1992 to 2023 as measured by a suite of radar altimetry satellite missions.

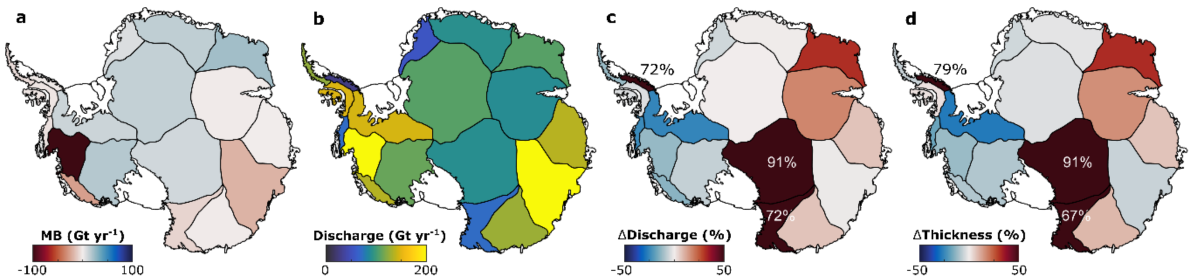

Figure A2. Creating FrankenBedAdj. (a) Observed rate of mass change from 1996 to 2021 based on the observed rates of ice surface elevation change in Figure A1. (b) Grounding line discharge, within each MEaSUREs regional basin, implied by the observed rates of mass change, given the surface mass balance from the mean of three regional climate models (described in text). (c) The percentage difference between the discharge in panel (b) and our average 1996-2021 discharge derived from FrankenBed. (d) The change in FrankenBed thickness required at the most downstream flux gate in order to reproduce panel (b).

Given that our adjustment is a simple proportional shift of the FrankenBed profile across each of the MEaSUREs glacier basins, we do not intend FrankenBedAdj to be taken as a superior bed elevation product for Antarctica. This proportional shift in ice thickness leads to greater cross-flow gradients in bed slope where thickness increases and lower gradients where thickness decreases (Fig. 1; Fig. A3). Our approach will be somewhat sensitive to the choice of basins used to perform the integration and it produces unrealistic steps in bed elevation at the boundaries between basins. These steps have little impact on our grounding line discharge estimate, but could be consequential if the modified bed data were used in, for example, ice sheet modelling applications.

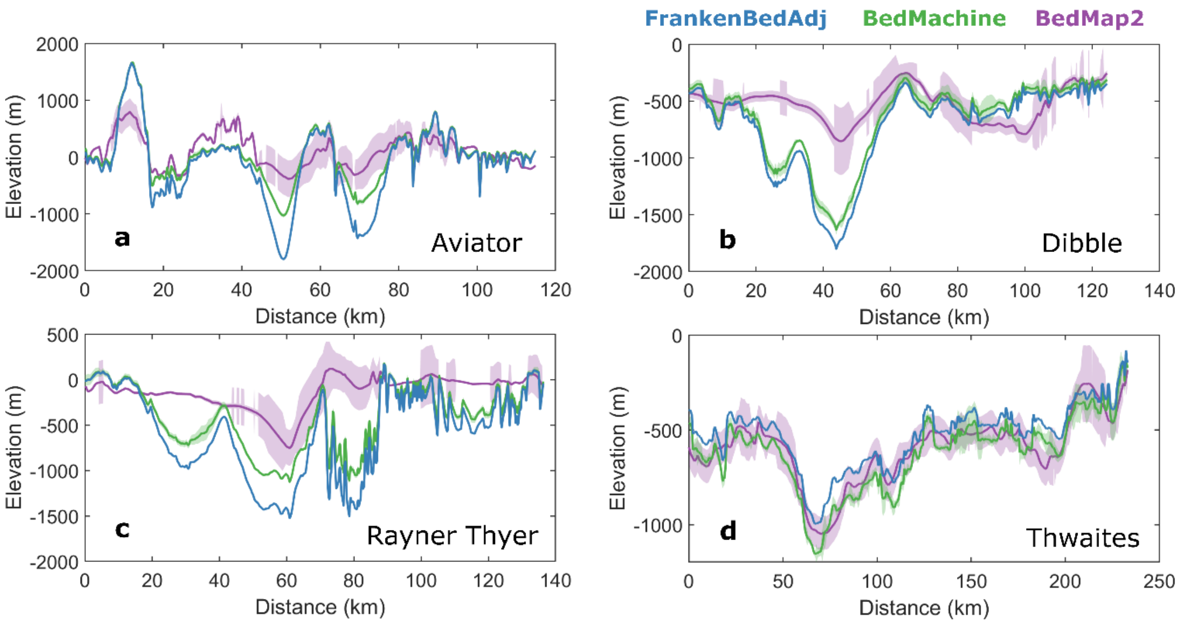

Figure A3. Bed elevation profiles. Each panel shows bed elevation in BedMachine v3 (green), BedMap2 (magenta) and FrankenBedAdj at our most seaward flux gate (blue) in example basins.

Appendix B: Sentinel-1 ice velocity maps

We generate monthly velocity mosaics from October 2014 through to January 2024 by applying standard intensity tracking techniques (Strozzi et al., 2002) to Copernicus Sentinel-1 synthetic aperture radar (SAR) single look complex (SLC) interferometric wide mode (IW) image pairs (Davison et al., 2023c; Hogg et al., 2017). We process all available 6- and 12-day image pairs acquired over Antarctica; all image pairs prior to the launch of Sentinel-1b in April 2016 and after the failure of Sentinel-1b in December 2021 are 12-day pairs. We estimate ice motion by performing a normalized cross-correlation between image patches with dimensions 256 pixels in range and 64 pixels in azimuth, and a step size of 64 pixels in range and 16 pixels in azimuth. To maximise tracking results in regions where velocity varies by more than an order of magnitude, we also use patch sizes of 362x144 and 400x160 pixels over East and West Antarctica, and four further patch sizes on the Antarctic Peninsula (192x48, 224x56, 288x72 and 320x80 pixels in range and azimuth). For scenes in East and West Antarctica, we use the a 1 km DEM (Bamber et al., 2009), whereas for scenes in the Antarctic Peninsula we use the REMA 200 m DEM (Howat et al., 2019). Prior to image cross-correlation, we perform image geocoding using the precise orbit ephemeris (accurate to 5 cm) where available and the restituted orbits otherwise (accurate to 10 cm) (Fernández et al., 2015). In common with comparable estimates of Greenland Ice Sheet velocity (Solgaard et al., 2021), we find no significant difference between pairs processed using each orbit type. Each image pair velocity field is posted on a 100x100 m grid in Antarctic Polar Stereographic coordinates (EPSG 3031).

For each image pair, we generate a signal-to-noise ratio-weighted mean velocity field of all available cross-correlation window sizes after removing outliers in the 2-D velocity fields. To remove outliers in each window size for every scene pair, we first compare each speed field to a reference speed map (Rignot et al., 2017); speed estimates more than four times greater or four times smaller than the reference map are considered outliers and removed. Secondly, flow directions more than 45 degrees different from the reference map are considered outliers and removed. Thirdly, pixels in which the speed differs by more than three standard deviations from its neighbours in a 5x5 moving window are removed. Similarly, pixels in which the flow direction differs by more than 45 degrees from its neighbours in a 5x5 moving window are removed. Finally, we use a hybrid median filter with a 3x3 moving window, which removes the central pixel if it more than three times the median of the horizontally and diagonally connected pixels. After forming the signal-to-noise-ratio (SNR) weighted mean of the resulting velocity fields, we generate Antarctic-wide mosaics of ice velocity for every unique date-pair since October 2014. From these date-pair mosaics, we generate monthly Antarctic wide velocity mosaics as the mean of all date-pairs that overlap with the target month. When doing so, we weight each date-pair by the number of days of overlap with the target month – in this way, 12-day pairs are weighted twice as much as 6-day pairs, which is appropriate because they should contribute more to the average velocity in the month. We also generate two quality parameters, the number of observations in each month in each pixel (after outlier removal) and the proportion of each month that is observed in each pixel, in addition to an error estimate defined the speed divided by the SNR (Lemos et al., 2018).