

We would like to sincerely thank Shin Sugiyama, the anonymous reviewer #2 and Andres Rivera for taking their time to review our manuscript; your thorough revisions and suggestions improved the quality of our paper. We have addressed all points below. In black are the comments from the reviewers and in green the authors responses. We have highlighted changes made to the manuscript.

Referee Comments

#1 Referee comments by Shin Sugiyama

Review comment on “Bedrock topography and ice thickness distribution of three major Patagonian outlet glaciers unveiled by helicopter-borne ground penetrating radar” by Moritz Koch et al.

- General comments

This manuscript reports ice thickness and bed elevation data for three lake-terminating glaciers in the Southern Patagonia Icefield. The data sets are based on helicopter-borne ice-radar measurements and numerical modelling of ice thickness distributions. Observational ice thickness data are sparse in Patagonia due to environmental challenges (severe weather conditions, heavily crevassed glaciers, large amounts of meltwater) and logistical constraints (glacier access, helicopter availability, material transport). The authors conducted helicopter observations over three large, rapidly changing glaciers on the eastern side of the Southern Patagonia Icefield. The obtained field data were used to estimate glacier ice thickness distributions using a numerical model. Also presented are error analyses of the ice thickness from the radar measurement and modeling.

The radar-measured ice thickness data are novel and important to the glaciological community. The presented field data cover critical areas of three large glaciers that have been the focus of glacier studies in the region. Our understanding of the rapid changes in these glaciers will be improved by ice-thickness and bed-geometry data. The modeled ice thickness and bed elevation maps are very useful for studies in the future. For example, they create a possibility of reliable ice flow modeling, which will contribute to more accurate projections of glacier mass loss and sea level rise. For these reasons, I congratulate the authors on obtaining the valuable data and strongly support the publication of the manuscript and the data in Earth System Science Data.

I list some suggestions to improve the presentation of text and data, from the perspective of a glaciologist engaged in the region. I hope the authors receive more specific guidance from other reviewers on the technical aspects of radar data processing and ice thickness reconstructions.

- Specific comments

1. Data presentation

The measured and modeled ice thickness and bed elevation are presented on maps with color scales. They show nice overviews, but I have a problem with the maps when detailed features are discussed in the text. For example, the subglacial ridge near the front of Glaciar Perito Moreno is mentioned several times in the text (Line 292, Line 333), but it is not clear which part of the map is referred to. Additional enlarged maps focused on the regions of interest would be very useful for readers. Please also consider using a discrete color scale and/or contour lines, because continuous color scales are less useful for quantitative discussion (Figures 6 and 9).

Thank you for the comment. Alongside other points, we will revise the figures in the final version of the manuscript so that bedrock features are more visible and areas of interest (such as the bedrock ridge or other features) are marked within the figures.

1. Lake bottom elevation

The bedrock elevation maps (Figure 7 and Supplementary Figure 1) are very useful. It would be more useful for glacier modeling, if lake bottom elevations near the glacier fronts are included. I am proposing this idea because

we have published the lake bathymetry near the glaciers studied in this paper (Sugiyama et al., 2016). The bathymetry data are available online.

Sugiyama, S. et al. (2016), Thermal structure of proglacial lakes in Patagonia, *J. Geophys. Res. Earth Surf.*, 121, 2270–2286, <https://doi.org/10.1002/2016JF004084>.

Sugiyama, S. et al. Bathymetry data from glacial lakes in Patagonia, Mendeley Data, V2, <https://doi.org/10.17632/47rhmznjs6.1>

We agree that broader spatial coverage would be valuable for ice-flow modellers interested in glacier evolution prior to 2000. However, in the present dataset, we have limited the reconstruction to pre-2000 glacier outlines to preserve spatial consistency between the bedrock topography and the associated uncertainty fields. Extending the product to additional bathymetric areas would require an uncertainty treatment that is not directly comparable to that applied within the reconstructed glacier domains. We therefore chose not to include these areas in the present release. Post-2000 bathymetric information has already been incorporated into the reconstruction where applicable, as described in the Methods section and in our response below. We will nevertheless clarify in the manuscript that bathymetric data are available for the fjords and will refer readers to the reviewer's dataset and other relevant datasets of which we are aware.

Ice thickness reconstruction

Details of the ice thickness modeling are missing. I assume the modeling requires various input data and parameters, including ice velocity, mass balance and sliding rate. However, nothing is clear from the manuscript. Please consider describing sufficient details, including how the ice thickness from the radar survey was incorporated into the model.

We have added the following section to the ice thickness reconstruction section:

“In addition to our measurements, we used an established ice-thickness reconstruction method that has been applied in several regions and can incorporate observational constraints (Fürst et al., 2017, 2018; Farinotti et al., 2021; Sommer et al., 2023; Fürst et al., 2024). This approach allows us to generate basin-wide ice-thickness maps for the year 2000, along with corresponding bed-elevation maps. The two-step method is primarily based on the principle of mass conservation (Fürst et al., 2017) and, more specifically, uses the shallow ice approximation (SIA) (Morlighem et al., 2011). In addition to the newly obtained thickness measurements, thickness values along the flight tracks of gravimetric surveys over the SPI plateau were used (Millan et al., 2019). Post-retreat lake-bed elevation data were derived from bathymetric surveys (Sugiyama et al., 2016; Minowa et al., 2023; Koch et al., 2025). At Glaciar Perito Moreno, data from a seismic survey and from two boreholes were also incorporated (Stuefer et al., 2007; Sugiyama et al., 2011). Ice thickness information was inferred from glacier retreat on land using Landsat imagery from March 2001 and 2016 (De Angelis, 2014; Meier et al., 2018; Sommer et al., 2023). The year 2000 reference DEM is based on the 30-m product of the SRTM v2.1 DEM (Farr et al., 2007). Data voids were filled with multi-resolution terrain elevation data from 2010 (Danielson and Gesch, 2011). Elevation change rates were based on TerraSAR-X Add-on for Digital Elevation Measurements (TDX) data (Krieger et al., 2013). The corresponding elevation change rates were derived from TanDEM-X DEMs from 2016 and 2019 (Malz et al., 2018; Braun et al., 2019). The surface mass balance (SMB) data used were derived from statistically and dynamically downscaled NCEP-NCAR atmospheric reanalysis data from 1965 to 2011 (Kalnay et al., 1996; Schaefer et al., 2015). Based on these data, the glacier SMB was derived using an enhanced temperature-index model that incorporates cloud-cover-corrected potential incoming radiation (Fürst et al., 2024). The surface velocity fields applied in the second step of the reconstruction and to estimate the frontal ablation and ice discharge are based on available mosaics from Mouginot and Rignot, (2015). The flux gates were placed close to present-day terminus positions, and the ice flux was computed as the product of ice thickness and the surface-velocity component perpendicular to each gate.

In the first step, we infer the glacier-wide ice-thickness fields without relying on surface velocities (Fürst et al., 2017, 2018). First, we apply an iterative flux-based method, in which the problem is formulated in terms of ice flux and subsequently converted to ice thickness using the Shallow Ice Approximation (SIA). This conversion depends on a spatially variable viscosity parameter, which is estimated in areas where ice-thickness observations are available. The classical approach was further updated by introducing a viscosity rescaling, which improves inferred thickness distributions farther from observational constraints (Sommer et al., 2023; Fürst et al., 2024). In the second step, the initial ice-thickness field is refined in areas where reliable surface-velocity observations are available. This is done by solving the mass-conservation equation directly for ice thickness. Because the equation is vertically integrated, the observed surface velocities must first be converted to depth-averaged velocities. The velocity-based correction is only applied in regions where surface speeds exceed 100 m yr^{-1} . In

these fast-flowing areas, basal sliding is assumed to dominate over internal deformation, so the surface velocity is taken to be equivalent to the depth-averaged velocity. The mass-conservation equation is then solved using the same Elmer/Ice implementation as in the first step. “

1. Smoothness of the text

I think the text is not very smooth in some places. Please get help to improve your English.

We will revise the manuscript accordingly.

- Specific comments

Line 13: "three of the largest outlet glaciers" >> According to (DeAngelis, 2014), Glaciar Viedma, Upsala and Perito Moreno are 2nd, 4th and 12th largest glaciers in terms of area. I agree that they are well known and important glaciers, but I think "three of the largest" is misleading.

You are right. Changed wording to: **three large western outlet glaciers.**

Line 14: "116.021" >> I understand "." is used as a thousands separator, but it is confusing because it's used as a decimal point elsewhere.

Kept “.” As a thousand separator and changed decimal separators to “,”.

Line 22-23: "the well-constrained glacier-wide grids" >> What do you mean?

That the lower parts of the glaciers are well constrained by the GPR surveys. Maybe a misleading formulation. However, it seems unnecessary. Removed that part of the sentence.

Line 32: "(Bojinski et al., 2014)" >> I think you need some other citations to state that glacier changes are clear indicators of "anthropogenic" climate change. Something like these?

Ben Marzeion et al. 2014. Attribution of global glacier mass loss to anthropogenic and natural causes. Science, 345, 919-921. <https://doi.org/10.1126/science.1254702>

Roe, G. H., Christian, J. E., and Marzeion, B. 2021. On the attribution of industrial-era glacier mass loss to anthropogenic climate change, The Cryosphere, 15, 1889–1905, <https://doi.org/10.5194/tc-15-1889-2021>

Thank you for the suggestions. We have added the citations.

Line 40: " Patagonian Andes" >> Because you have just introduced, you'd better discuss "SPI and NPI".

Agreed. Changed to SPI and NPI.

Line 47-48: "Bathymetric surveys of recently retreated outlets" >> Sounds odd to me because bathymetric surveys are performed in lakes and the ocean, but recently retreated outlets mean outlet glaciers.

Rephrased to: Bathymetric surveys of lake basins exposed by recent outlet glacier retreat demonstrate that ice-dynamic losses dominate glacier retreat, with lake depth and underlying bed geometry exerting primary control.

Line 49: "Minowa et al., 2023b" >> This appears before Minowa et al., 2023a. Please check the citations of Minowa's papers. It looks 2021a and 2021b, and 2023b and 2023c are duplicated (Line 561-574).

Removed duplicates. Minowa et al. 2023a appeared earlier in 2023 than Minowa et al. 2023b, so 2023a and 2023b are ordered accordingly in the reference list.

Line 60: "outlets" >> outlet glaciers?

Yes. Changed to outlet glaciers.

Line 64: GPR is already introduced in Line 61.

Now reads GPR.

Line 65: SPI is already introduced in Line 39.

Now reads SPI.

Line 68: "116.021" >> 116,021 or 116021

Kept "." as a thousand separator and "," as a decimal.

Line 79: "expanding" >> extending?

Changed to extending.

Figure 1, 1st line in the caption: "rotated by 90 degree" >> Isn't it (b) which is rotated from north up?

The entire figure is now facing north. Deleted "rotated by 90 degree".

Line 97: "Three of the largest": I think this is OK because they are 1st, 2nd and 4th largest glaciers on the eastern side of SPI.

Thanks for the clarification.

Line 101: "approximately 896 km² and 779 km²": Please revise to make it clear that these areas are for entire glaciers but not for accumulation zones. "approximately" sounds odd because 896 and 779 are quite precise numbers. The numbers are not consistent with previous studies (De Angelis, 2014, 974 and 647 km²) (Lo Vecchio et al., 2024, ~645 km² for Upsala). How do you measure the areas?

The areas are based on the updated RGI 7.0 Outlines. We chose to use "approximately" because the RGI outlines are also estimates of the area. Removed "approximately" and now cite RGI7 directly after the sentence. Added the updated area of Upsala due to fragmentation. It now reads: "The accumulation zones of Glaciar Viedma and Glaciar Upsala reach above 3200 m a.s.l. (according to the Copernicus DEM), and their entire basins cover approximately 896 km² and 779 km², respectively, as of 2024 (RGI Consortium, 2023). When Glaciar Upsala's tributary, Bertacci, is excluded due to fragmentation, the area is approximately 645 km² (Lo Vecchio et al., 2025)."

Line 114: Please consider referencing Minowa et al. (2026), as well.

Minowa, M. et al. 2026. Triggering mechanisms of dynamic mass loss at a freshwater-calving glacier in southern Patagonia, Earth and Planetary Science Letters, 681, 119930. <https://doi.org/10.1016/j.epsl.2026.119930>

Added Minowa et al. 2026.

Line 116: "a single borehole" >> Actually, it was a single location, but we drilled two boreholes (Sugiyama et al., 2011).

Now reads: "At Glaciar Perito Moreno a seismic measurement was conducted in 1996 and borehole measurements were conducted ~5 km from today's terminus (Stuefer et al., 2007; Sugiyama et al., 2011)."

Line 119: Move (Millan et al., 2019) to Line 119 after "... airborne gravity survey."

Moved citation after airborne gravity survey.

Line 123-125: This is already mentioned in Line 66-68.

Removed redundant information.

Line 127-133: What about setting up a table to present the numbers associated with the three glaciers?

Added a table “Survey dates and total glacier-profile lengths acquired for Glaciar Upsala, Perito Moreno, and Viedma.”

Glacier	Survey Date(s)	Profile Length (km)
Glaciar Upsala	20 October 2024	73
Glaciar Perito Moreno	19 & 21 March 2022	171
Glaciar Viedma	4 April 2022	149
Total	-	393

Line 143: "6 x 4 x 1 m">>"6 x 4 x 1 m³" or "6 m x 4 m x 1 m".

Now reads "6 m x 4 m x 1 m".

Line 144: "comparatively" >> What are you comparing with?

To unshielded antennas used in helicopter-borne surveys. Rephrased to: Although comparatively heavy, a shielded system reduces transmitter–receiver coupling and improves signal and imaging quality compared to unshielded antennas.

Line 159: Define "GNSS".

Defined GNSS. Now reads: “For accurate georeferencing, a Global Navigation Satellite System (GNSS) ...”.

Line 163: "multi-frequency" >> " dual-frequency"?

Technically multi-frequency is correct. The Leica GS16 is described as a multi-frequency GNSS receiver as it tracks L1, L2 and L5 frequency bands, as well as supporting GPS, GLONASS, Galileo and BeiDou.

Line 164: Please indicate the locations of the base stations in Figure 5.

The starting points are quite far away from the margins of Upsala and Viedma. The location of the base stations are now indicated in figure 1b.

Line "164-165": "a rover antenna was ..." >> Already mentioned in Line 159.

Rephrased to: in addition to the one mounted on the antenna

Line 166: Abbreviations (TBC and PPP) are not necessary because they are not used.

Removed Abbreviations.

Line 167: "rover trajectory were" >> rover trajectories were?

Yes, should be plural.

Line 170: "GPST–UTC offset " >> What do you mean by this?

The GPS Time to UTC offset arises because GPS time is a continuous timescale without leap seconds, whereas UTC is periodically adjusted with leap seconds to account for irregularities in Earth’s rotation. As a result, GPS time runs ahead of UTC by a known number of seconds, which must be applied as a correction when converting GNSS timestamps to UTC.

Line 206: " Between kilometer 4 and 5 " >> Sounds odd to me.

Rephrased to: “From km 4 to km 5 along the transect, the radar signal is attenuated by the glacier’s surface morphology.“

Line 215: (2016)

Added brackets.

Line 217: Isn't the radical sign too short? Don't you need numbers for the equations?

t's now properly formatted.

Added Eq. 1 (as well as for the following equations).

Line 220: "acquisition velocity" >> What do you mean?

The acquisition velocity refers to the velocity of the platform during data acquisition, added that information to the text, too.

Line 223: Please define the variables, x , y , H , ϵ .

Added this paragraph right after Eq. 1 (now L- 226): The error of the value from the radar measurement (ϵ_{HGPR}) and the error in thickness due to horizontal positioning errors ($\epsilon_{H,xy}$), where x and y denote the horizontal coordinates of each measurement point (with x representing distance along the transect), H is the derived ice thickness, and ϵ represents the associated uncertainty of each variable.

Line 224: What do you mean by "picks"?

Added "(as in bedrock delineation in a radargram)" to clarify what a pick means to in this context. In ReflexW the user can "pick" the bedrock reflections in a processed radargram, which then can be exported as ice thickness point values along the flight line.

Line 229: "picking uncertainty" >> Do you mean something like "uncertainty in time of measurement"?

Yes, exactly that. ϵt represents the uncertainty in determining the two-way travel time due to ambiguity in picking the bed reflection in the radar data. We added that explanation the text as well.

Line 228: Please use italic for variables, c and t . You do not need to define "TWTT".

Deleted (TWTT) and changed c & t formatting to Cambria Math.

Line 237: "WGMS)" >> WGMS

Deleted ")".

Line 246-247: Omit "with the air layer removed prior to calculation".

Removed.

Line 257: I suggest "thickness and bed elevation maps for entire glacial basins (for the year 2000)".

Agreed and implemented your suggestion. Moved (for the year 2000) behind ice thickness.

Line 266: I suggest "Comparing the modelled and observed ice thickness values (Appendix Fig. ...)".

Thank you, revised.

Line 267: How do you compute "misfit"? What do you mean by "The triangular model mesh"?

The modelled and measured ice thickness values were compared along the flowlines of the GPR measurements.

The triangular mesh here refers to an unstructured grid in which the model domain is discretised into interconnected triangular elements, enabling flexible spatial resolution and a better representation of complex glacier geometries than regular grids.

Line 276: " we perturbed the surface mass-balance gradient within plausible bounds" >> Please give values for the "plausible bounds". Anyway, I encourage the authors to describe more details about the modelling procedures.

We estimated uncertainty ranges from the SMB data used and changed the gradient from -50% to +50%, as well as perturbations for the viscosity scaling for all experiments. Changed wording to "In addition, we perturbed the surface mass-balance gradient within plausible bounds, from +50 % to -50%, with respect to the slope. This estimate was based on the uncertainty range from the modelled SMB compared to observed SMB values (Schaefer et al., 2015)."

We now also explain the input data and ice thickness reconstruction approach (see answer give above to your general statement).

Line 287: Do you mean that bed elevation was not available for 41% of the survey routes over the glacier?

Yes, exactly. The higher-altitude regions at Perito Moreno did not show any clear bedrock reflections, likely due to a combination of wet snow layers, crevasses, and the need to fly higher above the ground because of strong side winds. This and the regions over Viedma that were not interpretable.

Line 289: What about setting up a single table to present these numbers associated with each glacier?

We have inserted a table showing measurement statistics:

GLACIER	NUMBER OF MEASUREMENT POINTS	OF MAXIMUM ICE THICKNESS MEASURED	MEAN ICE THICKNESS	DISTANCE COVERED
UPSALA	23,479	812 m	383 m	47 km
VIEDMA	32,385	623 m	193 m	64 km
PERITO MORENO	60,252	706 m	312 m	120 km

Line 290: Please indicate in the plot the location of the measured maximum depth.

We will do that in the revised plot alongside the other revisions.

Line 292: Please indicate in the plot the location of the ridge. I encourage the authors to provide a larger plot of key areas, including the region near the front of Glaciar Perito Moreno. The following sentences describing ice thicknesses (180, 220, 130, 140 m) are difficult to follow without such an additional plot.

Thank you for the comment, alongside the other revisions we will change the layout of the figures to make them more accessible.

Figure 5, 2nd line in the caption: What do you mean by "densest survey grid was collected"?

We surveyed Perito Moreno most in terms of flights and distance between perpendicular transects, as well as additional flight loops close to the glacier tongue and over regions where prior thickness measurements were conducted.

Line 304: "The mean ice thickness" >> Is this the mean along the flight route or the mean of available data points?

Along the flight route. Added "along our flight lines the mean ice thickness is ...".

Line 306: "stepped glacier bed" >> Can you indicate in the plot which region you are referring to? An enlarged plot helps readers.

Indicating now the region where L306 refers to.

Line 323: "small-scale" >> How small?

This was misleading as they aren't "small" in the sense of the wording. Changed the wording to: More importantly, due to the well-constrained input dataset, bedrock features such as the subglacial bedrock ridge and valley constriction at Glaciar Perito Moreno, for example, are now represented in these thickness fields.

Line 325: Why don't you compare your measurements with existing data? Because such data sets are widely used, it is essential to validate them with observational data. That's one of the values of your measurements, I think. For example, Minowa et al. (2021) used inverted ice thickness for ice flux calculation, and Lannutti et al. (2024) studied the thickness distributions of the three glaciers that you studied. By the way, what do you mean by "REFs"?

REFs wasn't supposed to be there, deleted it.

We have added a section "5 Model intercomparison" which compares the bedrock elevation from our study to: Lanutti et al. 2024, Farinotti et al. 2019 (which served as a data source for Minowa et al. (2021), Fürst et al. 2024 and Millan et al. 2022. The differences are described alongside this new figure:

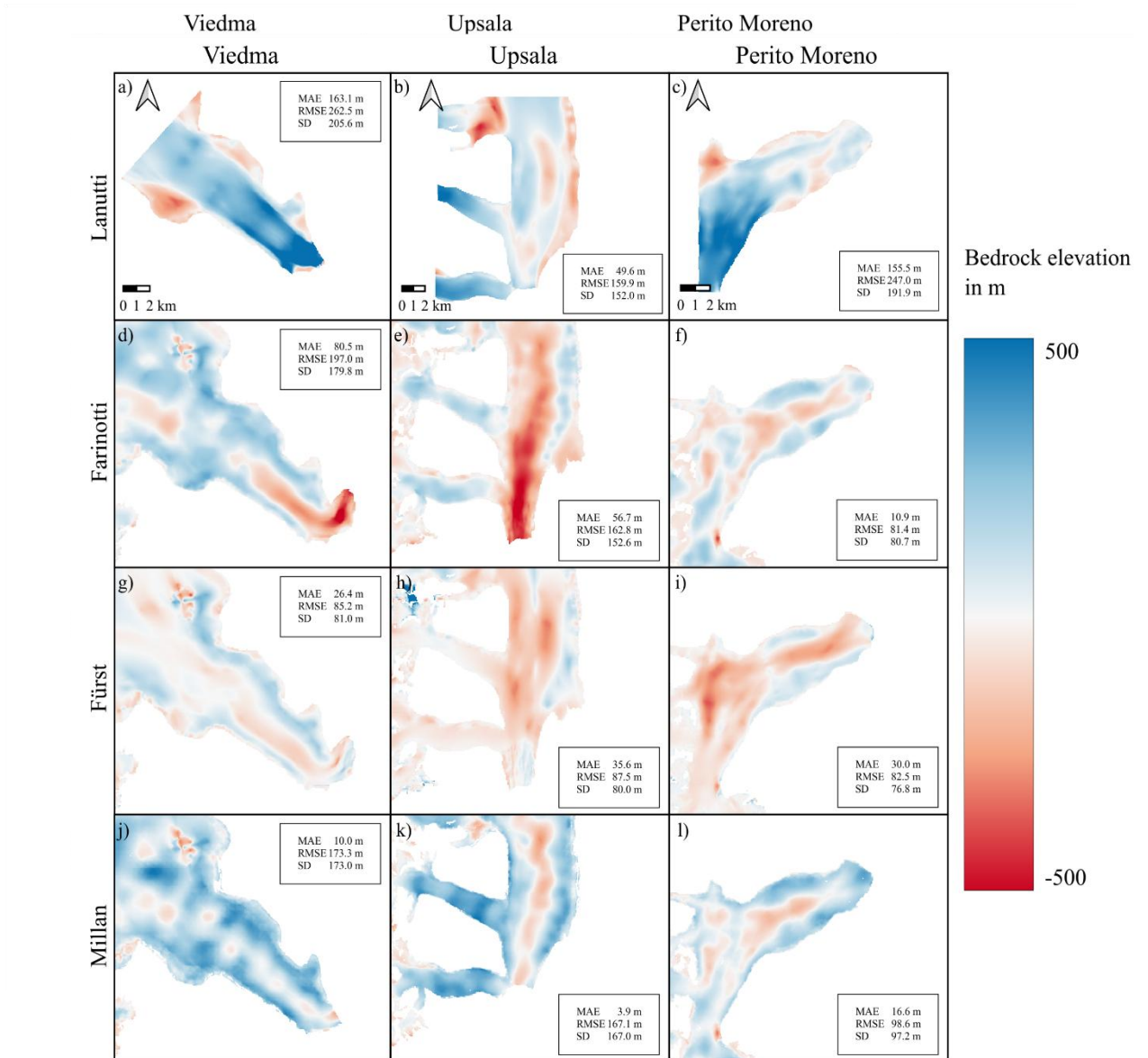


Figure X: Model intercomparison with Lanutti et al. (2024; panels a-c), Farinotti et al. (2019; panels d-f), Fürst et al. (2024; panels g-i) and Millan et al. (2022 g-i) for Glaciar Viedma (left), Upsala (middle), and Perito Moreno (right). The colour scale shows differences in bedrock elevation, calculated as the compared model minus this study, in metres. Blue regions indicate lower bed elevations in the compared model, whereas red regions indicate higher bed elevations. Stat boxes in each panel show the mean absolute error (MAE), the root mean square error (RMSE) and the standard deviation (SD).

There is a figure which shows the entire glacial basins in the appendix (for panel d), but we wanted to focus on the areas where we conducted our measurements and also Lanutti et al. reconstructed the ice thickness only for the lower regions of the glaciers.

Line 327: "2D reconstructions" >> the reconstruction of bed elevation?

Yes, changed the wording.

Line 333: Please show "subglacial ridge" on the plot.

Adding an element indicating the subglacial ridge.

Line 335: "1.292 m" >> 1292 m Where is the deepest part of the glacier?

Revised to 1292m. We will add an element to the figure indicating the areas with the highest ice thickness values.

Line 337: "well constrained" >> What do you mean by this? Based on which data?

We meant that the ice thickness distribution toward the glacier tongue is well constrained because this area has the densest GPR data coverage. We have rephrased the sentence to: "The ice thickness distribution toward the glacier tongue is well constrained by our newly obtained GPR data, and features such as lateral inflow from tributary glaciers are clearly visible in the thickness map."Based on our data. However, the wording isn't optimal. Rephrased to:

Line 340: "1.400 m" >> 1400 m

Revised.

Line 346: "in the Supplement" >> Refer to the figure number.

Added Figure number.

Line 350: "After" >> Above?

Yes you are right. Rephrased to: "Following a steep prograde section upstream, the bed elevation rises above the lake level."

Line 347-Line 359: Please consider providing additional maps focused on the regions near the terminus.

We will enlarge the panels to focus on the termini and provide maps of the entire basins in the appendix.

Figure 7, 3-4th line in the caption: Omit "areas at or below".

Revised.

Line 367: ... cross points of survey routes?

Yes. Added "cross points of the flight lines".

Line 388: Please clarify that Figure 9 shows the uncertainty of the ice thickness obtained by modeling.

Rephrased to: "Absolute mean uncertainty of the ice thickness reconstruction in m from all model runs..."

Figure 9: Please indicate the regions covered by the radar survey because the uncertainty should be directly affected by the existence of field data.

Added the flight lines to the uncertainty maps.

Line 409: Omit "densely gridded".

Omitted “densely gridded”.

Reviewed by Shin Sugiyama

Referee comments by Reviewer #2

General comment: the manuscript presents a valuable investigation of the ice thickness and the bed topography of three Patagonian outlet glaciers, revealing ice thickness up to 800 m. Such a record of penetration depth combined with the dense coverage of GPR profiles is a valuable adding to the existing knowledge. Therefore, I think a comparison with previous studies is essential to frame the results of the manuscript in the context of Patagonian glaciers ice thickness.

The structure of the whole manuscript needs to be improved, as some results are described in the section methods. Figures 3 and 4 show two GPR sections which should require a dedicated section in the results, not in the methodology (data interpretation is 3.2, while it should be the first subsection of the results, so 4.1). Also, as the maximum depth of investigation is exceptionally high in Upsala Glacier, I suggest to show the profile where it can be seen, so it may be a solution to merge figures 3 and 4 into one figure showing a GPR profile for each glacier. The coherency between figures and text should be revised, as in paragraph 4.1 about ice thickness, the description of channelized bedrock topography is associated to figure 5, which shows ice thickness. For the data processing and modelling, it would be better to have more detail about the parameters' choice.

Thank you for the constructive comment. We have moved Fig. 3 and 4. Into the result section and have added a line indicating the bedrock reflection. We have revised the sections in the manuscript to be coherent with the appearance of the figures as suggested. We have expanded the method section significantly (see reply to Shin Sugiyama about model parameters / input data description) and added further information on the parameter choice of the GPR processing. We decided to keep the Profile of Upsala Glacier because it best shows the effects of debris to the radar measurement, but added additional profiles to the Supplementary Material.

A note about the data release: it would be more useful for the public to have also the processed data in a format that is usable from most of the community. The standard format for geophysical data is a SEG-Y (.sgy). I encourage the authors to think about releasing also the processed sections, otherwise consider to release the raw file in .sgy format.

We have converted the raw files (including the trace headers) to .SGY for each survey flight (3 over Perito Moreno, 2 over Viedma and 1 over Upsala) and will update the repository during the revision.

Considering the comment above, I recommend publishing the manuscript after revisions, primarily by comparing it with the previous dataset and focusing on improving its quality.

Thank you very much for your positive and constructive revision. We have added Section 5, where we compare our findings with previously published data from regional and global studies. Please see our reply to S. Sugiyama above.

I thank the authors for the very interesting reading, and I am very looking forward to see this paper published.

Specific comments

L14: I suggest to present the dataset in terms of kilometer of profiles interpreted, instead of points measurements. So, the sentence would be “The dataset comprises X km of ice-thickness measurements along 232 km of flight tracks”.

The 232 km are only the parts of the flight tracks containing thickness information. However, we rephrased the sentence to:” The dataset comprises 232 km of radar transects, totalling 116,021 individual ice-thickness measurements.”

L18: Reporting the highest ice thickness is perfect, as it is really extraordinary, but reaching 800 m may be due to a combination of factors, not a standard. So, treat this value with care. Have you calculated the distribution of the ice thicknesses and defined a reasonable depth of investigation?

Thank you. We agree that 800 m is close to, or at, the maximum penetration depth we would expect to measure over a temperate glacier. You are right that GPR data should be treated with care, as it has inherent inaccuracies and subjective biases. We have added the calculated uncertainty range (41 m) to the reported 800 m here to reflect this range of possible depths more transparently.

Penetration here could be deeper than elsewhere, which might be related mainly to two factors: we were experiencing quite strong headwinds at the transects going south. While maintaining a travel velocity of ~60 km/h, our true air speed was lower due to the headwind. Lower true airspeed leads to denser along-track trace spacing for a fixed pulse repetition frequency. This allows more traces to be averaged over a given horizontal distance, improving the signal-to-noise ratio. Also, the crevasses are comparably shallow in this region, and there is no visible debris layer. It was likely a combination of favourable environmental conditions and surface geometry that allowed for such deep penetration, which is ultimately close to, but within, the physical possibilities of our system.

L38: the abbreviation NPI is never used again in the manuscript, so remove it

Removed.

L61: have you checked if there are some measurements of ice thickness from satellite or airborne radar?

There are ice-thickness measurements from Millan et al. (2019), published here: <https://doi.org/10.1029/2019GL082485>, in the accumulation areas of the glaciers. These measurements are based on airborne gravimetric surveys and are included in the ice-thickness reconstruction. However, Millan et al. did not survey the lower regions of any of the glaciers investigated in our study. To our knowledge, no other airborne campaigns have been conducted over the three glaciers surveyed here.

L65: you have already defined SPI, so there is no need to do it again

Removed.

L69: same comment as L14. You can report the % or interpreted bedrock over the whole survey.

Yes of course. The entire flight lengths are now reported in Table 1 in section 3.1. The 232 km correspond to 59% of the total 393 km of survey flights. We have also added that information in L70.

Figure 1: I think that a zoom in is necessary here to see the survey lines better.

We have rotated the map. Flight lines should now be better visible.

L98: If you decide to use “Glaciar” it, is fine, but be sure to be consistent throughout the manuscript. Anyway, the English version “Glacier” should be used.

We have decided to keep the local (spanish) version and made sure it is consistently named throughout the manuscript.

L116: replace “seismic measurement” with “seismic survey”

Revised.

L134-138: a reference to support the hypothesis of temperate glaciers is needed here, as well as for the scattering due to water pockets

Added De Angelis et al. 2007 as a reference for the SPI being temperate and a study from Ogier et al. 2023, which addressed scattering and attenuation effects due to englacial water inclusions.

De Angelis, H., Rau, F., & Skvarca, P. (2007). *Snow zonation on Hielo Patagónico Sur, Southern Patagonia, derived from Landsat 5 TM data*. *Global and Planetary Change*, 59, 149–158. DOI: 10.1016/j.gloplacha.2006.11.032

Ogier, C., van Manen, D.-J., Maurer, H., Räss, L., Hertrich, M., & Bauder, A. (2023). *Ground penetrating radar in temperate ice: englacial water inclusions as limiting factor for data interpretation*. *Journal of Glaciology*, 69(278), 1874–1885. DOI: <https://doi.org/10.1017/jog.2023.68>

L142: is it a commercial GPR antenna or it was built by Blindow et al., 2011?

No, the antenna is not commercial. It was initially developed and built by N. Blindow at the University of Münster and was called UMAIR. It was later used at the German Geological Survey (BGR) under the name BGR-P30. The FAU 25 MHz system is an adapted and improved version of the BGR-P30, also developed by N. Blindow.

L154: The references should appear in chronological order

Thanks for the spot. Changed the order chronologically.

L156: Was the stacking set to 256 in the acquisition settings? Just for clarity

Exactly. We chose, prior to our first flight, and based on experience from prior studies, to set the stacking to 256-fold.

L175: you have already named the software, just remove the sentence and start straight with processing steps

Deleted the sentence.

L183: why did you choose 20 traces for background removal? I guess 20 traces gave the best result, right?

Yes exactly. We have chosen the window size of 201 traces because it yielded the best result. We have changed parameters in the processing flow and found this window size to yield the best results.

L190-198: I am a bit confused about the steps here, what is the manual layer determination? Was it associating the first arrival to the topographic surface? If so, what are the ice layers then? From the description I am a bit confused with the interpretation step, which is the picking phase, right? The air-layer correction is the topography correction where you considered the elevation of the platform, the elevation of the helicopter and the topography? I suggest to be more precise in the description of the processing steps. Have you tried other migration algorithm? Why did you choose diffraction stacking?

Thank you for the comment. Your assumptions are correct. In this step the Air/Ice boundary layer is manually delineated (picking the first arrival). The ice layer is actually not “picked” per se, but acts as a lower boundary for the migration in the next step to reduce the processing time. We “limited” the velocities lower boundary at ~1200 m depth.

From these two picks and the platform height you can create a 2D-velocity model, which is a required input for the migration. That way, the travel speed in different mediums is accounted for (air vs ice).

We have rephrased the description of step 7 to:

“The boundary between air and ice (surface) was manually delineated by tracing surface reflections. By doing so the distance between antenna and glacier surface is determined for each trace. This information is needed to create a 2D velocity model that accounts for wave propagation speed of 0.3 m ns⁻¹ in air and 0.168 m ns⁻¹ in ice. The velocity model is required for the migration in step 8.”

Similar to other processing steps we have also tried out several other migration algorithms and the diffraction stacking increased the visibility of weak / deep reflectors the best.

L202-211: as said in the general comment, these lines should be moved in the first subsection of the results. The figures should be described more carefully, for instance the “smiley features” at the bottom of figure 3 are not comment. Please move somewhere else the (a) because it covers a part that is described in the text. Since you comment on the surface morphology between km 4 and km 5 it is hard to see what you are referring to. For the detailed features maybe consider to use the appendix for more figures. In the text there is a reference to figure 3(c) which does not have a correspondence in the figure.

We were referring to the debris in the yellow square in the optical imagery (right side) of Fig. 3c. We will revise

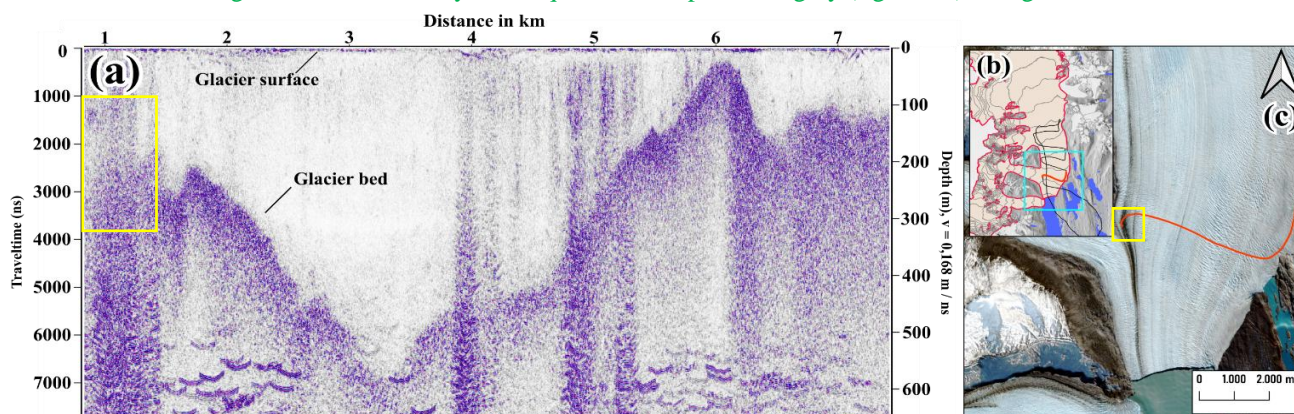


Figure 3 Radargram (a) acquired along a cross-section located approximately 2 km upstream from the terminus of Glacier Upsala. The corresponding flight line is shown in panel (b), with its location indicated in panel (c). In the left portion of the radargram, the influence of the thick debris cover is evident, as bedrock reflections become indistinct or no longer discernible. Background imagery in (c) is a Sentinel-2 scene acquired on 28.08.2025.

this figure and indicate the area of interest alongside the other comments.

I suggest to merge figure 3 and 4 into one figure with three panels plot, one for each glacier. For Upsala, plot the GPR sections where the ice thickness reaches 800m. I also recommend to plot the section with the topography correction applied.

We will move Fig. 3 and 4 including a new Figure for Perito Moreno to the GPR result section, and discuss visible features.

L228: give value for picking uncertainty, how was it calculated? Referring to velocity uncertainty, you are using 0.168 m/ns which is the velocity for pure ice. It is totally fine to use it, but as you said that the glaciers are temperate, have you tried to quantify the difference in terms of ice thickness if you use a lower velocity, as is expected for warm ice?

Also, Perito Moreno glacier has some snow layer, how thick is it? Does it affect the time to depth conversion if you take this layer into account? Maybe you should discuss also this source of uncertainty.

Radio-wave velocity uncertainty is often estimated empirically. Lapazaran et al. (2016) report typical uncertainty ranges of approximately 1-5%, equivalent to ± 1.7 -8.4 m us⁻¹ for a velocity of 0.168 m ns⁻¹. We adopted the conservative upper bound of 5% for the radio-wave velocity uncertainty, ϵ_{τ} , because of the large ice thicknesses surveyed and the likely presence of englacial water inclusions in temperate ice, which can reduce propagation velocity. This uncertainty range encompasses a lower-end velocity of approximately 0.160 m ns⁻¹, comparable to values reported for the temperate Bench Glacier by Bradford et al. (2009).

The travel-time uncertainty, ϵ_{τ} , is defined as the uncertainty associated with identifying the reflector arrival time in the radargram. Following Lapazaran et al. (2016), we used a conservative constant value equal to one period of the 25 MHz radar signal:

$$\epsilon_{\tau} = \frac{1}{f} = 40 \text{ ns}$$

which corresponds to an ice-thickness uncertainty of approximately 3.4 m for a radio-wave velocity of 0.168 m ns⁻¹. We have added these values and their derivation to the manuscript.

We were not able to identify clear bedrock reflections in the snow-covered upper-altitude sections of Glaciar Perito Moreno during the survey. Therefore, we did not include an additional uncertainty term for propagation through a snow layer. We have clarified this in Section 3.3:

"As our acquisitions were conducted almost entirely over snow-free ice, we did not account for varying propagation velocities within firn or snow layers. Although the profiles over Glaciar Perito Moreno reached into the accumulation area, reflections in these upper sections were not sufficiently clear for reliable bedrock picking and were therefore excluded from the analysis."

Source:

Bradford, John H.; Nichols, Joshua; Mikesell, T. Dylan; and Harper, Joel T., "Continuous profiles of electromagnetic wave velocity and water content in glaciers: an example from Bench Glacier, Alaska, USA" (2009). Geosciences Faculty Publications. 36

L276: give value for the plausible bounds. I think you should give more details for the whole modelling procedure.

Agreed. We have added information about the model input as well as reasoning for choosing upper and lower bounds for the perturbation experiments:

In addition to our measurements, we used an established ice-thickness reconstruction method that has been applied in several regions and can incorporate observational constraints (Farinotti et al., 2021; Fürst et al., 2017, 2018, 2024; Sommer et al., 2023). This approach allows us to generate basin-wide ice-thickness maps for the year 2000, along with corresponding bed-elevation maps. The two-step method is primarily based on the principle of mass conservation (Fürst et al., 2017) and, more specifically, uses the shallow ice approximation (SIA) (Morlighem et al., 2011). In addition to the newly obtained thickness measurements, thickness values along the flight tracks of gravimetric surveys over the SPI plateau were used (Millan et al., 2019). Post-retreat lake-bed elevation data were derived from bathymetric surveys (Sugiyama et al., 2016; Minowa et al., 2023; Koch et al., 2025). At Glaciar Perito Moreno, data from a seismic survey and from two boreholes were also incorporated (Stuefer et al., 2007; Sugiyama et al., 2011). Ice thickness information was inferred from glacier retreat on land using Landsat imagery from March 2001 and 2016 (De Angelis, 2014; Meier et al., 2018; Sommer et al., 2023). The year 2000 reference DEM is based on the 30-m product of the SRTM v2.1 DEM (Farr et al., 2007). Data voids were filled with multi-resolution terrain elevation data from 2010 (Danielson and Gesch, 2011). Elevation change rates were based on TerraSAR-X Add-on for Digital Elevation Measurements (TDX) data (Krieger et al., 2013). The corresponding elevation change rates were derived from TanDEM-X DEMs from 2016 and 2019 (Malz et al., 2018; Braun et al., 2019). The surface mass balance (SMB) data used were derived from statistically and dynamically downscaled NCEP-NCAR atmospheric reanalysis data from 1965 to 2011 (Kalnay et al., 1996; Schaefer et al., 2015). Based on these data, the glacier SMB was derived using an enhanced temperature-index model that incorporates cloud-cover-corrected potential incoming radiation (Fürst et al., 2024). The surface velocity fields applied in the second step of the reconstruction and to estimate the frontal ablation and ice discharge are based on available mosaics from Mouginot and Rignot, (2015). The flux gates were placed close to present-day terminus positions, and the ice flux was computed as the product of ice thickness and the surface-velocity component perpendicular to each gate.

In the first step, we infer the glacier-wide ice-thickness fields without relying on surface velocities (Fürst et al., 2017, 2018). First, we apply an iterative flux-based method, in which the problem is formulated in terms of ice flux and subsequently converted to ice thickness using the Shallow Ice Approximation (SIA). This conversion depends on a spatially variable viscosity parameter, which is estimated in areas where ice-thickness observations are available. The classical approach was further updated by introducing a viscosity rescaling, which improves inferred thickness distributions farther from observational constraints (Sommer et al., 2023; Fürst et al., 2024). In the second step, the initial ice-thickness field is refined in areas where reliable surface-velocity observations are available. This is done by solving the mass-conservation equation directly for ice thickness. Because the equation is vertically integrated, the observed surface velocities must first be converted to depth-averaged velocities. The velocity-based correction is only applied in regions where surface speeds exceed 100 m yr^{-1} . In these fast-flowing areas, basal sliding is assumed to dominate over internal deformation, so the surface velocity is taken to be equivalent to the depth-averaged velocity. The mass-conservation equation is then solved using the same Elmer/Ice implementation as in the first step.

L286: as above for L14 and L69

Added the total coverage, too.

L290: I guess we are talking about Perito Moreno Glacier

Yes. Added Perito Moreno so its clear which glacier this statement refers to.

L296: You are describing figure 5 showing ice thickness, so the bedrock morphology description is not coherent with the figure. You should mention the channelized bed topography referring to figure 7. Please take care of the coherency between figures and text.

Technically yes, Fig. 5 shows the ice thickness. The thickness distribution however already indicates the presence of two channels in that area. We have added a reference to both Fig 5a and 7a so the link becomes more obvious.

L300: please show previous measurement in fig 5a

We will indicate the locations of the previous measurements over Perito Moreno in Fig 5.

L303: same as L69

Added total flight coverage.

L309: same as above

Added the total coverage, too.

L325: REFs, which ones?

That was a typo. Deleted.

L323-327: I think a comparison with previous dataset is highly valuable at this point, as I said before. I agree with Reviewer 1 that this is one of the values of your measurements.

See our reply above regarding the model comparison.

L330: in line 290 you say that the maximum ice thickness for Perito Moreno Glacier is 706m, not 681m.

This refers to the reconstructed ice thickness fields. Added that information to the text.

L333: as said before, discussion about bed morphology should refer to figure 7

In our opinion the ice thickness distribution also reveals the presence of a subglacial feature. Additionally referring to Figure 7.

Figure 6: I suggest to put the flight path on the glaciers or at least the lines where the bedrock was interpreted. Also, contouring lines might help with the visualization.

Added the flightpaths over Fig. 6 and contours lines.

L349: I am not sure what “constriction” means here?

A narrowing of the glacier bed. We will indicate that in the figure too and refer to it.

L375: the system is optimized for operation over temperate ice, but at this point one would be curious about details. This info should be in the method section where you describe the system. The scattering due to water has a higher impact than the lateral reflection. You never mentioned the lateral reflections due to steep rocky walls; it is a common problem with airborne surveys. Did you have any? Did you correct them with migration? If so, this should be said in the methods when describe processing steps.

We used a low-frequency, shielded helicopter-borne GPR system specifically designed for deep temperate-ice sounding. Temperate ice is challenging for radar sounding because liquid water inclusions and englacial channels cause absorption and strong internal scattering. Following the design rationale of the BGR-P30 system, we therefore used a centre frequency below 30 MHz, where scattering and surface-roughness effects are reduced

sufficiently to allow bed detection in deep temperate glaciers. Blindow et al. report that 30 MHz or lower centre frequencies produce good-quality data in temperate ice and that the BGR-P30 system penetrated temperate ice to more than 700 m. Our 25 MHz centre frequency corresponds to a wavelength of about 6.7 m in ice which makes it less sensitive to scattering from decimetre- to metre-scale water inclusions, while still retaining sufficient resolution for bed picking and 2-D migration.

Based on the BGR-P30 performance documented by Blindow et al. and our own observations, we estimate the practical penetration range in temperate Patagonian outlet glaciers to be on the order of 600–800 m, depending on local englacial water content, debris cover, surface roughness, and bed geometry. In our dataset, bed reflections were obtained up to ~800 m depth, while in some transects the radar backscatter faded at about 600–650 m, illustrating the site-dependent attenuation typical of temperate ice.

We agree that side-wall reflections can be a concern in airborne GPR surveys in narrow glacier valleys. However, the acquisition geometry and system layout in our survey makes this effect unlikely to affect the dataset. Side reflections are frequently observed with fixed-wing aircraft systems flying at altitudes like 400 m parallel to the valley walls, especially with unshielded antennas (e.g. Zamora et al. 2009).

Our antenna is shielded to obtain directionality towards the ground and was flown close to the glacier surface, typically at ~30 m above ground, and profiles were kept at ~100 m from the glacier margin. In addition, most flight lines were not flown parallel to steep rock walls for extended distances. Flight patterns are designed primarily as transverse profiles to enable 2-D migration. Under these conditions, potential lateral reflections are easily discerned and suppressed by their apparent slopes corresponding to diffractions in air, and would not be expected to form spatially continuous bed-like reflectors along the profiles. We therefore interpret the continuous basal reflectors as true glacier-bed returns, while acknowledging that isolated side echoes may occur locally but are unlikely to affect the main bed picks.

L385: these issues during acquisition should be first said in the methods when you describe the survey. Then, they can be mentioned again here in the discussion when you discuss the attenuation of the signal.

We have added the following paragraph during the presentation of the radar data in section 4.1: “In the large southward-oriented branch, and with increasing elevation, no clear bedrock reflections were visible. We attribute this mainly to two factors. First, increasingly strong katabatic crosswinds and gusts forced us to fly substantially higher above the glacier surface, at approximately 100 m. Consequently, the radar wave had to travel a substantially longer distance through air, resulting in greater signal attenuation and, therefore, weaker potential reflections. Second, at these elevations, the glacier surface became snow-covered. Because the survey was conducted at the end of the austral summer, we assume that the snowpack was likely wet, which may have further attenuated the radar signal.”

“

Figure 8: from figure 5 to 9, they look almost identical in the layout. It makes the manuscript a bit linear. I would put figure 8 in the appendix, you can describe GPR uncertainty in the dedicated section referring to figure 8 in the appendix. I would leave figure 9 in the main text.

We have moved figure 8 to the appendix as suggested and kept figure 9.

Referee 3 comments:

This is an interesting work about ice thickness data collected by a helicopter borne radar system used to survey some of the biggest Southern Patagonia Icefield (SPI) eastern freshwater calving glaciers. The area is contributing to sea level rise at high rates, therefore, knowing the total volume of ice storage there is very important. Several subglacial topography models have been published in recent years, however, validation data based upon in situ surveys are lacking. This manuscript is providing a great data set that will certainly improve our estimations of the total ice thickness in the area. This data set will be useful for several kind of studies and the effort and high costs of producing the data is highly appreciated.

In spite of the above very positive first impression, I have the feeling that some issues in the manuscript must be addressed in order to improve the presentation of the results. A great effort was put on describing the method and uncertainties, but I'm missing more discussions about the data, for example, not only describing where they got nice bottom reflections, but also, where the data are a bit obscure or noisy. Why these problems? We know that water is precluding good penetration ranges using radar, but at Perito Moreno they got useful data almost everywhere, even if previous works (<https://www.nature.com/articles/ngeo1218>) are showing a water table within the lower glacier tongue. Apart from water, there are more issues; Internal structures? Surface debris? Ash bands? I'm encouraging the authors to use the opportunity to discuss a bit more about the technique, the results and the limitations.

Thank you very much for your feedback on the paper. We have added sections describing the measurement and modelling process in more detail. Additionally, we have added figures and discussed the effect of water inclusions/debris and or crevassing in more detail in the discussion.

Regarding the water table at Perito Moreno. We did find a pattern, which would indicate a water table at the lake surface elevation of Brazo Rico/Canal de los Témpanos.

Also, I think the figures including maps must follow typical cartographic frameworks, especially with North to the top of every map.

In spite of these comments, I think the manuscript deserves to be published after addressing these points.

Below some more specific comments. I hope these will help to improve the manuscript.

Abstract:

Check the use of "." for thousands and not for decimals or vice versa. Check all along the manuscript

We have revised consistency and use “.” for decimal separation and “,” for thousands.

Line 40-43

This is a regional study (eastern side of the SPI) not including glaciers advancing or having at present positive mass balances (Perito Moreno has been considered a glacier in equilibrium, but looks like in recent years this is changing). However, within the SPI there other “advancing glaciers like Pio XI that are not discussed or at least mentioned. The projections for these glaciers are not validated neither calibrated, therefore there are very high uncertainties in rprojections, and not only related to frontal ablation as stated. I suggest adding a paragraph about uncertainties related to future surface mass balance and also mentioning "anomalous" glaciers. This will give to the reader a most balanced and wider understanding of the complex glacier processes taking place in the region.

We have added a section to the introduction which should give the reader a better understanding of the heterogeneity of glacier retreat in the region and the importance of measurement for potential glacier future evolution.

Line 56

There are also some on the ground surveys worth mentioning, like Rivera & Casassa 2002 https://doi.org/10.1007/978-1-4615-0645-4_10

Added a citation.

Regarding Figures (1, 5a, 5c, 6a, 6b, 7a, 7c, 8a, 8c, 9a, 9c, and Supplementary figure 1a and Supplementary

2c)

I strongly recommend to rotate all the above mentioned figures in order to show the North up. Cartographically, North is normally to the upper part of the figures been this way easy for any reader. The listed figures are rotated (maybe) for a better use of the journal space, but this rotation is adding in my point of view, complexities to the maps, since commonly we see North Up like in Upsala figure's. Better to have all figures with the same direction/orientation.

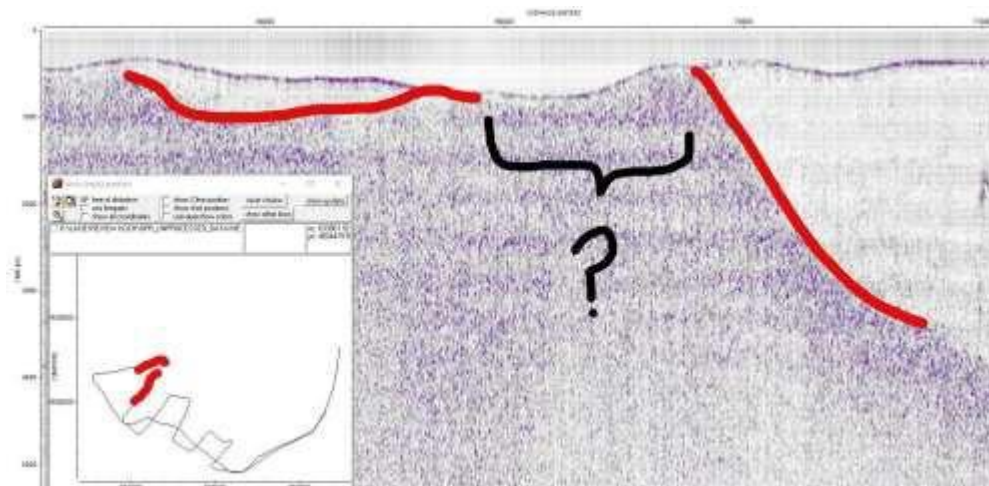
We have revised all figures to be oriented northwards.

Line 148

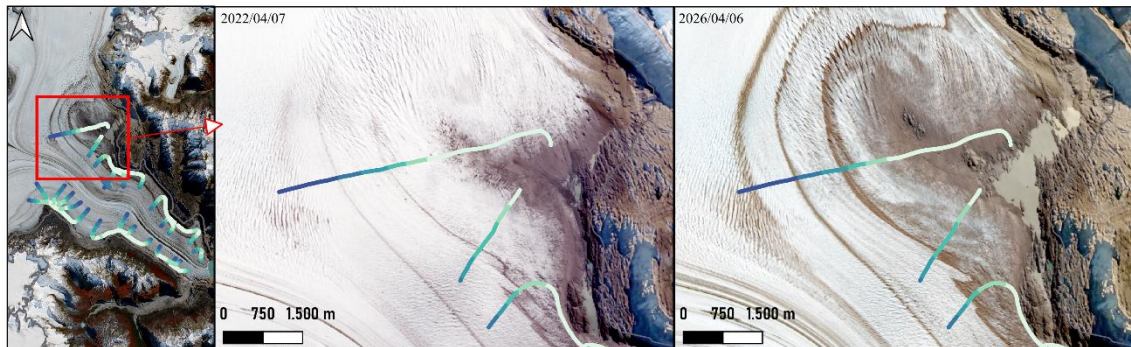
I was wondering if horizontality is always obtained, especially when the helicopter is turning along the track (near the edges of a glacier for instance). I repeated the analysis of all the radargrams using Reflex, and I found some profiles where looks like the antenna was tilted (not sure of course) or the interpretation could be not clear due to this and other factors (debris, water, etc).

This is a good question. The system is designed to be horizontally plane at a travel velocity of 60 km/h. Of course the system is expected to slightly tilt when doing a turn. However, if you look at the distances we travelled when doing a turn which are in the order of 500 m to 1000 m the expected tilt during a turn becomes small, since the lateral acceleration is small. We did some calculations for a roll/tilt of the antenna of 2.5° to 5° (which are maximum expected ranges) which gives out of plane offsets of 2.5 m to 7.5 m (at 30 m above ground). The error from antenna tilt is therefor expected to be comparably small.

For example, in the following profile obtained at Viedma, around the turn of the track, the bottom is visible as a red line (see the location below where the points with ice thickness data are shown on top of a satellite image), but then, at the center of the figure the signal is missing in spite of been above. After few meters to the right and left, the bottom is clear again in the radargram, but in between something happened that the bottom is missing. Is this obscure return due to the angle of the antenna during the turn? Or is the partially debris covered surface? A moraine? Many possibilities; I think is worth discussing this kind of problems in the data. The clear part of profiles look great (like the right side of this radargram), but it is also very useful to discuss more obscure data.



In this specific case which you have highlighted the radargram is not skewed from out of plane effects but simply because the glacier is so thin here and as you can already suggest from the remote sensing imagery mixed with debris. See the picture below.



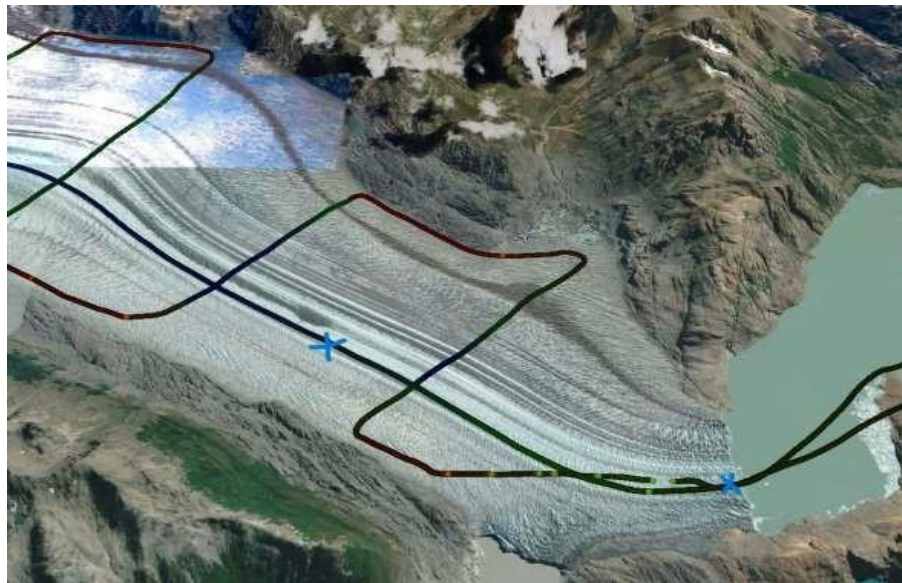
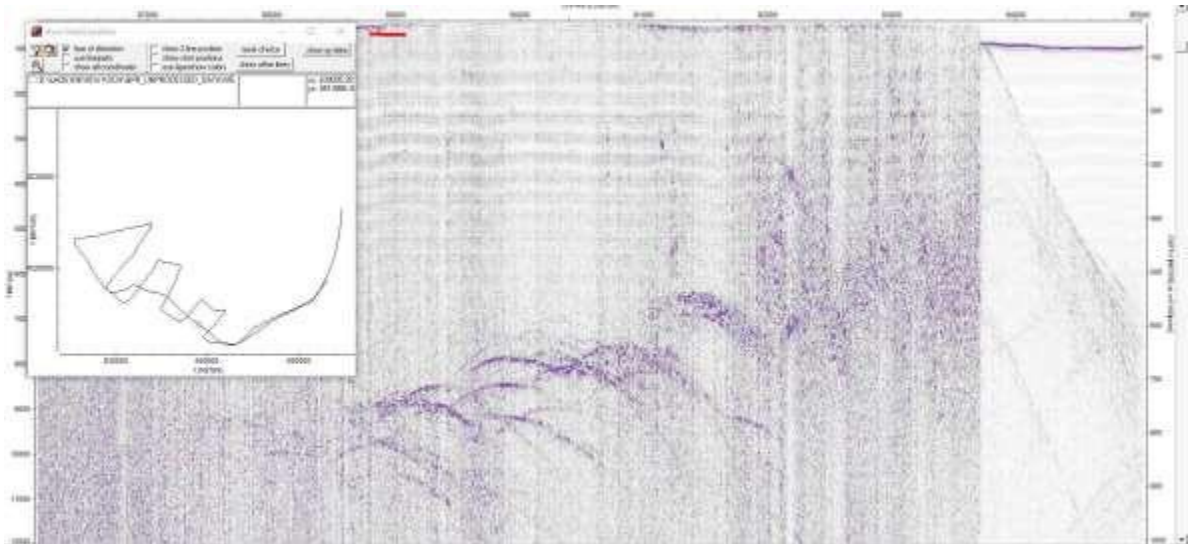
This is a sentinel 2 scene from 2022-04-07, so close to acquisition and from 2026-04-06. Even though there was



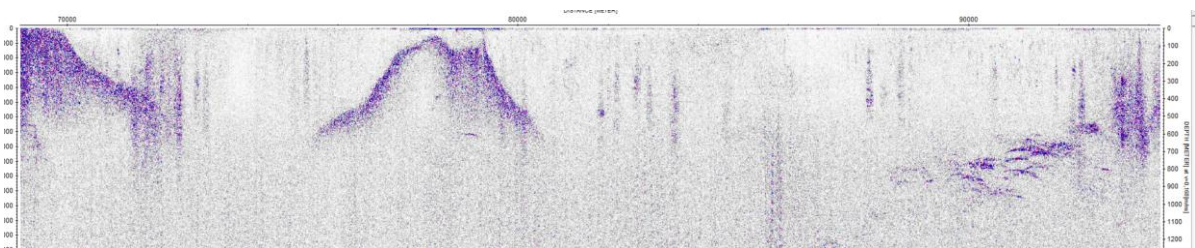
still some ice left in 2022, you can see from the recent imagery that there was not much ice left above the bedrock, in fact just some meters (<10 m). Additionally, a lot of debris is being deposited in that area of the glacier and combined made the bedrock reflection and surface reflection “dissolve” in the radargram. We have added this figure alongside to discuss some effects of “no” data in more detail.

In general I agree with the interpretations of the bottom reflections. The data are very nice all over the glaciers. In few cases I think the interpretation is too conservative, and in few others is probably too overoptimistic, but in general I think the data is extremely useful and well collected and interpreted.

There are few intriguing cases. For example, in the following track there are no interpreted ice thicknesses along the profile until the lake, but the radargram is full of hyperbolas (around 700m depth) that partially could be related to the bottom or more likely to lateral reflections, however, at this location, the lateral rock walls are more than 1000 m away the track. In this case, I did not apply migration to the data, that probably helped dismissing the bottom as was finally decided, but the presence of these hyperbolas are indicating something that could be interested (water conduits? moraine material?) This kind of features are worth been discussed in more detail. The same could be said for the near lake record that looks much noisy or obscure, probably due to water and crevasses. I think the discussion of these dasta could be expanded a bit. This will help readers to better appreciate this nice data set.



You are right in your assumption that the hyperbolas visible in the section close to Viedma's terminus were not giving a clear reflection. Here is a screenshot after migration:



This also shows how “clearly” some of the bedrock reflections are visible after migration, but since the ones close to the terminus (right hand side of the plot) remained so ambiguous we did not pick them as bedrock reflectors.

We will add these points to the discussion, thank you for looking into that.

Line 154

Maybe you can say more about Blindow et al, 2012 since it was related to Nef and Colonia glaciers also in Patagonia.

We have added the following to the manuscript: “For example, in 2012, a predecessor of our antenna system operating at 30 MHz was deployed on Colonia and Nef, two outlet glaciers of the Northern Patagonian Icefield. Both glacier surfaces are heavily crevassed and partially debris-covered. Despite this pronounced surface roughness, the measurements demonstrated that the 30 MHz system was capable of penetrating up to 800 m of temperate ice (Blindow et al., 2012).”

Figure 3 and 4

Please confirm that left side of (3a) is also the left side of the red profile in (b) and (c).

In order to avoid any misunderstanding about the left and right side of the profiles, it could be better to have A-A' in (a) (b) and (c)?

Yes it is. We added an indication to make that clearer to the reader.

Line 213.

In similar works related to radar data, the thicknesses at crossing tracks are compared in order to estimate uncertainties. Did you compare ice thicknesses at crossing points? There are several tracks crossing each other, and I think the differences on these points can illustrate very clearly the potential errors.

We have included a 4 panel plot which shows the mean offset of cross points per 100 m of depth for Perito Moreno, Viedma and Upsala and for the entire dataset.

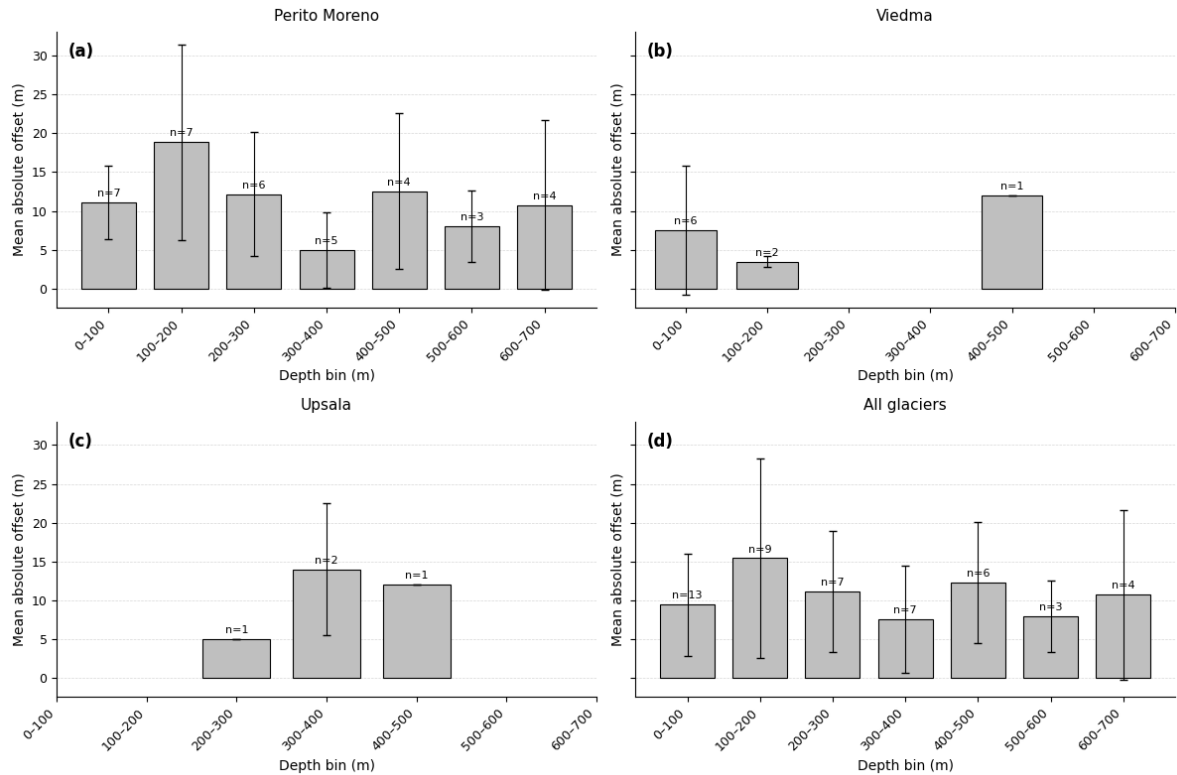


Figure 1 Mean absolute offset between crossing-point depth picks as a function of depth, grouped into 100 m bins, for (a) Perito Moreno, (b) Viedma, (c) Upsala, and (d) all glaciers combined. Error bars indicate ± 1 standard deviation; n denotes the number of observations in each bin.

Table 1:

Above sea level, meaning the elevation data is "geoidal"? Maybe is better to confirm that. Normally GPS data is based upon ellipsoidal reference.

The surface elevation is indeed ellipsoidal. Revised Unit format in Table 2 (former table 1).

Line 256

I suggest to include here the work done by Lannutti et al., 2024

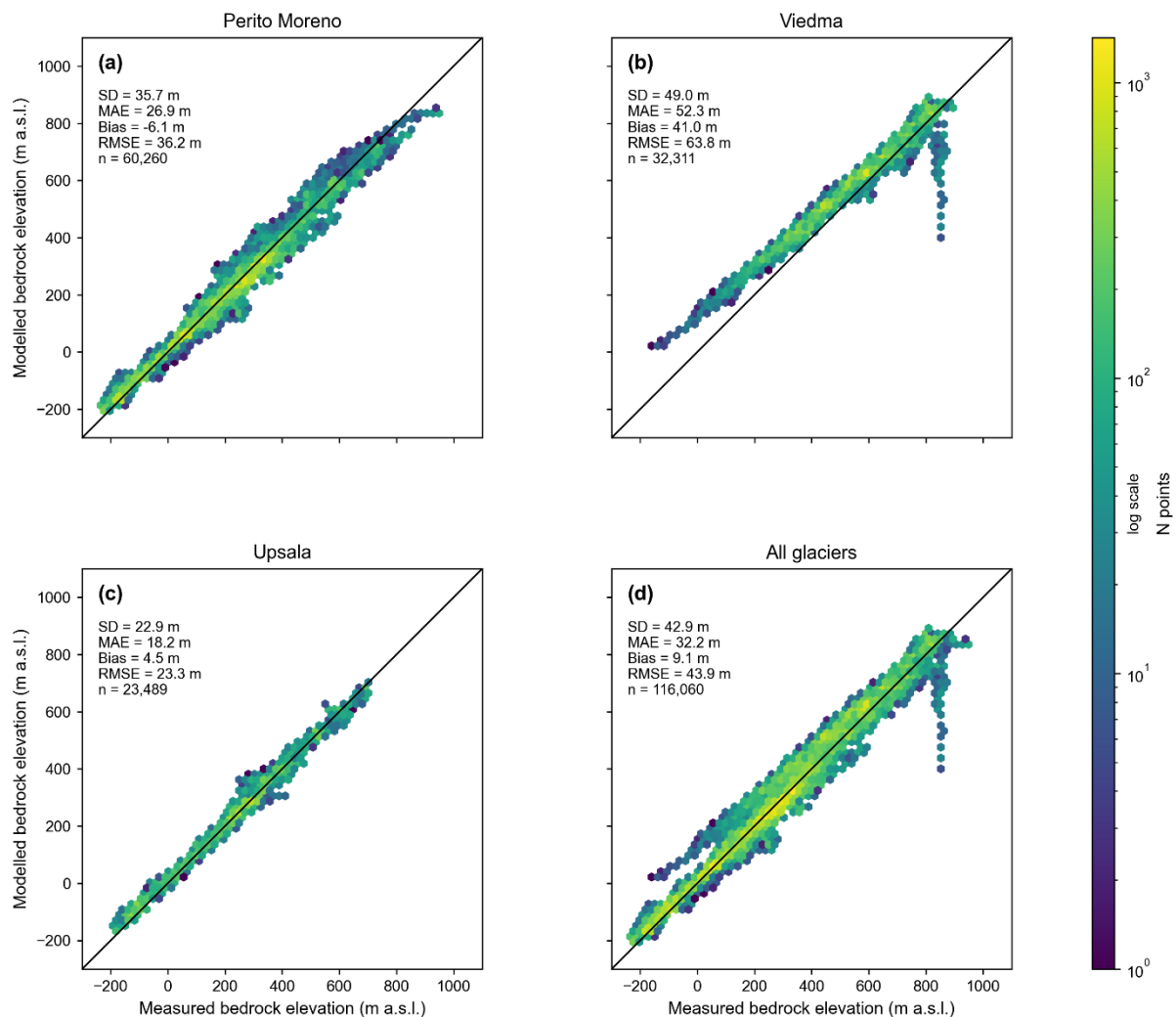
<https://doi.org/10.1016/j.coldregions.2024.104158>. They reconstructed the bed topography of the same glaciers, including validation with available radar as well as bathymetric data

We refer to studies here which use the same technique to reconstruct the ice thickness distribution. These studies are all based on the work of Fürst et al. 2017. Farinotti et al. 2021 is mentioned here, because the approach of J. Fürst was also compared in the comparison study by Farinotti et al. 2021. However, we have included the work from Lanutti et al. 2024 in our model comparison section.

Line 266

This analysis is important and I think it deserves more details. In Supple Figure 2 looks like there are two "data groups", one very dense data points and the second one, in parallel, with less data. Why? Are these two "families" related to different glaciers?

Yes, that is a very good observation. The two "groups" which show a systematic offset was because I compared the measured ice thickness values from 2022/2024 to the reconstructed ice thickness values which are dated to 2000. The offset you are referring to is thus due to surface lowering, which is ~200 m in the lower regions of Upsala since 2000 for example. We have therefore now plotted the bedrock elevation, which is time independent.



This plot shows the bedrock elevations along the survey lines together with the modelled bedrock elevation. The systematic offset caused by surface lowering is no longer apparent. A notable group of outliers occurs at Glacier Viedma, which we attribute to the proximity of our measurements to the gravimetric constraints. The bedrock-elevation points derived from the gravimetric measurements (see Fürst et al., 2024) indicate lower bedrock elevations than our radar-derived values. Consequently, the inversion attempts to reconcile both datasets, resulting in the observed bias between our measurements and the modelled bedrock elevation from the ice-thickness inversion.

We have added the figure to section 4.2 with the following explanation:

“Figure XX shows The comparison between measured and modelled bedrock elevations. generally good agreement across all three glaciers, with most points clustering close to the 1:1 line. The combined dataset yields an RMSE of 43.9 m and an MAE of 32.2 m, indicating that typical absolute deviations are on the order of a few tens of metres. The overall bias is small and positive at 9.1 m, suggesting a slight tendency for the modelled bed elevations to be higher than the measured values. Glacier-specific performance varies, with Upsala showing the lowest errors (MAE = 18.2 m; RMSE = 23.3 m), followed by Perito Moreno (MAE = 26.9 m; RMSE = 36.2 m), while Viedma shows the largest deviations (MAE = 52.3 m; RMSE = 63.8 m). The comparatively larger error and positive bias at Viedma indicate that the modelled bed is systematically higher than the measured bed in parts of this glacier. A notable group of outliers occurs at Glaciar Viedma, which we attribute to the proximity of our measurements to measurements from a gravimetric survey by Millan et al. (2019). The bedrock-elevation points derived from the gravimetric measurements indicate lower bedrock elevations than our radar-derived values. Consequently, the inversion attempts to reconcile both datasets, resulting in the observed bias between our measurements and the modelled bedrock elevation from the ice-thickness inversion. Overall, the statistics support the robustness of the modelled bedrock dataset.”

By the way, I think is better to keep Supplementary figure 2 (and not Appendix Fig. 2)

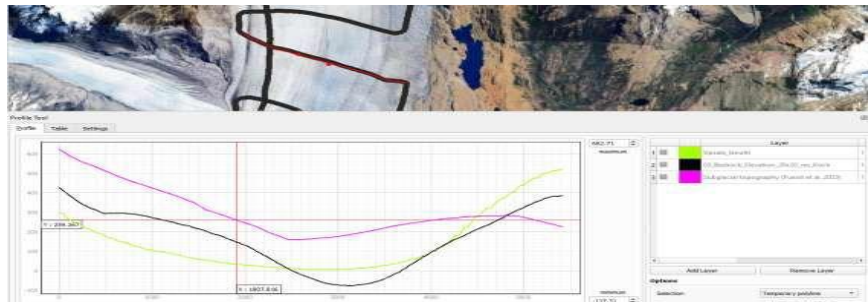
Removed since supplementary fig. 2 has been moved to the main text now.

Line 296

“align well” is not very precise. In spite of some good numerical comparison described in this paragraph I suggest adding topographic profiles with the differences between available models and available data

The use of topographic profiles will help to better see the results and improvements. Below, I added a profile along a transversal track measured at Upsala (red line on the upper figure).

Along the profile, pink is Fûrst et al, 2024. Black is Koch under review and green is Lanutti et al, 2024. There are some strong differences that deserve to be discussed and addressed in the manuscript.



We have added the following figure to the appendix, including a discussion of the difference in results. We have chosen to plot the topography alongside the central flow line provided by the RGI v7.

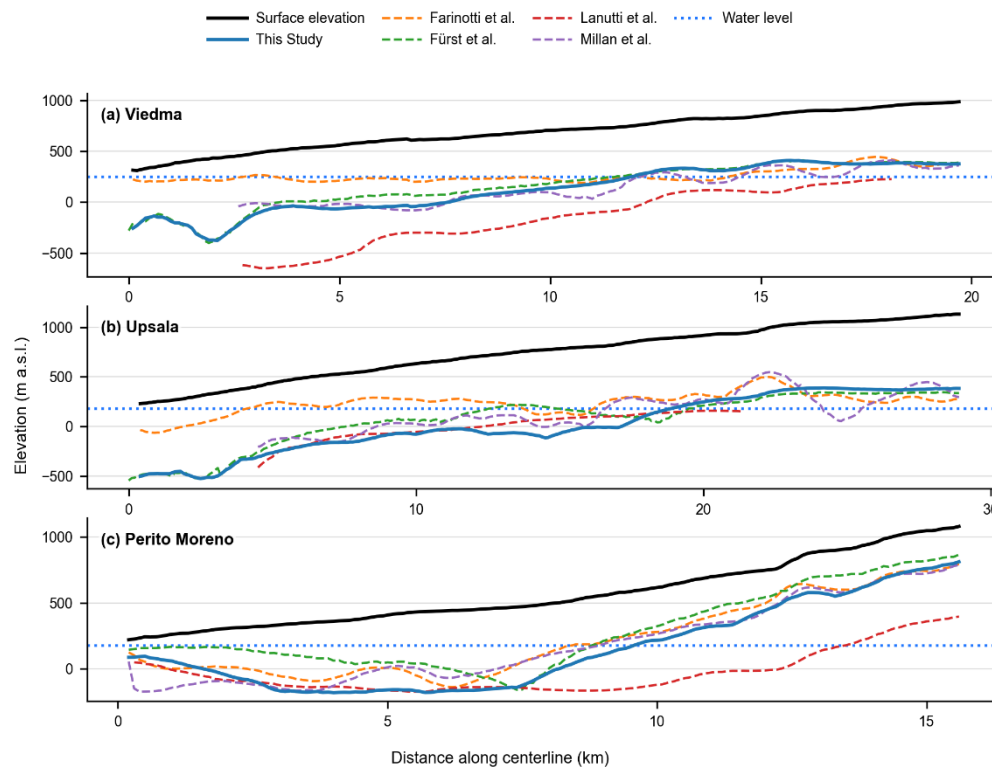


Figure X. Longitudinal elevation profiles along the glacier centerlines (according to the RGI v7) of **(a) Viedma**, **(b) Upsala**, and **(c) Perito Moreno**. Black lines show surface elevation from the year 2000 (SRTM DEM), while coloured lines show bed elevation estimates from this study and from the model products of Farinotti et al., Fürst et al., Lanutti et al., and Millan et al. Blue dotted horizontal lines indicate the approximate lake water level used for reference, corresponding to 252 m a.s.l. for Viedma and 179 m a.s.l. for Upsala and Perito Moreno. Distances are measured along each glacier centerline from the lower glacier margin towards the upper glacier.

Line 316

Rivera et al., 2022 detected 900 m near the Viedma 2022 glacier front. ¿Is this water depth consistent with your data? see: <https://revistas.unlp.edu.ar/geoacta/article/view/14210>

The bedrock elevation in our reconstruction reaches approximately -400 m a.s.l., corresponding to a lake depth of 652 m when assuming a lake level of 252 m a.s.l. for Lago Viedma. This estimate is consistent with the bathymetric data of Minowa et al. (2023), although the location lies farther from the position referenced in your technical report. Given the fjord-like geometry, an overdeepening in this part of the trough is plausible. However, because no direct observations are available in this area, the model does not fully capture the measured values reported there. We address this point in the discussion.

Line 342

“Consistent” is arguable, especially when there are bathymetric data closer to the glacier front indicating much deeper water depths (as said before, have a look to Rivera et al., 2022 : “Estudio de la profundidad del lago Viedma, Parque Nacional Los Glaciares, Argentina”).

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Please see answer above.