Gravity-derived Antarctic bathymetry using the Tomofast-x open-source code: a case study of Vincennes Bay

Author Responses to Referee Comments

Lawrence A. Bird   Vitaliy Ogarko   Laurent Ailleres
Lachlan Grose   Jeremie Giraud   Felicity S. McCormack
David E. Gwyther   Jason L. Roberts   Richard S. Jones
Andrew N. Mackintosh

Dear Joseph MacGregor:

We thank you and the two referees for the comprehensive review of our manuscript. Feedback and constructive comments from all three reviews have improved the clarity of the manuscript.

Below, we provide a general response to all reviews and include information on updates made to the manuscript (Section 1). We subsequently respond in turn to comments from yourself (Section 2), one anonymous referee (Referee 1; Section 3), and Dr. Hannes Eisermann (Referee 2; Section 4). We respond (in blue) to each comment (in black). All line and section numbers refer to the original manuscript.

Sincerely,

Lawrence Bird and co-authors

1 Overview

All three reviews highlighted that the manuscript was relevant and well written. In addressing the referee comments, we identified an error in our implementation of minimum depth constraints from instrumented seal dives. That is, when aggregating seal dive data within each horizontal model grid cell, we were incorrectly attributing the minimum seal dive depths (rather than maximum) as minimum depth constraints. This impacted Section 5 of the manuscript, leading to shallower bathymetry than is likely in a region in the west of our domain and in a small area east of the Vanderford Glacier ice shelf. We have corrected the error and updated analysis throughout the manuscript, including figures: 4a (minimum depth constraints); 7 (model parameter selection); 9 (inclusion of integrated IBCSO bathymetry); 10 (modelled bathymetry); 11 (bathymetry cross-sections); 12 (bathymetry error maps); and 13 (ocean model results).We have updated values reported in Sections 5 and 6 accordingly.

In response to a comment around model bias from Referee 2 we have also made improvements to our discretisation approach. We applied the improved discretisation approach to all analysis (including the synthetic model application) and found that it reduced the overall Vincennes Bay model bias from –38 m to –16 m. We have updated all figures and in-text values accordingly.

We stress that the corrections and improvements made to the analysis as summarised above lead to *relatively minor changes* in values and the final bathymetry surface, and do not change the findings of the manuscript.

2 Editor comments

Thanks for your relevant, interesting and timely Research Article submission to TC/EGUsphere. After reading it, I believe that it is suitable for further peer review. However, I made note of several minor issues that I urge you to address following receipt and response to future external peer reviews. They are mostly geared toward accessibility and clarity. I will now send it for peer review.

We are glad that you found our manuscript to be relevant, interesting, and timely. We appreciate your review and comments, and have addressed these to improve accessibility and clarity of our manuscript.

Specific comments

50-51: Is the issue that the code is poorly documented or rather that it is closed source? Open-source software can also be poorly documented.

We have amended the sentence for clarity, as follows:

"... the underlying code-base is often inaccessible, resulting in a"black-box" application..."

55: "softwares" is an awkward term

We have amended the term "softwares" to *"software packages"*.

65-74: I'm not convinced that this final signposting paragraph is necessary for a regular MS, especially given the preceding paragraph alludes and references section numbers for most of the elements. Consider simply slightly expanding the preceding paragraph and dropping this one.

We agree that this paragraph includes some repetition with the preceding paragraph and may be unnecessary. A similar comment was also provided by Dr. Hannes Eisermann. We have combined this paragraph with the preceding paragraph. The final paragraph of Sect. 1, beginning on line 56, now reads:

"The primary aim of this study is to demonstrate the applicability of Tomofast-x (Ogarko et al., 2024), an open-source geophysical inversion platform, to derive sub-ice shelf and open ocean bathymetry from airborne gravity data, and to apply this method to the Vincennes Bay region of East Antarctica. A secondary aim is to assess the impact of the updated bathymetry on warm water pathways and sub-ice shelf basal melt across Vincennes Bay. Following an overview of gravity inversion and description of applicable features of Tomofast-x in Sect. 2, we introduce the Vincennes Bay study area and provide details on airborne gravity data, the model set-up, and a-priori information used as input to our gravity inversions (Sect. 3). In Sect. 4, we present a synthetic application (hereafter referred to as the"Synthetic model") to demonstrate the applicability of Tomofast-x to derive bathymetry and provide details of a quantitative ensemble modelling approach used to identify optimal model parameter choices. In Sect. 5 we subsequently use Tomofast-x to derive sub-ice shelf and open ocean bathymetry across Vincennes Bay in East Antarctica (hereafter referred to as the "Vincennes Bay model"), compare the new bathymetry to other current estimates, and discuss model uncertainty. In Sect. 6, we discuss the results and consider the implications for processes relevant for ice sheet retreat, including potential warm water pathways and ocean model-derived melt rates. Finally, we provide a conclusion of this work and comment on the future outlook for improving bathymetry estimates around Antarctica in Sect. 7."

104-107: Is 3-D not always better than 2-D in the case of gravity inversions, and is it not always better to have a priori constraints on subsurface density information? This sentence reads a bit too milquetoast.

We have replaced this sentence to highlight the approach used in our study, as follows:

"…Muto et al., 2013). In this study, we conduct a three-dimensional gravity inversion and assume homogeneous subsurface densities. We discuss the associated limitations of this assumption in Sect. 6.3."

195: It was in this section on the gravity data that I would expect some discussion of the uncertainty in those data themselves, either from cross-over errors or other manufacturer-stated instrument accuracy. That didn't come until much later in Section 5.2.2.

We agree that there is merit in including mention of uncertainty associated with the gravity data themselves in this section. As such, we have moved lines 408 – 410 from Section 5.2.2 to this section (line 209) which now reads:

"…along-line resolution of ~6 km. We quantify the uncertainty associated with instrumentation errors based on cross-over analysis from selected ICECAP flight lines. Using a simple Bouguer slab correction based on a density contrast of 1643 kg m^{-3} *between rock and water, the*

RMSE crossover error of 2.61 mGal corresponds to a bathymetry error of ~38 m. Additional processing...”

in Section 5.2.2, line 408 now reads as follows:

“Uncertainty associated with instrumentation errors results in a bathymetry error of ~38 m (Sect. 3.2). We estimate uncertainty associated with...”

230-236: These statements confused me. Doesn’t BedMachine v3 already do this, i.e., calculate ice-shelf thickness using hydrostatic equilibrium? See its User Guide and Supplementary Information for v1. Further, they use a firn correction to broadly address radar/hydrostatic discrepancies? The latter part of the adjustment may still be necessary, but there seems to be significant overlap with what BedMachine has already done.

This is a good point. Indeed, BedMachine v3 does perform these same corrections. However, it is often necessary to re-impose such corrections after interpolating the BedMachine v3 geometry products to a different resolution as we have in this study (i.e. our model mesh is a 2 km resolution while BedMachine v3 is natively provided at a 500 m resolution). Furthermore, the bulk of this correction is necessitated by our adjustment of the ice mask to correct the Vanderford Glacier grounding line position. This correction introduces a region of floating ice that was grounded in BedMachine v3 (and hence, not in hydrostatic equilibrium). Therefore, we place this ice in hydrostatic equilibrium, consistent with all other floating ice regions. Re-imposing corrections used in BedMachine v3 and adjusting the grounding line position at Vanderford Glacier result in some areas where the calculated ice base is below the bed/bathymetry. To prevent a large “step” in the bed/bathymetry at the grounding line (i.e. if we were to adjust the bed where the ice base is below the bed), we adjust the ice base to enforce a minimum water column thickness of 50 m. This approach results in ice that is no longer in hydrostatic equilibrium in these areas; however, this approach is reasonable since Chartrand and Howat (2023) suggest that the assumption of hydrostatic equilibrium is less robust close the Vanderford Glacier grounding line.

To improve clarity, we have rephrased lines 225 – 249 as follows:

“We use existing bed topography, bathymetry, and ice geometry datasets from BedMachine v3 (Morlighem et al., 2020) to constrain our models using hard and soft bound constraints (Sect. 2.2). All data are referenced to the WGS84 ellipsoid and interpolated onto a 2 km x 2 km mesh, consistent with the horizontal model resolution (Sect. 3.3), using bi-linear interpolation. We discretise the model mesh using the BedMachine v3 ice mask (Morlighem et al., 2020) to identify regions of grounded ice, floating ice, ice-free land, and open ocean. However, we adjust the ice mask to correct the Vanderford Glacier grounding line position to the 2017 grounding line from Picton et al. (2023) to be consistent with the date of the gravity survey. This leads to an increase in the area of floating ice across the Vincennes Bay ice shelf (Fig. 3). Following interpolation to the model mesh and adjustment of the Vanderford Glacier grounding line, we re-impose the same geometric corrections used in BedMachine v3. That is, we assume all floating ice (including the new region of floating ice introduced at Vanderford Glacier) is in hydrostatic equilibrium and calculate the ice shelf thickness from

the BedMachine v3 ice surface. Where the depth of the calculated ice base is lower than the BedMachine v3 sub-ice shelf bathymetry (predominantly close to the grounding line) due to the effects of interpolation, we enforce a minimum water column thickness of 50 m by raising the ice-base, rather than lowering the bathymetry. Raising the ice base results in ice that is no longer in hydrostatic equilibrium; however, this approach prevents the introduction of unrealistic gradients in the initial bed topography close to the grounding line and is supported by the fact that the assumption of hydrostatic equilibrium is less robust close to the Vanderford Glacier grounding line (Chartrand and Howat, 2023).

For both the Synthetic and Vincennes Bay models, we initialise the models with grounded bed topography and the modified ice geometry discussed above, and use hard bound constraints to fix regions of grounded ice and floating ice geometry. Soft bound constraints enforce the modified BedMachine v3 ice mask discussed above. This approach prevents floating ice from becoming grounded by enforcing a minimum water column of 50 m (i.e. one model cell) below floating ice. For the Vincennes Bay model we make use of additional hard bound constraints in regions of known bathymetry from: 1) multibeam swath bathymetry mapping collected by the RSV Nuyina offshore the Vanderford Glacier (Commonwealth of Australia, 2022); and 2) single beam acoustic depth soundings collected during Australian Antarctic Division voyages since 2012 (Sowter et al., 2016; Vander Reyden et al., 2016; Walter et al., 2016). We interpolate multibeam swath bathymetry onto our model mesh using bi-linear interpolation and take the median depth of single beam acoustic depth soundings within each 2 km x 2 km horizontal model cell. In addition, we use hard bound constraints to enforce minimum depth constraints across open ocean regions using seal dive depths from McMahon et al. (2023). We select the deepest recorded dive depth within each 2 km x 2 km horizontal model cell. A summary of bathymetric constraints used in the Vincennes Bay model is shown in Fig. 4. Additional information on the specific use of a-priori information, and hard and soft bound constraints for the Synthetic and Vincennes Bay models is provided in Sect. 4 and Sect. 5, respectively."

Adding on to the above point, did the authors verify that IBCSO v2 is incorporated in BedMachine v3 as expected? Such merging/interpolation is rarely simple. This verification seems worth doing to avoid surprises in interpretation and given how often the MS refers to IBCSO rather than BedMachine.

Documentation associated with BedMachine v3 is available at the following location, confirming that ocean bathymetry is taken from IBCSO v2:

> Morlighem, M. (2022). MEaSUREs BedMachine Antarctica. (NSIDC-0756, Version 3). [Data Set]. Boulder, Colorado USA. NASA National Snow and Ice Data Center Distributed Active Archive Center. https://doi.org/10.5067/FPSU0V1MWUB6. Date Accessed 11-01-2022.

Figure 1 below shows ocean bathymetry taken from BedMachine v3 (Figure 1a) and IBCSO v2 (Figure 1b). Differences in Figure 1c arise from reprojection of the IBCSO v2 data from its native projection to be consistent with the BedMachine v3 projection.

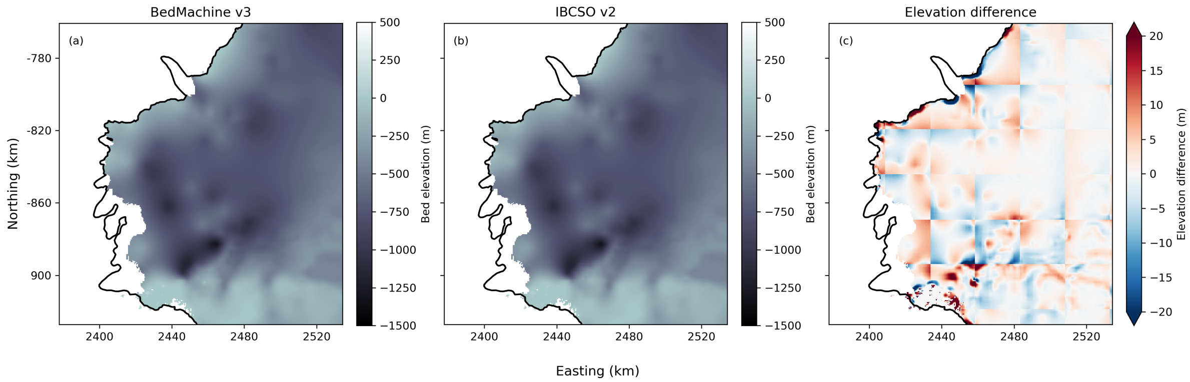

Figure 1: Ocean bathymetry from (a) BedMachine v3 and (b) IBCSO v2 in the Vincennes Bay region. (c) shows the difference in bed elevation, calculated as (a) - (b). The black line is the MEasUSREs v2 grounding line (Mouginot et al., 2017).

Section 6.2: While I respect that the authors consider this a minor element of the MS, this element of ocean modeling is sufficiently nuanced (although well-presented and valuable in the context of this study), that it really ought to be introduced earlier, i.e., in a Methods section. The Discussion section shouldn't present what are effectively new results.

We appreciate that the ocean modelling conducted here appears slightly disjointed in its current presentation. As such, we have added a section titled "Vincennes Bay ocean modelling" to Sect. 5. Here, we present the text that was previously included on lines 509 – 522, as well as the ROMS model setup that was previously included in the Supplementary Information. We opted to leave the remaining discussion of the ocean modelling in Sect. 6.2 since the ocean modelling is primarily intended to highlight the implications of bathymetry on ocean circulation and basal melt rates, rather than to present new comprehensive basal melt rate estimates for Vincennes Bay. This adjustment to the manuscript structure introduces a new Sect. 5.3 that now reads as follows:

"Bathymetry is known to have important controls on sub-ice shelf basal melt rates and ocean circulation (Goldberg et al., 2020). Given the common reliance of sub-ice shelf basal melt estimates and/or basal melt parameterisations on regional ocean models, accurate regional bathymetry estimates are critical to accurately model near-shore ocean dynamics. Here, we apply a regional ocean model of Vincennes Bay using the Regional Ocean Modelling System (ROMS; Shchepetkin and McWilliams, 2005) to assess the impact that the potential warm water pathways revealed in our gravity-derived bathymetry have on sub-ice shelf basal melting in Vincennes Bay. We run two model simulations, each with different ocean bathymetry: 1) uses IBCSO v2 and 2) uses our gravity-derived bathymetry. We compare the resultant modelled bottom ocean temperatures and sub-ice shelf melt rates in Fig. 13.

Ocean simulations were conducted with ROMS, with modifications for ice shelf mechanical pressure and thermodynamics, following Galton-Fenzi et al. (2012) and Dinniman et al. (2003).

The model was built on a polar stereographic grid with a spatial resolution of ~2 km and 25 vertical layers (producing minimum vertical resolutions of ~10 – 20 m on the deep continental shelf and less than ~2 m within the ice shelf cavity). This kernel has been previously employed for simulations of this region (e.g. Gwyther et al., 2014; McCormack et al., 2021). Lateral forcing (i.e. temperature, salinity, and velocity) is sourced from ACCESS-OM2-1 (Kiss et al., 2020). Surface forcing is also sourced from ACCESS-OM2-1, and consists of wind, and heat and salt fluxes which together represent sea ice formation. We employ the sea ice flux parameterisation as used previously (e.g. Richter et al., 2022), rather than a dynamic sea ice model. Two simulations were conducted, where the only difference is the bathymetry surface product (i.e. IBCSOv2 and our modelled bathymetry). For further technical details on the model setup, we refer the reader to previous implementations of this model kernel (e.g. Gwyther et al., 2014).

High spatial gradients in ocean bathymetry can result in numerical instabilities in ocean models (Mellor et al., 1998), often requiring ocean modellers to 'smooth' and/or manually adjust bathymetry datasets. As such, we use the gravity-derived bathymetry from the ensemble (Fig.10b) without the high-frequency bathymetry variations introduced by integrating minimum depth constraints to minimise the amount of manual adjustment required for numerical stability. The bathymetry was smoothed to remove any overly steep gradients and a minimum water column (of ~20 m) was enforced. The resulting change in bathymetry was minimal and key features (e.g. the Vanderford Valley and ice shelf cavity shape) were preserved. Ten years of forcing were simulated and we analyse only the final year, allowing a 9 year spin-up period. We discuss the implication of warm water pathways revealed in our gravity-derived bathymetry on ocean circulation and basal melt rates in Sect. 6.2. We note that the limited scope of our ocean modelling is not intended to provide comprehensive estimates of sub-ice shelf basal melt, but to demonstrate the influence of different bathymetry estimates on basal melt rates."

The "ROMS Ocean Model Setup" section in the Supplementary Information has subsequently been removed. We have added the following text to the beginning of Sect. 6.2:

"To assess the implications of warm water pathways revealed in our gravity-derived bathymetry on ocean bottom temperatures and sub-ice shelf melt rates, we compare ocean model output from our two ocean model simulations (Sect. 5.3)."

All figures: Descriptively label individual figure panels. Use legends instead of caption text to identify individual graphical elements (easier on reader than moving focus back and forth, and increases value of figures for use as-is in presentations). Use discretized color scales instead of continuous ones to more easily distinguish large-scale patterns (also goes hand-in-hand with color blindness considerations).

We have added legends to plots where they do not obstruct key information. We have left full descriptions in the caption text. We chose to maintain continuous colour scales on plots that display continuous data so as not to obscure any information. We have amended select figure captions to improve readability. We have added titles to select figure panels to improve readability.

Figure 3a: Very hard to identify focus area from Antarctica panel, so perhaps add a big arrow pointing to it. Blue coastline on blue bathymetry?

We have amended Fig. 3 to include a black star at the location of the study area.

3 Referee 1 comments

This paper sets out to demonstrate the use of Tomofast-x for inversion of gravity data for bathymetry beneath ice shelves and poorly surveyed open water regions around Antarctica. Using both a synthetic model, and a real case study in Vincennes Bay the authors demonstrate the method and discus its limitations. In addition they implement their new bathymetry within a local ocean circulation model to show the impact of the revised bathymetry on ice shelf basal melt rate, and hence the relevance of this type of inversion for understanding potential ice sheet stability.

The paper is well written and clearly laid out. The methods are clearly explained, and results appear convincing.

I have a few minor comments relating to other work and clarity of the text laid out below.

We are glad that the reviewer found the manuscript to be well written and clearly laid out, and we thank them for their constructive feedback.

Specific comments

It might be interesting to contrast your results with the recent work of Charrassin, et al 2025 https://www.nature.com/articles/s41598-024-81599-1 who used an inversion of the continent-wide ANTGG dataset to recover bathymetry all around the continent. I think it may reveal the benefit of using more local inversions for specific important use cases.

We thank the reviewer for this suggestion. We have included a comparison of our modelled bathymetry with that from Charrassin et al. (2025) below (Figure 2). We have added this figure to the Supplementary Information and included a comment on line 482 to discuss where high-resolution local- and regional-scale inversions may be useful in deriving bathymetry around Antarctica, as follows:

"Comparison of our gravity-derived bathymetry to the recent pan-Antarctic gravity-derived bathymetry from Charrassin et al. (2025) (Fig. S5) highlights where high-resolution and regional studies can provide additional benefits in deriving bathymetry around Antarctica, and indeed may be necessary for resolving some bathymetric features. Charrassin et al. (2025) use the Antarctic gravity anomaly and height anomaly grids (AntGG2021; Scheinert et al., 2024) that have a spatial resolution of 5 km. For Vincennes Bay, this has implications for how well the Vanderford Valley – a deeply incised, narrow channel that may be essential for the transport of warm water to the Vanderford cavity – is resolved. This also highlights the need

for comprehensive swath bathymetry mapping across the continental shelf to reliably constrain gravity inversion models, and the necessity of high-resolution airborne gravity to support local- and regional-scale gravity inversions for key areas around Antarctica, including within ice shelf cavities."

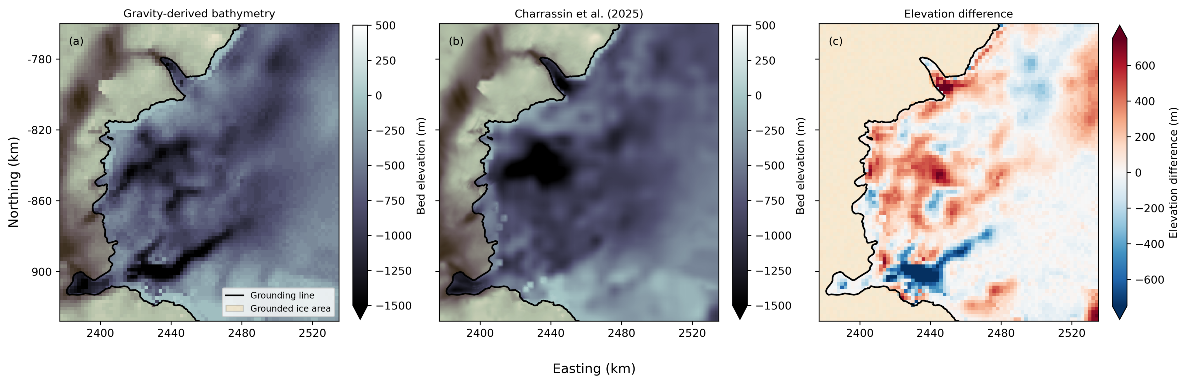

Figure 2: Comparison of (a) modelled bathymetry with (b) gravity-derived bathymetry from Charrassin et al. (2025). (c) shows the difference in bed elevation, calculated as (a) - (b). The black line denotes the MEaSUREs v2 grounding line, modified to include the 2017 grounding line from Picton et al. (2023).

L125-129 It might be worth stating here that it is the removal of the interpolated misfit between forward and inverse gravity model which is the method used in this study for minimising the impact of both long wavelength effects such as isostatic variations in crustal thickness, and local variations in crustal density.

We have added the following sentence to the end of line 129:

"We use this approach of interpolated gravity misfits to generate a residual gravity field across Vincennes Bay for use in our inversion (Sect. 5.1)."

Figure 11 caption. (c) should be (b).

Corrected.

L424 to 426. When discussing uncertainty it may be worth mentioning that significantly higher errors may be found in areas with rugged topography, as the wavelength of the gravity data means that features <~6 km wavelength cannot be resolved.

We comment on the limitation associated with the wavelength of the gravity data on lines 455 – 457. For clarity, we have amended line 457 as follows:

"...in our bathymetry model and significantly higher errors may occur in regions of rough bathymetry."

L509 "Vincennes Bay meltwater pathways and implications". It may be clearer to say something like "Vincennes Bay pathways for warm ocean water and implications for ice shelf melt".

Meltwater would be what is coming out from beneath the ice sheet, or the freshwater generated from the ice shelf, which I do no think is what is meant.

We have updated the title of this sub-section to *"Warm water pathways and implications for basal melt across Vincennes Bay"* for clarity.

4 Referee 2 comments

The submission entitled 'Gravity-derived Antarctic bathymetry using the Tomofast-x open-source code: a case study of Vincennes Bay' by Bird et al. presents a bathymetric model of the Vincennes Bay region, East Antarctica, including ice shelves and the open ocean. The resulting bathymetric model is combined with oceanic modeling to infer basal melt rates. The inversion is done by adapting an existing open-source software, Tomofast-x, towards the purpose of modelling (subglacial) bathymetry. In doing so, they provide a valuable alternative to existing licensed software, allowing improved accessibility and reproducibility.

Overall, the paper was a delight to review. It is well-structured and the results are very well presented. In the following are mostly minor general comments and some line-specific comments/suggestions.

We are glad that Dr. Eisermann found the manuscript to be well-structured and well presented, and we thank them for their constructive feedback.

General comments

Bathymetry model, constraints

Figure 4c shows available minimum depth constraints from meop data in the model area. Here, seal dives are shown beneath the ice shelf. Is this due to positioning issues of the meop data? (In Fig. 4d of McMahon et al., 2023, these sub-ice shelf data are not shown). If it is due to bad positioning, these constraints are not trustworthy and should be removed.

We thank Dr. Eisermann for raising this point. As discussed in Section 1, we have corrected the use of minimum depth constraints from instrumented seals. In doing so, we were unable to verify the validity of data beneath ice shelves and therefore opted to remove these data where position estimates may be less reliable. We have updated line 244 as follows:

"...hard bound constraints to enforce minimum depth constraints across open ocean regions using seal dive depths from McMahon et al. (2023).".

In IBCSO V2, there are a number of 'isolated soundings' in the area. Was it a conscious decision not to include these as constraints?

We assume this refers to various isolated data points in IBCSO v2 with a Regional Identifier (RID) of 11232 and Type Identifier (TID) of 13 (isolated sounding - depth value that is not part of a regular survey or trackline). The source, and therefore the quality and accuracy, of these data points could not be verified. As such we opted not to include these points as constraints within our inversion so as not to introduce potential spurious geometries.

Bathymetry model, regional gravity field

The interpolation of the regional gravity field in Fig. 9c does not appear to be ideal. Values below -20 mGal mostly appear in interpolated areas and rarely in constrained parts. This is quite noticeable at the trough continuation of the Vanderford Glacier, and offshore of BG and ANG. Did you compare different interpolation methods and respective results, other than MC?

This is a good point. The methodology used to interpolate gravity data can have implications on the subsequently derived bathymetry. We opted to use a minimum curvature algorithm to ensure that gravity observations at constraint points were respected, since data at these locations provide the highest confidence. While comparison of different interpolation methods was outside the scope of this study, we have commented on the this limitation on lines 555 – 556 as follows:

"...in this region (Sect. 5.2.2). Furthermore, the choice of interpolation technique used to interpolate gravity misfits from constraint points can influence the resultant gravity field and thus the subsequent inferred bathymetry. Here, we interpolate gravity misfits using a minimum curvature algorithm to ensure that calculated gravity misfits at constraint points are respected, since data at these locations provide the highest confidence gravity data. Comparison of different interpolation methods on the resultant gravity-derived bathymetry was outside the scope of this study. To our knowledge, no studies have quantitatively assessed the optimal distribution of geometry constraints and the influence of different interpolation techniques to ensure reliable inversion results, and this should be a focus of future research efforts."

Bathymetry model, gravity misfit

The gravity misfit in Fig. 10d should be described and discussed, especially:

- The high misfits close to the grounding line; this is likely caused by keeping the 'hard constraints' fixed close to the grounding line. The misfits could potentially be minimized by allowing the areas close to the grounding line to move (possibly within the vertical resolution; $\pm$ 50 m).

As Dr. Eisermann suggests, gravity misfits close to the grounding line are likely influenced by the transition from hard bound constraints across grounded ice, to soft bound constraints below floating ice and in open ocean. It is in this region close to the grounding line where occurrences of water below rock exist in our inversion, again, likely influenced by the transition between these different bound constraints (line 386).

We tested allowing regions of grounded ice to vary in order to mitigate this; however, due to the property-inversion approach used by Tomofast-x, this resulted in some regions where ice was introduced below rock (in a similar manner to the introduction of water below rock in some regions of bathymetry). As such, we opted to enforce hard bound constraints across grounded ice to prevent this behaviour in these regions. This approach is reasonable since grounded bed topography estimates from BedMachine v3 are likely better than would be returned by our gravity inversion since they are constrained by radar measurements and mass conservation modelling (Morlighem et al., 2020).

As we discuss in Sect. 6.3, future development of Tomofast-x should include local constraints on vertical lithology ordering. This enhancement would allow regions of grounded ice, particularly in critical areas such as close to the grounding line, to vary whilst respecting the order of lithologies. We note that the region where these variable gravity misfits exist close to the grounding line is primarily in regions of coastline where no ice shelves are present and there is relatively little ice loss. Therefore, the impact on our gravity-derived bathymetry likely does not have considerable influence on subsequent estimates of sub-ice shelf basal melt rates or ocean circulation.

We have adjusted the wording of lines 383 – 390 to comment more fully on this region, and update values associated with the updated analysis as follows:

"The inversion model selected from the ensemble modelling yields the bathymetry shown in Fig. 10b, with an RMSE gravity misfit of 1.27 mGal (Fig. 10d). Ensemble modelling results for the Vincennes Bay model are shown in Fig. S2 and Fig. S3, identifying two models with comparable overall success (Fig. S3). We select the model that results in the smallest mean bathymetry error in regions of mapped bathymetry. As with the synthetic model, the selected model has a few occurrences of water cells below rock, primarily close to the grounding line. These regions are associated with highly variable gravity residuals close to the grounding line, particularly in the eastern portion of our domain. We attribute the variable gravity residuals and unphysical occurrences of water below rock in these regions to the transition from hard bound constraints across grounded ice to soft bound constraints across open ocean. We discuss this limitation further in Sect. 6. We correct these unphysical artefacts in the model core (by recategorising water cells below rock as rock), and run one additional forward simulation to generate a final model which has a subsequent RMSE gravity misfit of 1.84 mGal (< 2% of the dynamic range of the gravity data). We note that this post-processing does not affect the modelled bathymetry. Furthermore, the impact of these artefacts is localised to close to the grounding line in regions of coastline where no ice shelves are present and there is relatively little ice loss. Therefore, any impact on our modelled gravity (hereafter referred to as"gravity-derived bathymetry") likely does not have considerable impact on subsequent sub-ice shelf basal melt rates or ocean circulation (Sect. 6.2)."

- High positive gravity residuals in central part of VB ice shelf and at UG; does your model suggest grounding here? Either way, discuss these areas please.

Based on this comment and a later comment regarding discussion of the water column, we have added the below Figure 3 of the water column thickness to the Supplementary Information (Fig. S5). As Dr. Eisermann suggests, these regions of high gravity residuals indicate regions where the water column is shallow and where there could be potential re-grounding of floating ice. Within our inversion, we enforce the modified ice mask (Sect. 3.4) such that floating ice must remain floating and grounded ice cannot become floating. As such, these regions of high gravity residuals below floating ice indicate regions where re-grounding of floating ice may occur, although it is not explicitly modelled in our inversion due to the enforced water column thickness of 50 m.

Based on this comment and the updated analysis, we have revised Section 5.2.1 as follows (italicized text is new text in the updated manuscript; in-text values have been updated to reflect the updated analysis):

"The gravity-derived bathymetry is, on average, 80 m deeper than IBCSO v2, with localised differences greater than 1850 m in the region of the Vanderford Valley (Fig. 10c). Our analysis reveals various large-scale bathymetric features that were not present in previous bathymetry estimates, with sub-ice shelf and offshore bathymetry ranging from -63 m to -2167 m (Fig. 10b). In particular, the gravity-derived bathymetry resolves the Vanderford Valley, a ~6 km wide trough which extends ~66 km offshore the Vanderford Glacier ice shelf cavity, reaching a maximum depth of 2167 m, and connects the Vanderford Glacier ice shelf cavity to the continental shelf (Fig. 10b and Fig. 11a). Towards the centre of the Vanderford Glacier ice shelf, gravity-derived bathymetry reveals a topographic sill that reaches an elevation of -556 m, upstream of which and close to the present-day grounding line, the bathymetry deepens to ~1600 m which is approximately 340 m deeper than IBCSO v2 (Fig. 10c and Fig. 11a). West of the Vanderford Valley, a smaller bathymetric trough, with an average depth of ~1200 m, is revealed offshore the Adams Glacier (Fig. 11b–c). This feature extends ~60 km offshore the Adams Glacier ice shelf cavity and reaches a maximum depth of 1566 m (Fig. 11b). *Localised regions of high gravity misfit below floating ice (Fig. 10d) suggest potential grounding zones, where modelled water column thicknesses are $<$ 100 m (Fig. S4). In particular, below the Vincennes Bay ice shelf, regions of high gravity misfit and shallow water column correspond with localised regions of previously grounded ice based on the MEaSUREs v2 grounding line (Fig. S4). We note that by imposing a minimum water column thickness of 50 m (i.e. one vertical model cell) to enforce the modified ice mask (Sect. 3.4), our model does not explicitly allow grounding in these regions; however, it identifies regions where a shallow water column thickness may promote re-grounding of floating ice."*

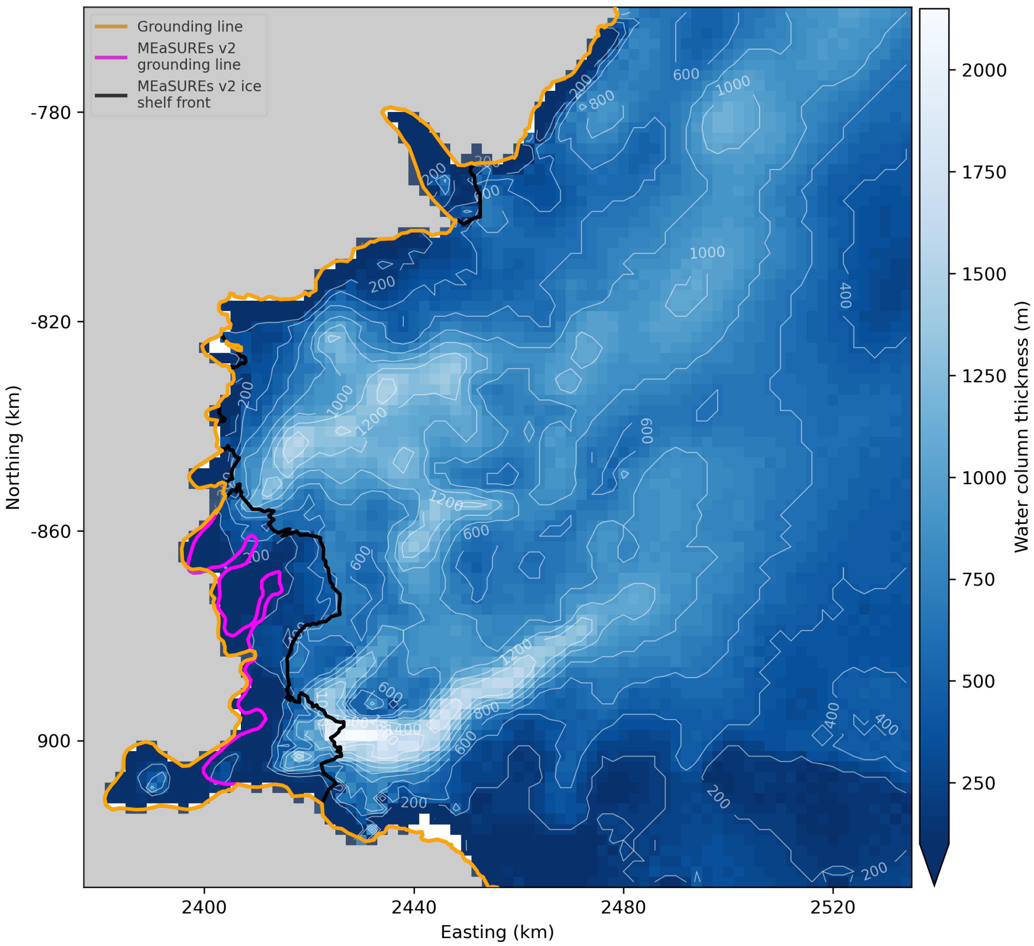

Figure 3: Gravity-derived water column thickness across Vincennes Bay. Below floating ice, the water column thickness represents the cavity height between the ice base and the bed. The orange line denotes the MEaSUREs v2 grounding line, modified to include the 2017 grounding line from Picton et al. (2023) used in the inversion. The magenta line denotes the MEaSUREs v2 grounding line. The black line is the MEaSUREs v2 ice front.

Bathy model, setup of initial bathymetry

This is regarding the difference of mapped bathymetry and your bathymetric model. With a mean diff of -34 m, it shows a clear trend. One way to mitigate that would be to use a first iteration of your bathymetric model instead of IBCSO V2 to fill in the gaps between constraints and then recalculate the forward model, and subsequently the regional gravity field. If IBCSO V2 is generally too shallow, then your modelled bathymetry might end up being too shallow, especially close to and at constraints.

We thank Dr. Eisermann for this comment and the great suggestion for potential improvement. As noted in Section 1, we made improvements to our discretisation method that improved the model bias from –38 m to –16 m. The suggestion to iteratively recalculate the regional gravity field may indeed yield minor improvements to the residual gravity field used to drive the inversion. However, given the vertical resolution of our model mesh (50 m) and the absolute mean difference of the gravity-derived bathymetry in regions of mapped bathymetry, it is unlikely to yield notable differences in our subsequent modelled bathymetry. Furthermore, this modification to the methodological approach is unlikely to reveal other features that are not currently resolved in our gravity-derived bathymetry that have implications on ocean circulation and sub-ice shelf melting. In this case, we have opted to instead discuss the additional uncertainty of this choice in our approach, as per Dr. Eisermann's later comment that suggests re-modelling is not necessary. We discuss the implications of modelling assumptions on the absolute depth of bathymetric features in lines 571 – 585 and have amended line 585 as follows:

"One possible way to reduce the mean bias in our gravity-derived bathymetry (–16 m), would be to have used an initial Tomofast-x solution to interpolate between constraints rather than IBCSO V2. However, as the magnitude of this bias is smaller than the model vertical resolution, we believe it unlikely that such a procedure would have yielded a notably different bathymetry."

Bathy model, overall

I'm not necessarily suggesting re-modelling here, but the regional gravity interpolation and gravity residuals should be discussed more thoroughly. Same goes for the water column. Please add a grid of it to one of the figures. And discuss it, especially if there are areas where your model suggests grounding, but the ice surface doesn't.

This comment has been fully addressed in our handling of previous comments from Dr. Eisermann. In particular, we have added a figure showing the estimated water column thickness and text discussing localised re-grounding potential. The discussion about the gravity interpolation and residuals was expanded to address previous comments.

Basal melt rates

How do the basal melt rates you modelled compare with the melting rates derived from satellites (e.g. Davison et al., 2023). Is 13e closer to these than 13d?

Mean annual melt rates across the Vincennes Bay ice shelf from our ocean modelling and from satellite-derived products (e.g. Paolo et al., 2022, and Davison et al. (2023)) are as follows:

- Modelled sub-ice shelf basal melt rate generated using IBCSO v2 ocean bathymetry (Figure 13d) = 2.4 m yr^{-1}
- Modelled sub-ice shelf basal melt rate generated using our gravity-derived bathymetry (Figure 13e) = 3.7 m yr^{-1}
- Satellite-derived sub-ice shelf basal melt from Paolo et al. (2022) = 6.4 m yr^{-1}
- Satellite-derived sub-ice shelf basal melt from Davison et al. (2023) = 5.3 m yr^{-1}

Note that no satellite-derived basal melt estimates are available for Underwood Glacier. The purpose of our ocean modelling was not necessarily to provide basal melt rates comparable to observations, but to demonstrate the sensitivity of basal melt rate estimates to bathymetry. We have added clarification to this end on line 522 (now in Sect. 5.3), as follows:

"...Supplementary Information). We note that the limited scope of our ocean modelling is not intended to provide comprehensive estimates of sub-ice shelf basal melt, but to demonstrate the influence of different bathymetry estimates on basal melt rates."

However, since our gravity-derived bathymetry yields basal melt rates closer to those derived from satellite, we have amended line 538 as follows:

"...v2 bathymetry. Compared to those generated using the IBCSO v2 bathymetry, basal melt rates generated using our gravity-derived bathymetry are closer to current satellite-derived estimates (e.g. Paolo et al., 2022; Davison et al., 2023), suggesting that large-scale bathymetric features in the region likely have important influence on sub-ice shelf melting at Vanderford Glacier."

Specific comments

ll 7-9: This sentence should be slightly rephrased to clarify. You are not showing the deep offshore trough for the first time in '[y]our new bathymetry', you are showing its continuation beneath the ice shelf, correct?

While the Vanderford Valley has previously been mapped (Commonwealth of Australia, 2022), it is not resolved in existing regional bathymetry datasets (e.g. IBCSO v2). We have amended this sentence (line 7-9) for clarity, as follows:

"Our new bathymetry reveals large-scale bathymetric features, some of which were previously known to exist but are not resolved in existing regional bathymetry datasets, including the deep marine trough recently mapped offshore the Vanderford Glacier. A smaller and previously

unknown bathymetric trough that reaches depths of more than 1500 m offshore the Adams Glacier is also identified.

l 31: IBCSO V2 also includes steering points beneath some ice shelves to mimic the continuation of onshore troughs (this is the case for the VB ice shelf).

We have updated line 31 to include mention of artificial steering lines that are included in sub-ice shelf bathymetry interpolation, as follows:

"…open ocean measurements and grounded ice topography (Dorschel et al., 2022). Where glacially incised troughs exist adjacent to ice shelf cavities (such as below Vanderford Glacier), IBCSO v2 uses artificial steering lines to model continuation of these troughs (Dorschel et al., 2022)."

ll 52: 'there is a desire to provide …' is a bit vague, albeit true. It could be rephrased by giving some benefits of that approach instead (e.g., higher accessibility without software costs, improved reproducibility without the black-box approach).

We have rephrased this sentence for improved clarity, as follows:

With a move towards "Open Research" (Wilkinson et al., 2016), an open-source solution to the application of gravity inversion to derive bathymetry around the periphery of Antarctica would provide more transparent methodologies, increased reproducibility of analysis, and increased accessibility without software costs."

l 56: include reference for Tomofast-x here (Ogarko et al., 2024?).

Added.

l 64: end with ref to sect. 6, to stay consistent.

We have amended this paragraph to remove the subsequent signposting paragraph (see comment below). We have updated all section references accordingly.

ll. 65 ff.: the last paragraph is not necessary here and could be dropped.

We agree that this paragraph includes some repetition with the preceding paragraph and may be unnecessary. A similar comment was also provided by the handling editor, Joseph MacGregor. We have combined this paragraph with the preceding paragraph. The final paragraph of Sect. 1, beginning on line 56, now reads:

"The primary aim of this study is to demonstrate the applicability of Tomofast-x (Ogarko et al., 2024), an open-source geophysical inversion platform, to derive sub-ice shelf and open ocean bathymetry from airborne gravity data, and to apply this method to the Vincennes Bay region of East Antarctica. A secondary aim is to assess the impact of the updated bathymetry on warm water pathways and sub-ice shelf basal melt across Vincennes Bay. Following an overview of gravity inversion and description of applicable features of Tomofast-x in Sect. 2, we introduce the Vincennes Bay study area and provide details on airborne gravity data, the model set-up, and a-priori information used as input to our gravity inversions (Sect. 3). In

Sect. 4, we present a synthetic application (hereafter referred to as the"Synthetic model") to demonstrate the applicability of Tomofast-x to derive bathymetry and provide details of a quantitative ensemble modelling approach used to identify optimal model parameter choices. In Sect. 5 we subsequently use Tomofast-x to derive sub-ice shelf and open ocean bathymetry across Vincennes Bay in East Antarctica (hereafter referred to as the "Vincennes Bay model"), compare the new bathymetry to other current estimates, and discuss model uncertainty. In Sect. 6, we discuss the results and consider the implications for processes relevant for ice sheet retreat, including potential warm water pathways and ocean model-derived melt rates. Finally, we provide a conclusion of this work and comment on the future outlook for improving bathymetry estimates around Antarctica in Sect. 7."

l 357: 'the the'

Removed duplication.

l 385: do you mean Fig. S2 and Fig. S3?

Corrected.

l 396: What's the difference between 'Vanderford Glacier ice shelf' and 'Vincennes Bay ice shelf'? If there is none, please stay consistent throughout the manuscript and only use one. If there is one, differentiate the two more clearly at the start (esp. in Fig. 3).

The largest ice shelf located in Vincennes Bay is defined as the 'Vincennes Bay ice shelf' (Mouginot et al., 2017). The Vanderford Glacier and Adams Glacier are the dominant glaciers that contribute ice mass to the Vincennes Bay ice shelf. Given the location of the Vanderford Valley offshore the Vanderford Glacier, we use the term 'Vanderford Glacier ice shelf' to refer to the portion of the Vincennes Bay ice shelf that included the main trunk of the Vanderford Glacier. We have updated Figure 3 to identify both the Vincennes Bay ice shelf and the Vanderford Glacier ice shelf and have amended the figure caption to include:

"...The Vanderford Glacier ice shelf is not explicitly defined by Mouginot et al. (2017), but here we use "Vanderford Glacier ice shelf" to refer to the portion of the Vincennes Bay ice shelf that includes the main trunk of the Vanderford Glacier...."

l 420: how do you get to '±34–104m' here? If you refer to the sentence before, it states a mean difference of '-34' (not '±34') and rmse of 95.

We have clarified our quantification of uncertainty presented in Section 5.2.2. We have updated lines 408 – 426 to reflect the updated analysis and clarify the uncertainty quantification, as follows:

"Uncertainty associated with instrumentation errors results in a bathymetry error of ~38 m (Sect. 3.2). We estimate uncertainty associated with local variations in the geology which are not removed by the regional/residual separation (Sect. 5.1) using the gravity misfit at points of known geometry (i.e. grounded ice and mapped bathymetry). The RMSE gravity misfit of 1.0 mGal at constraint points corresponds to a bathymetry error of ~15 m. The vertical resolution of the model grid (50 m) results in an inherent uncertainty of ± 25 m due to the

discretisation of all geometry data onto individual model cells. Without knowing the degree of correlation associated with individual components of model uncertainty, we sum individual sources of uncertainty (i.e. instrument uncertainty, geological uncertainty, and vertical model resolution) to provide a conservative uncertainty estimate of ±78 m.

Without using hard bound constraints to enforce minimum depth constraints from instrumented seal dives and mapped bathymetry during the ensemble modelling process, the geometry of open ocean and sub-ice shelf bathymetry is unconstrained. This provides an alternate approach to quantify model uncertainty, by comparing the gravity-derived bathymetry with mapped bathymetry. Fig. 12 compares gravity-derived bathymetry with mapped bathymetry (Fig. 12a) and minimum depth constraints from instrumented seals (Fig. 12b). The gravity-derived bathymetry has a RMSE difference of 86 m (and a bias of –16 m) compared to mapped bathymetry (Fig. 12a). These uncertainty estimates are comparable with uncertainty estimates provided for other studies that derive bathymetry by way of gravity inversion (e.g. Eisermann et al., 2024; Constantino and Tinto, 2023; Jordan et al., 2020)."

Furthermore, based on our updated analysis, we have updated the "exclusionary boundary" used to blend our gravity-derived bathymetry with the larger regional bathymetry dataset used for ocean modelling. As such, we have revised line 432 as follows:

"…Instrumented seal dives highlight a second region offshore, west of Underwood Glacier, where gravity-derived bathymetry is too shallow (Fig. 12b). We attribute this…"

We have updated lines 442 – 444 as follows:

"…As such, we exclude this region of bathymetry when blending the gravity-derived bathymetry with larger regional bathymetry datasets to support ocean modelling (Sect. 6.2), ensuring a smooth transition at the edge of our model domain."

l 511: replace or scratch one of the two 'accurate(ly)'.

We rephrased this line as follows:

"…regional ocean models, accurate regional bathymetry estimates are critical to reliably model near-shore ocean dynamics."

Figure 11: (c) should be (b). and (d) should be (c).

Corrected.

Table 1: The model padding in the synthetic model is 10k in every direction. That reduces the model core by 20k Easting and Northing. Shouldn't a model padding of 20k in the Vincennes Bay Model then reduce the model core by 40k? And not by 20k Easting and 10k Northing?

We thank Dr. Eisermann for highlighting this discrepancy. The value of 176000 was a typo which should read 166000. In addition, the discrepancies in expected values arises due to difference between the "model mesh" (defined in Sect. 3.3) and the "model domain" (undefined). Given the definition of the "model mesh" (i.e. the "model core" and the "gravity buffer region") provided in Sect. 3.3, the current values for "Model domain size" presented in Table 1 refer to the “Model mesh size” (i.e. excluding the padding region). Given the consistent “gravity buffer region”, the values in brackets should all be 20 km smaller than those unbracketed (given a 10 km gravity buffer in all directions). We have corrected the terminology used in these column headings and updated the Table caption as follows:

“Summary of model dimensions. Values in brackets represent dimensions of the model core (i.e. excluding the gravity buffer region from the model mesh). The model padding region extends beyond the model mesh in all directions.”

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