Response to Reviewers' Comments on ESSD-2025-745

We thank the reviewers for their time, constructive comments, and valuable suggestions, which have significantly improved the quality of our manuscript.

We have addressed all comments from the reviewers in detail. The reviewers' comments are presented in black, our responses are given in blue, and the corresponding revisions in the manuscript are indicated in green.

Reply to RC1: "Comment on essd-2025-745" (Moritz Koch)

General comments:

In the introduction, the authors mention previous GPR surveys of the glaciers; I understand that these measurements were carried out in the late 80s and 90s and are not necessarily as accurate as today's surveys. However, I believe it would be very valuable to compare the newly obtained measurements with the earlier studies in this paper. There is also a detailed overview of the methods previously used, and it would be very interesting to build on that.

We thank the reviewer for this valuable suggestion. We agree that a comparison with previous RES studies is important and have already included such comparisons in the manuscript. Previous RES investigations of Swedish glaciers are summarized in Table 1. Among these, Björnsson (1981) investigated Rabots glaciär (RG), while Herzfeld et al. (1993) compiled all earlier measurements (RES survey 1, 2, 4, and 5 in Table 1) and derived a bed topography map for Storglaciären (SG). We therefore compare our results with these two maps for SG and RG (Fig. 8a–b). These comparisons are discussed in Section 4.3 (Line 311): "Our results and previous RES-derived bed topography of SG (Herzfeld et al., 1993; Eriksson, 1993) and RG (Björnsson, 1981) show strong agreement in both values and spatial patterns (Fig. 8). Both our and previous maps of SG reveal two depressions in the central-eastern section (~1150 m a.s.l.) and a smaller depression at ~1400–1450 m in the northwestern part. Similarly, both maps of RG show a deepening along the central section towards the terminus. Owing to denser and more modern RES measurements, our high-resolution maps additionally resolve finer-scale topographic features. Moreover, our digital datasets enhance reusability." In addition, for Riukojietna (RIV), we compare our ice thickness results with earlier observations (Holmlund, 1986), as discussed in Section 4.2 (Line 241): "…The ~20 m difference between our maximum ice thickness and previous estimates can likely be attributed to mass loss over the past ~28 years".

All the other studies previously included in Table 1 (RES study 6 to 13) refer to applications of RES in other fields (e.g., thermal and hydrological studies). To improve focus and avoid confusion, we have now removed these studies from the table.

You include uncertainty maps in the database, but they are not shown or discussed in the text. When I first read through the article, I thought they weren't provided. Clarify that somewhere in the manuscript or, better still, include them as figures and discuss the spread of the uncertainty ranges.

We thank the reviewer for this comment. The uncertainty maps are already shown in the manuscript (Fig. 5a–d), and their interpretation is discussed in the text (Line 245) in Section 4.2. We acknowledge that this may not have been sufficiently clear. We have therefore added more description of this figure in Line 245: "...for the four glaciers (Fig. 5a–d). The spatial distribution of uncertainties is shown in Fig. 5a–d, with larger uncertainties concentrated in the thicker, interior regions of the glaciers, while lower uncertainties are observed towards the margins where ice thickness is better constrained by modelling. Misfits between…".

Specific comments:

L 7: While measurement points are an interesting metric, how much spatial coverage do the radar transects in their entirety have? I think this should be mentioned here.

We thank the reviewer for this helpful comment. We agree that the spatial coverage of the radar transects is an important metric. We have therefore added a new column ("Coverage") to Table 2, indicating that the RES surveys cover 87%, 83%, 70%, and 92% of MG, SG, RG, and RIV, respectively. In addition, the spatial distribution of the measurements is described in Section 3.1 Line 105.

L 13: Is it necessary to provide the data in individual repositories? If not, I would recommend merging them and offering the dataset in a single repository; citing four different repositories seems cumbersome to me.

We thank the reviewer for this suggestion. The four glaciers investigated in this study are Swedish reference glaciers, for which data repositories have already been established separately within the TRS database, including also long-term mass balance records. To maintain consistency with this existing data structure, we have therefore deposited the RES datasets in their respective repositories. We agree that a unified repository could improve accessibility, and we will consider compiling datasets into a single repository when additional RES data from other glaciers become available in the future.

L 28: I am confused by the citation Houssais et al., in prep. Since there is no preprint available, there is no way to evaluate how and on what basis that point was made. If it will be available as a pre-print likely during the revision process, I don't think that's a problem. If not, I would reconsider citing it here.

We thank the reviewer for this valuable suggestion. The previously cited work is currently under review and not yet publicly available. However, the method used to delineate glacier outlines and calculate glacier area has already been published and applied to assess Swedish glacier area changes for 2017–2023 (Houssais et al., 2025). We have therefore revised the sentence to rely solely on this published source as follows: "Based on satellite image analysis, Swedish glaciers lost 13% of their total area during 2023–2024, with eight glaciers disappearing in an unprecedented year of mass loss. This loss is nearly as large as the cumulative area loss over the previous six years (Houssais et al., 2025)." We have also deleted this unpublished reference in other parts of the manuscript.

L 34: Insert "the" before "present-day"

We thank the reviewer for this correction. We have added "the" before "present-day".

L40: I think there should be a citation at the end of that statement.

We thank the reviewer for this suggestion. We have added appropriate references (Carey, 2010; Welling et al., 2015) to support this statement.

L43: … "with uncertainties ranging from a few meters to several tens of meters." This is true for comparably shallow glaciers, but I would argue that the realistic uncertainty range can be significantly higher when ice thickness values are large. Especially in deep temperate glaciers, airborne RES can yield substantially higher uncertainties.

We thank the reviewer for this important comment. We agree that uncertainties may increase in deep or temperate glacier settings due to signal attenuation and bed picking challenges. We have now revised this sentence to "Direct observations are typically obtained through ground-based or airborne radio-echo sounding (RES), which provides reliable ice thickness measurements (Lindbäck et al., 2018). The associated uncertainties generally range from a few meters to several tens of meters, although they may exceed this range depending on ice thickness and survey conditions (Gogineni et al., 2014; World Glacier Monitoring Service, 2020)."

L75: maybe rephrase to: … merge into a comparably flat plateau before …

We thank the reviewer for this helpful suggestion. We have rephrased the sentence accordingly.

L80: … and a generally more negative mass balance? (I assume all glaciers have negative SMBs)

We thank the reviewer for this comment. We agree that the previous wording may have been unclear. MG, SG, and RG generally retain an accumulation zone (except in years with extreme mass loss), whereas RIV does not exhibit a persistent accumulation zone. We have revised the sentence to "RIV's subdued surface topography also leads to a mass balance pattern that differs from those of the other three glaciers, i.e., a lower mass balance gradient and the absence of a persistent accumulation zone, whereas the other glaciers generally retain accumulation areas".

L87: The inset showing the location of the glaciers in Fig. 1a and the glacier outlines in Fig. 1b are barely visible. I suggest changing the colour scheme or increasing the figure's contrast size.

We thank the reviewer for this helpful suggestion. We have revised the colour scheme of the inset in Fig. 1a and have used a fill colour in Fig. 1b to improve the visibility.

L94: Table1. While I think it is very nice to have such a detailed overview of the previous work conducted at the reference glaciers, have you done any comparison of your findings with the data from previous surveys? (This relates to my general comment 1.)

We thank the reviewer for this comment. Yes, we have compared our results with previous RES surveys. Specifically, we compare our subglacial topography maps with earlier studies (Eriksson, 1993; Herzfeld et al., 1993) for SG and RG (Fig. 8), and discuss these comparisons in Section 4.3 (Line 311). In addition, for RIV, we compare our ice thickness results with previous measurements (Holmlund, 1986), as described in Section 4.2 (Line 241). To improve clarity and maintain focus, we have revised Table 1 by removing RES studies that are not directly related to ice thickness or bed topography.

L96: During which season did you conduct the studies? I ask because this could influence the properties of the snow, which, depending on the depth of the snow cover, could affect the uncertainty of the measurement.

We thank the reviewer for this comment. All RES surveys were conducted between March and April, and the specific survey dates for each glacier are listed in Table 2. We agree that snow conditions can influence radar-wave propagation and thus affect uncertainty estimates. In our uncertainty analysis, we account for this by considering a variability in radio-wave velocity of ~1–5%, which is consistent with empirical values reported for polythermal glaciers (Lapazaran et al., 2016). The corresponding methodology and results are described in Sections 3.3 and 4.1, respectively.

L115: I would rephrase this sentence to mention that the temperate areas of the glacier contain ice at its pressure melting point and thus water-filled cavities, pockets, and tables, which is what is visible in the radargram and also absorbs more energy than cold ice due to differences in dielectric permittivity.

We thank the reviewer for this helpful suggestion. We agree that it is important to describe the physical properties of temperate ice. As our intention here is to highlight the general visible differences between cold and temperate ice in radargrams for data processing purposes, we aim to keep the description concise and avoid introducing detailed descriptions of small-scale englacial structures. We have therefore revised this sentence to "...In contrast, water-filled temperate ice, which is at the pressure melting point, exhibits increased scattering and attenuation due to its different dielectric properties, and thus appears opaquer in radargrams, which can lead to ambiguous bed detection (Dowdeswell & Evans, 2004) (Fig. 2a)."

L118f: It would be very interesting to know the parameters which you applied in the mentioned processing steps in Reflex (where it applies).

We thank the reviewer for this helpful suggestion. We have now provided the parameters where fixed settings were used in the revised manuscript. For some other processing steps (e.g., gain, 2-D filtering, and migration), the parameters need to be adjusted for individual profiles and are therefore not reported as fixed values. Instead, we now describe the functions of these steps. We have revised the processing flow as follows: "The data processing workflows for valley glaciers MG (Fig. B1), SG (Fig. 2), and RG (Fig. B2) are designed to enhance bed reflections and include the following steps: dewow, time-zero correction, dynamic correction to account for the 15 m antenna separation, topography correction, signal divergence compensation, 2-D filtering to remove horizontal banding, Butterworth bandpass filtering to retain low-frequency signals (1–5 MHz), and Kirchhoff migration. For RIV, which contains relatively shallow ice, a simplified processing flow comprising static correction, dynamic correction, topography correction, 2-D filtering, and Kirchhoff migration was applied (Fig. B3)."

L122: "The radargrams have been correctly scaled according to the trace spacing recorded by the GPS." I don't fully understand that statement. Are you referring to matching the radar data (traces) to the coordinates you recorded with the GPS?

We thank the reviewer for pointing out this ambiguity. Here, we refer to the correction of trace spacing in the radargrams. Due to variations in acquisition speed, the spacing between traces is not uniform. Therefore, during processing, the radar data are rescaled using the GPS-derived positions, so that the horizontal axis represents true distance. We have revised this sentence to "The radargram (Fig. 2) was rescaled using GPS-recorded positions to account for variable trace spacing caused by changes in acquisition speed, ensuring that the horizontal axis represents true distance."

L124: While I agree with the subjective bias in RES data interpretation, we are not yet at the stage where human labelling is surpassed by automated methods (especially in polythermal glaciers). For example, if a single annotator selects the bed reflection, there should be some consistency within the dataset. I agree, however, that a combined approach is likely more time-efficient, but it would be interesting to know how many human annotators identified the bed reflections.

We thank the reviewer for this important comment and agree that the automatic methods have not yet reached a stage where they can replace manual picking for polythermal glaciers. We developed the automated approach primarily for preliminary data quality assessment and for rapidly mapping ice thickness and subglacial topography of entire glaciers based on multiple RES profiles, which would be particularly useful during field work. However, all ice thickness results presented in this study were thoroughly checked and manually repicked to ensure data quality.

The bed reflections were initially identified by a single interpreter. To minimize subjective bias, the picking strategy was discussed with co-authors prior to interpretation. During picking, the radargrams were examined at high zoom levels, and the picks were iteratively reviewed and adjusted multiple times. Furthermore, only bed reflections that were visually clear and unambiguous were retained in the final dataset. Bed picks at RES crossovers show good consistency (Section 3.3).

We acknowledge that some degree of subjectivity remains, particularly in complex polythermal settings. Therefore, picking uncertainty has been explicitly incorporated into our uncertainty analysis (Line 166: "...Considering the additional uncertainties introduced by data processing and manual interpretation, ε_t values of 7 m, 10 m, and 15 m were assigned to bed reflections of varying identification quality.").

L135f: "The RES data after static correction only were first used for manual repicking." Can you elaborate what that exactly means?

We thank the reviewer for pointing this out and have revised the sentence as follows: "For manual repicking, bed reflections were first traced on radargrams that were not bandpass filtered, in sections where they were clearly visible and not obscured by temperate ice. Subsequently, filtered radargrams retaining only the low-frequency components were consulted in cases where the bed reflection was ambiguous or not visible. This process allows bed identification while minimizing inaccurate interface tracking caused by filter-induced pulse broadening."

L139: "We calculated the point ice thickness …" (insert)

We thank the reviewer for this suggestion. We have revised the text by replacing "ice thickness" with "point ice thickness" to improve clarity.

L160: How thick do you estimate the snow cover to be? Radio-wave velocities can travel considerably faster in dry snow; have you already accounted for that in your error budget?

The snow depth was predominately between 2–4 m during survey time, although accumulation zones of MG and SG could have snow depth up to 10 m. We agree that snow cover can influence ice thickness estimation. The effect of snow and firn on radio-wave velocity has been taken into account in our analysis. We consider a relative uncertainty in radio-wave velocity ranging from ~1% to 5%, consistent with empirical values reported for polythermal glaciers (Lapazaran et al., 2016). The corresponding uncertainty analysis is described in Sections 3.3 (Methods) and 4.1 (Results).

L173: Prior you mentioned an acquisition velocity of 4-6 m/s. Here, you write 4 m/s. Is this based on the average, or did you choose the lower end for the error assessment?

We thank the reviewer for this important comment. The range of 4–6 m/s refers to the acquisition velocity when driven at a steady speed, while 4 m/s represents the lower bound. We have double checked the velocity records from each RES profile, and have changed this number to 5 m/s to better represent the average speed. The uncertainties have been modified accordingly.

L202ff: You mention that you have repeated the modelling with the lower and upper bounds of the measurement uncertainty for the ice thickness reconstruction. I think it would be very valuable to share the results of these modelling runs as uncertainty maps for distributed ice thickness fields. (This relates to my general comment.)

We thank the reviewer for this suggestion. Distributed uncertainty maps of ice thickness, derived from modelling with the lower and upper bounds of the measurement uncertainty, are already presented in Figures 5a–d. To highlight these maps, we have revised Line 245 to read as follows: "The spatial distribution of uncertainties is shown in Fig. 5a–d, with larger uncertainties concentrated in the thicker, interior regions of the glaciers, while lower uncertainties are observed towards the margins where ice thickness is better constrained by modelling…".

L219: On one hand, I think it's helpful to see the point value of each uncertainty source, but I found it quite difficult to interpret the distribution on the map. Perhaps you could create a four-panel plot for the measured ice thickness, with one plot for the total point uncertainty and move the other panels to the appendix? I also recommend fixing the data range for each variable to make the plots more straightforward to interpret.

We thank the reviewer for this helpful suggestion. We have revised Figure 3 to improve clarity by retaining the point ice thickness and the total point uncertainty in this figure, while the individual uncertainty components have been moved to the appendix.

L235: “the ice thickness…”

We thank the reviewer for noting this. We have added “the” before “ice thickness” in the revised manuscript.

269: I think that is a very interesting point. Can you give the overestimation of the other approaches in %?

We thank the reviewer for this constructive suggestion and agree that a quantitative estimate of the potential overestimation would be valuable. However, there are two main limitations that prevent a robust calculation. First, annual glacier area records prior to 2017 are not available, which introduces uncertainty in reconstructing earlier ice volumes. Second, the input datasets used in previous studies were acquired at different times, making it difficult to determine the exact reference year of their ice-thickness estimates. Due to these limitations, we are unable to reliably quantify the ice loss between the periods represented by previous studies and our observations, and thus cannot provide a robust estimate of the overestimation in percentage terms. An exception is Frank and van Pelt (2024), who suggested that their estimates correspond approximately to the year 2010, as discussed in detail in the next comment.

271: Since the surface lowering of these glaciers is very well known, are the larger reported values within a range you would expect?

We thank the reviewer for this insightful comment. Frank and van Pelt (2024) suggested that their estimates correspond roughly to 2010. Potential uncertainties related to seasonal snow cover and the absence of DEM products in 2010 limit a direct comparison based on surface elevation changes. Therefore, we use two methods to estimate the volume and ice thickness changes during 2010–2024.

Ice thickness change: We use continuous mass balance records (Tarfala Research Station Staff, 2025a–d) to estimate cumulative ice thickness changes. The cumulative net balance during 2010–2024 is −13.5 (MG), −8.9 (SG), −14.7 (RG), and −15.9 m w.e., corresponding to approximately 14.7, 9.7, 16.0, and 17.3 m of ice thickness loss (assuming an ice density of 917 kg m^{-3}). These values are substantially larger than the differences between our results and those of Frank and van Pelt (2024), which are 2 m, 4 m, and 4 m for MG, SG, and RG, respectively (RIV is excluded due to inconsistencies in glacier outlines). In this case we suggest that Frank and van Pelt (2024) underestimated the ice thickness in their study by 13%, 6.4%, and 15.7% for MG, SG, and RG.

Ice volume change: We already quantify the volume loss during 2017–2024 in our manuscript (0.030 (MG), 0.019 (SG), 0.029 (RG), and 0.026 km^3 (RIV)). Assuming similar mass loss rates during 2010–2017 as observed for 2017–2024, the total ice volume loss over 2010–2024 would be approximately 0.060 (MG), 0.038 (SG), 0.058 (RG), and 0.052 km^3 (RIV). Under this assumption, Frank and van Pelt (2024) would slightly underestimate ice volume for MG by ~2.7%, while overestimating ice volume for SG and RG by ~7.1% and ~4%, respectively. However, given the unknown glacier area evolution prior to 2017, these estimates are not robust and should be interpreted with caution.

In summary, the previously reported ice volumes fall within the expected range, while the reported ice thicknesses are somewhat lower than expected but remain within a reasonable range considering model uncertainties.

We have now added the following statement to the manuscript: “Frank and van Pelt (2024) suggested that their estimates correspond approximately to the year 2010. Assuming similar mass loss rates during 2010–2017 as observed for 2017–2024, their results would slightly underestimate ice volume for MG by ~2.7%, while overestimating ice volume for SG and RG by ~7.1% and ~4%, respectively.”

278: I would remove “ground truth”.

We thank the reviewer for this suggestion. We have removed “ground truth” from the manuscript.

290: I would not argue that this statement is incorrect, but perhaps note that global or regional studies often use coarser data, trading resolution for broader coverage.

We thank the reviewer for this helpful comment and have rephrased the sentence accordingly: “...Although these global and regional studies often rely on coarser data, trading spatial resolution for broader coverage, this comparison still highlights the importance of RES measurements for accurately mapping ice-thickness distributions...”

306: Remove “clearly”.

We thank the reviewer for pointing this out. We have removed “clearly” from the manuscript.

312: change “great” to “good” or “very good” / “high”.

We thank the reviewer for this suggestion. We have replaced “great” with “good” in the manuscript.

312: How well do the two datasets compare to each other? Can you provide an example here?

We thank the reviewer for this comment. The historical subglacial topography maps (Herzfeld et al., 1993; Eriksson, 1993; Björnsson, 1981) were originally hand-contoured and do not include precise GPS information. For comparison, Fig. 8 was georeferenced and digitized based on archived paper maps by us, which introduces unavoidable uncertainties that may be significant. Therefore, a quantitative comparison is not considered reliable, and we restrict our comparison to a qualitative assessment. Specifically, as now stated in Line 312, both our results and previous maps for SG reveal two depressions in the central-eastern section (~1150 m a.s.l.), as well as a smaller depression at ~1400–1450 m in the northwestern part. Similarly, both datasets for RG show a pronounced deepening along the central flowline towards the terminus.

L313: Fig 6b: What do the black numbers mean?

We thank the reviewer for pointing it out. The black numbers originated from an underlying layer that was not intended to be displayed in this figure. We have now removed these numbers.

L321: Maybe replace ground-truth with “newly obtained ice thickness measurements”?

We thank the reviewer for this helpful suggestion. We have replaced “ground-truth ice thickness” with “newly obtained ice thickness measurements” in the manuscript.

L347: That is a very cool figure!

Thank you!

Reply to RC2: “Comment on essd-2025-745” (Anonymous Referee #2)

Section-wise general comments:

Study area: It would be nice if you could add information about the elevation range and equilibrium line altitude if available. For example, starting on L73

We thank the reviewer for this helpful suggestion. We have now added a description of the elevation range and equilibrium line altitude in Line 73: “These four glaciers have surface elevation ranges of approximately 1300–1800 m (MG), 1200–1900 m (SG), 1100–1900 m (RG), and 1200–1450 m (RIV) (Porter et al., 2022), with equilibrium line altitudes of 1601 m (MG), 1499 m (SG), 1514 m (RG), and 1380 m (RIV) (WGMS, 2026).”

On the data processing workflow description on 3.2: The description of the data processing steps is not entirely clear and reproducible as it is now. Which 2-D filter/filters did you apply? Which gain filter (e.g. AGC gain or energy decay?) and which bandpass filter did you use? I also wonder why you applied migration only for RIV? Migration is a particularly important filter to collapse diffraction hyperbolas which are typically more prominent in steep terrain. Given that RIV is the only ice cap type glacier in your dataset, while SG, MG and RG are valley glaciers I would expect those to be more prone to dipping reflectors.

We thank the reviewer for this insightful comment. We have now added a more detailed description of the data processing steps in the manuscript (see below).

We agree that migration can improve the positioning of dipping reflectors and collapse diffraction hyperbolas, particularly in valley glaciers. After applying filtering to keep only low frequency signals (for identifying deep glacier bed obscured by temperate ice), the radar signal exhibits a broader effective bandwidth, which introduces large uncertainties in bed identification (Figure 2B in the manuscript). The relative impact of migration is small compared to these uncertainties, which is why migration was not included in the previous version of the manuscript.

To get more reliable bed picks and in response to the reviewer’s next comment, we have now reprocessed the data by including dynamic correction and migration.

We have revised the data processing flow (L118) to: “The data processing workflows for valley glaciers MG (Fig. B1), SG (Fig. 2), and RG (Fig. B2) are designed to enhance bed reflections and include the following steps: dewow, time-zero correction, dynamic correction to account for the 15 m antenna separation, topography correction, signal divergence compensation, 2-D filtering to remove horizontal banding, Butterworth bandpass filtering to retain low-frequency signals (1–5 MHz), and Kirchhoff migration. For RIV, which contains relatively shallow ice, a simplified processing flow comprising static correction, dynamic correction, topography correction, 2-D filtering, and Kirchhoff migration was applied (Fig. B3).”

The revised manuscript, datasets, and the code are updated accordingly. As the changes in bed picks are smaller than the uncertainties of RES-derived ice thickness, and as uncertainties in the input ice thickness were also considered in the ice thickness modelling, the resulting maps do not show clear differences.

Another question about the data processing I have is whether you corrected for antenna distance when processing the data (dynamic correction in ReflexW or NMO in other processing softwares and packages)? This step is crucial when working with relatively low frequency/large wavelength antennas (15 m antenna separation and 16.8 m central wavelength in this case) as the measured TWTT considerably differs from the vertical TWTT, especially at more shallow depths.

We thank the reviewer for this helpful suggestion. We have reprocessed the datasets considering the reviewer's suggestion on migration and dynamic correction. The revised manuscript, datasets, and the code are updated accordingly. As the changes in bed picks are smaller than the uncertainties considered in the study, the resulting maps do not show clear differences.

In 3.2 RES data processing and interpretation, you describe the steps for automated preliminary glacier bed picks, however I could not find the code for the automated picking in the Zenodo code repository. Maybe it is there but hard to find? If that is the case, consider expanding the readme file to refer to the file containing the automated picking workflow. If the picking workflow is not in the code repository, consider adding it.

We thank the reviewer for this question. The automated picking code was not initially included in the Zenodo repository, as all bed picks used in this study were manually checked and repicked to ensure data quality. We will add the automated picking code to the repository and update the README file.

Conclusion: Add uncertainties in ice thickness measurement and distributed ice thickness values

We thank the reviewer for this helpful suggestion. We have now added the uncertainties in ice thickness measurement and distributed ice thickness in the conclusion.

Specific comments:

L7-9: Include uncertainties on mean ice thickness values.

We thank the reviewer for this helpful suggestion. We have now included uncertainties on mean ice thickness in the abstract.

L9: Consider rephrasing "RES-measured ice thicknesses" to "RES-derived ice thickness measurements"

We thank the reviewer for this suggestion. We have now rephrased "RES-measured ice thicknesses" to "RES-derived ice thickness measurements".

L19: Meanwhile implies an opposing argument. The argument here is however supporting the previous one. Replace with similarly, similar or delete.

We thank the reviewer for pointing this out. We have deleted "Meanwhile".

L23: Haualand et al. (2025) would be another recent example of studies on local meteorological processes.

We thank the reviewer for the comment. We have now added this reference in the revised manuscript.

L24: It is not entirely clear what you mean by "disappear entirely at equilibration". Please clarify.

We thank the reviewer for this comment. We have now clarified by rephrasing the sentence to: "Scandinavian glaciers are projected to disappear entirely at climatic equilibrium, i.e., once glaciers have fully adjusted to a stabilized climate under the global warming scenario associated with current policies (+2.7°C relative to pre-industrial levels...)."

L39: Check the citation. To my knowledge it should be Johansson et al. 2022.

We thank the reviewer for pointing this out. We have corrected the citation from “Ekblom Johansson et al., 2022” to “Johansson et al., 2022” and updated the reference list accordingly.

L41: Replace “integration of these two approaches” with “integration of the two”.

We thank the reviewer for the comment. We have replaced “…integration of these two…” with “…integration of the two…”.

L43: Move reference to end of sentence, except if it does not mention uncertainties. If that is the case, you should add a reference stating the typical range of uncertainties.

We thank the reviewer for pointing this out. We have added references (Gogineni et al., 2014; World Glacier Monitoring Service, 2020) to the end of the sentence.

L46-51: When listing the main previous studies on glacier ice thickness inversion and/or physical constraints, Millan et al. 2022 should be mentioned somewhere for completeness.

We thank the reviewer for the suggestion. We have added the reference (Millan et al., 2022) when listing previous studies on glacier ice thickness modelling based on surface velocities.

L70: Reference not needed. Delete in prep. References as this are grey literature and cannot be checked for validity. It should therefore not be referenced. Same for L193.

We thank the reviewer for pointing this out. We have deleted these references and rephrased the relevant sentences.

L76: Delete “downslope”. Surface elevations decrease downslope per definition.

We thank the reviewer for pointing this out. We have deleted “downslope”.

L78: replace “plateau-glacier” with “small ice cap” to be conform with WGMS glacier type classification

We thank the reviewer for the suggestion. We have replaced “plateau-glacier” with “small ice cap”.

L80: What do you mean by: “generally negative mass balance across the glacier”? Please clarify. More negative than the other glaciers or did the glacier lose its accumulation zone. Please add mass balance trends quantitatively for e.g. the last 30 years for all glaciers.

We thank the reviewer for this comment. We agree that the previous wording may have been unclear. MG, SG, and RG generally retain an accumulation zone (except in years with extreme mass loss, e.g. 2024), whereas RIV does not exhibit a persistent accumulation zone. We have revised the sentence to “RIV’s subdued surface topography also leads to a mass balance pattern that differs from those of the other three glaciers, i.e., a lower mass balance gradient and the absence of a persistent accumulation zone, whereas the other glaciers generally retain accumulation areas”. We have also added a quantitative description of mass balance “Over the past 30 years, all four glaciers exhibit cumulative mass losses of approximately −14 to −28 m w.e. (largest for RIV and smallest for SG). Although there is considerable interannual variability, the overall mass balance trend is dominated by increasingly negative summer balances. In contrast, winter accumulation shows relatively small variability and is insufficient to offset enhanced summer melt, indicating sustained glacier thinning and retreat across all sites (Tarfala Research Station Staff, 2025a–d)”.

L100: Please add the centre frequency of the antenna you used, 10MHz.

We thank the reviewer for the comment. We have replaced “…a central wavelength of 16.8 m…” with “…a central frequency of 10 MHz…”.

L101: What is the reason that you used 125MHz sampling rate for all glaciers except RG where you used 250MHz?

We thank the reviewer for this question. The RES surveys on MG, SG, and RIV were conducted in 2024 using a sampling rate of 125 MHz, which was selected to ensure a sufficiently long recording time window to capture the glacier bed. Subsequent data processing showed that the ice thickness at these sites is generally <300 m, and the recording window was longer than required. In addition, the radar signal still retained higher-frequency components (~20 MHz). Therefore, in 2025, when we conducted survey at RG, we adopted a higher sampling rate (250 MHz) to improve the temporal resolution of the radar signal and better utilize the available signal bandwidth, while still maintaining sufficient recording depth. We have now clarified the reason under Table 2: “A higher sampling rate (250 MHz) was used in the second survey year for RG to improve temporal resolution of RES signal.”

L110: Could you add the total length of RES surveys to table 2 as well?

We thank the reviewer for the comment. We have added the total length and total points to Table 2.

L114: You write, “in polythermal glaciers, the cold surface layer has few reflectors or scatters”. Please rephrase cold surface layer to cold layers as not all polythermal glaciers have a cold surface layer and temperate bottom layer, it can also be the other way around or they can have a cold layer in the middle. Also, add a reference to this statement e.g. (Pettersson et al. 2004).

We thank the reviewer for pointing it out. We have now replaced “cold surface layer” with “cold layer” and added the reference after “...which can lead to ambiguous bed detection”(Pettersson et al., 2004).

L118: Delete link in software citation here and add it in the reference list

We thank the reviewer for the suggestion. We have deleted the software link and added it to references.

L121-122: It is not entirely clear to me what you mean with this sentence. Consider rephrasing it to make it clearer.

We thank the reviewer for pointing out this ambiguity. We have revised this sentence to: “The radargram (Fig. 2) was rescaled using GPS-derived positions to account for variable trace spacing caused by changes in acquisition speed, ensuring that the horizontal axis represents true distance.”

L149: add “, “ after “In total”

We thank the reviewer for the comment. We have added “,” after “In total”.

L242: Add “by” between observations and Holmlund.

We thank the reviewer for pointing it out. We have added “by”.

L259-262: This sentence it very long. Consider splitting it into two sentences for better readability.

We thank the reviewer for the helpful suggestion. We have rephrased the sentence as: “Compared with our results and the other two modelled estimates, these ice thicknesses (Millan et al., 2022) are clearly overestimated. This discrepancy is likely related to the model’s strong dependence on surface flow velocity, which is relatively low (0–18 m yr^{-1} in 2022 reported by Gardner et al. (2024)) and thus difficult to constrain accurately for the four Swedish reference glaciers (Table 5).”

L274-276: This sentence is not entirely grammatically correct. Split into two sentences such that the second sentence becomes: Rendering the modelled thicknesses in such areas is unreliable.

We thank the reviewer for the helpful suggestion. We have split the long sentence and rephrased it as: "Moreover, ice-free terrain included within the overly large outline violates a key requirement for meaningful ice thickness inversions, which generally rely on a glacier mask to define the modelling domain. As a result, the modelled thicknesses in such areas are unreliable".

L278: Delete ground-truth. RES derived ice thicknesses are, although measurements, still indirect.

We thank the reviewer for pointing it out. We have deleted "ground-truth".

L280: What do you mean by "inaccurate mass balance data"? Please clarify. What data are you referring to?

We thank the reviewer for the question. We have clarified the meaning in the revised manuscript: "…may result from inaccuracies in the mass balance data used in the modelling, as both Frank and van Pelt (2024) and Farinotti et al. (2019) rely on elevation-dependent gradients, but could also…"

L290: Keep present tense here for consistency.

We thank the reviewer for this suggestion. We have used past tense in this paragraph when referring to previous studies. Therefore, to maintain consistency, we have revised the sentence before to the past tense: "Overall, Frank and van Pelt (2024) and Farinotti et al. (2019a) captured the broad patterns of the ice-thickness distribution for MG, SG, and RG."

L303-304: Delete "other". Consider rephrasing the sentence to improve grammar: Unlike the (three) valley glaciers, the glacier bed at RIV does not vary substantially in elevation.

We thank the reviewer for the comment. We have rephrased this sentence as: "Unlike the three valley glaciers, the glacier bed at RIV does not vary substantially in elevation"

L306-307: Please refer to figure containing the bed and surface elevation plots of selected profiles -> Figure 7.

We thank the reviewer for this suggestion. We have now added a reference to Fig. 7 here.

L307-309: It is not entirely clear to me what you want to emphasise with this sentence. Consider rephrasing for more clarity and conciseness.

We thank the reviewer for this helpful comment. We agree that the original sentence was not sufficiently clear. We have rephrased it to better highlight the relationship between bed topography and ice thickness distribution as: "In MG (Fig. 7a), a small depression in bed topography in the northwestern section (500–1200 m) corresponds to locally thicker ice in the upper glacier. In contrast, SG (Fig. 7b) and RG (Fig. 7c) show a more continuously descending bed, which is associated with thicker ice along the central flowline, extending towards the central and lower parts of the glaciers."

L315: What do you mean with "finer short-wavelength features"? Please clarify.

We thank the reviewer for the comment. We have rephrased this sentence to "...our high-resolution maps reveal small-scale undulations of bed topography".

L321: Replace "The ground-truth ice thicknesses" with "Measured ice thickness".

We thank the reviewer for this suggestion. We have replaced "The ground-truth ice thicknesses" with "The newly obtained ice thickness measurements".

L327-329: Put references in either chronological or alphabetical order.

We thank the reviewer for the helpful comment. We have put references in chronological order in the manuscript.

L335-L337: What do you mean by “in the future post-glacial period”? Please clarify and add references to support the statements.

We thank the reviewer for the suggestion. We have clarified the definition of “post-glacial period” and added references. We have rephrased the sentence to “The above predictions are crucial for local policymaking during glacier retreat and in the post-glacial future, when formerly glacier-covered areas become ice-free. This is particularly relevant for tourism planning, infrastructure development, and the sustainable livelihoods of Indigenous communities who rely on natural environments (Carey, 2010; Welling et al., 2015).”

L342: Delete first m in 10 m x 10 m.

We thank the reviewer for pointing it out. We have deleted the first “m”.

L347: Delete “High”

We thank the reviewer for the comment. We have deleted “High”.

Figures and tables:

Figure 1:

Consider adding a north arrow in panel (a).

We thank the reviewer for the comment. We have now added a north arrow in panel (a).

In panel (b), consider using a different color for the glacier outlines or use a fill color. It is not well-distinguishable from the background.

We have now used a fill color in panel (b).

In panel (c), the purple line is difficult to distinguish from the black lines. Consider using a lighter purple.

We have now used a lighter purple in panel (c–f).

On the figure caption and general information: ©Esri (Esri, 2025) -> please add information about which background map you used, e.g. Worldmaps?

We have replaced “©Esri (Esri, 2025)” with “©Esri World imagery (Esri, 2025)”.

The maps have grids with projected coordinates; however the figure caption lacks the information about which coordinate system is used here. I see that this is included in the dataset publications, please add it in the figure caption here as well.

We have added the coordinate reference system in the last sentence to the figure caption: “...Maps were made in QGIS using the SWEREF99 TM coordinate reference system (QGIS Development Team, 2025).”

Why do you use Sentinel-2 L1C imagery as background maps instead of L2A products? I believe that using L2A products could improve the maps as L2A products are atmospherically corrected and thereby better represent the surface reflectance. Consider changing this for all maps where you use Sentinel-2 products as background maps (Figure 6, 8). In addition, it would be helpful for the reader if you would specify which year the Sentinel-2 images are from.

We thank the reviewer for this helpful suggestion. We have now replaced Sentinel-2 L1C imagery with L2A products in Fig. 1c–f, Fig. 6, and Fig. 8. In addition, we have specified the acquisition year and month of the Sentinel-2 images in the caption of Fig. 1.

Delete Houssais in prep. Reference

We have deleted this reference in the manuscript.

Table 3: Do the numbers given in the "number of crossovers" column represent the number of single crossovers or the number of points (less than 5 m apart) included in the crossover analysis? Please specify. It seems like large numbers if it is single crossovers.

We thank the reviewer for the question. The crossovers here refer to pairs of RES data points from different survey directions less than 5 m apart, as defined in the manuscript (Line 277). This number is large because multiple neighbouring traces from different survey directions can form several crossover pairs (e.g., trace 2780 and trace 3676, trace 2779 and trace 3677, trace 2780 and trace 3677, trace 2780 and trace 3678 in profile APRIL2FILE1N). All the crossovers for each glacier are recorded as crossover.csv in the uploaded code. We have now also clarified it in the table caption: "The number of crossovers refers to pairs of RES data points from different survey directions located within 5 m of each other".

Figure 3: Here I have three comments,

consider using a discrete color scale to improve the visibility

please use the same limits for the color-scale for all plots in one row (i.e. a-d) to improve comparability. It is very difficult to visually assess the meaning of the colors when the scale is different in each plot

personally, to me it would seem more logical/intuitive if the color-scale was inverted i.e. shallow=yellow, thick=blue, but I see that there is no consistency on this matter in other publications on ice thickness and the Viridis or Parula color palette (among others) has been used both in the order you present here as well as inverted. As such, this comment is more a general appraisal on the lack of consistency in the use of color palettes in the field than critique on the chosen approach here. Nevertheless, the use of the Parula color palette as you apply here is unfortunate as a very similar shade of yellow appears twice along the scale (lower and higher than orange).

We thank the reviewer for this thoughtful comment. We agree that the clarity of the previous figure panels could be improved. Taking into account this comment together with the related suggestions from another reviewer, we have made the following revisions: i) We have simplified the figure by retaining only the measured ice thickness and total point uncertainty in this figure, while moving the individual uncertainty components (previously shown in panels e–l) to the appendix. This improves the readability of the main figures significantly; ii) We have replaced the Parula colormap with the Viridis colormap to avoid repeated yellow tones and improve visual distinguishability across the scale; iii) We have changed the continuous color scale to a discrete color scale.

We also agree that consistent color scales can enhance comparability between panels. However, as the four glaciers are independent systems with different ice thickness ranges, applying a consistent color scale would reduce the visibility of spatial variations within individual glaciers (We have plotted glacier ice thickness as examples to compare the visual effects of different color scales in Figs. R1–4), especially for RIV that holds much shallower ice. Whereas their individual thicknesses are what we would like to emphasize in this manuscript. Therefore, we have retained color scales with different ranges to better highlight the internal variability of each glacier.

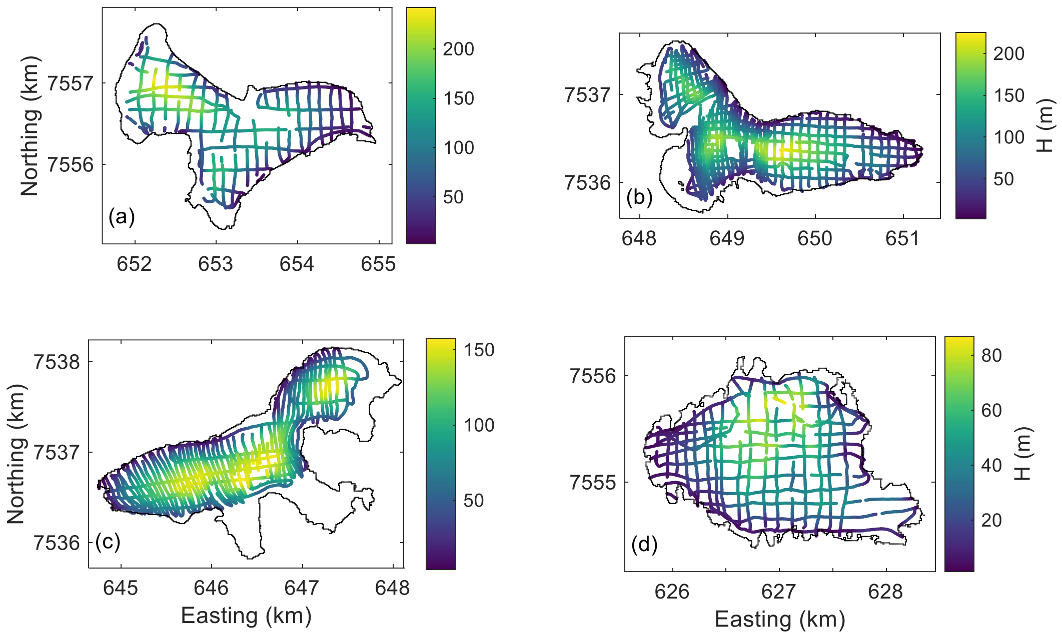

Figure R1. Different and continuous color scales.

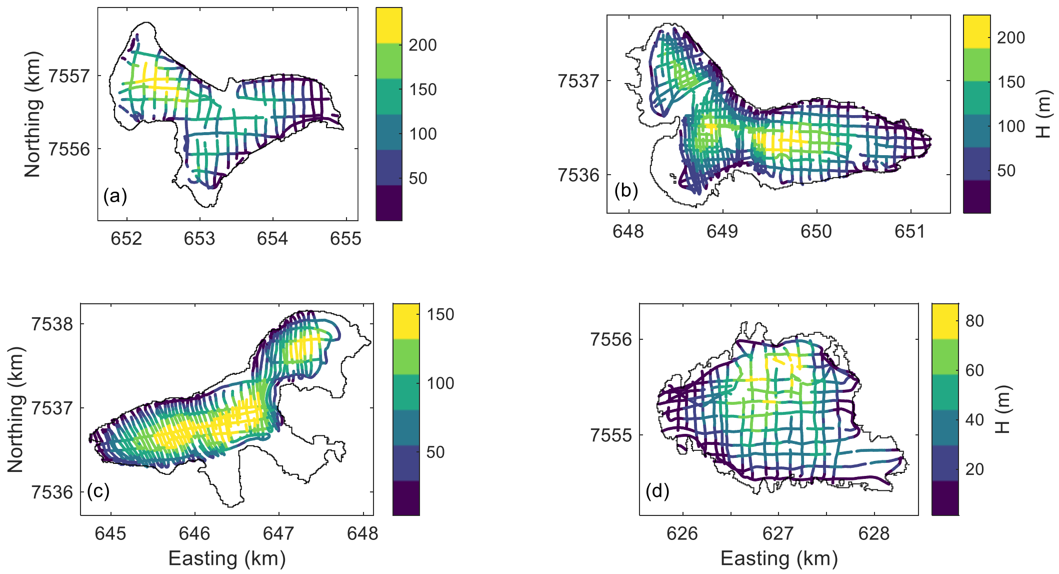

Figure R2. Different and discrete color scales.

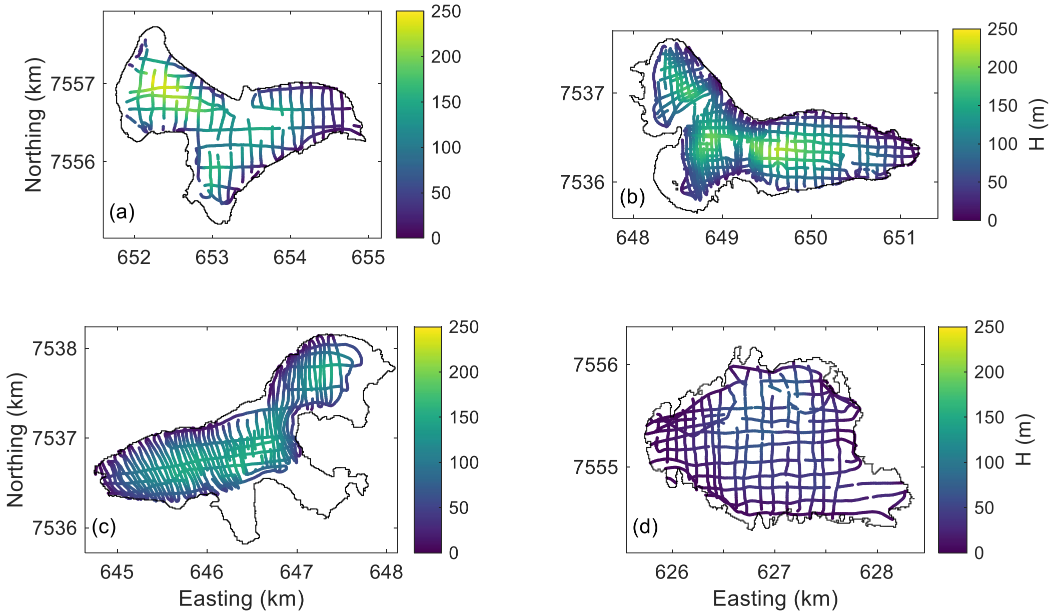

Figure R3. Consistent and continuous color scales.

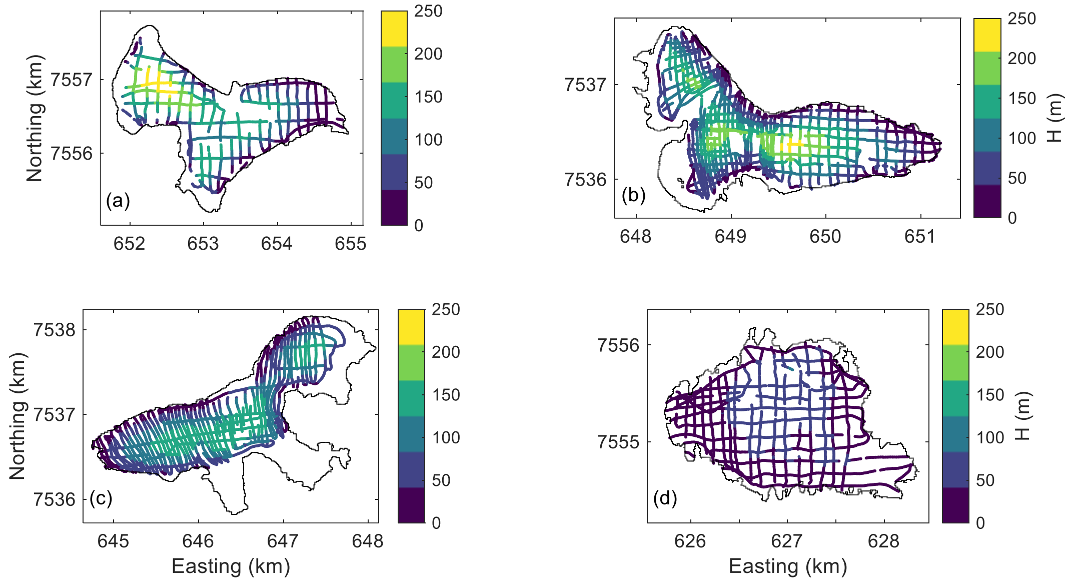

Figure R4. Consistent and discrete color scales.

Figure 4: As in figure 3, use the same limits for the color scale for each glacier, i.e. all plots showing MG should have the same limits etc.

We thank the reviewer for this comment. We have now used the same color scale limits for our results and previous results for each glacier to improve comparability. An exception is RIV, where the previously modelled ice thickness shows an overestimation of up to 275%, resulting in a much larger thickness range. We have also changed the colormap to Viridis.

Figure 5: As above, use unified limits for the color scale to improve comparability/readability of the plots. Consider using a discrete color scale instead of stretched.

We thank the reviewer for this comment. In response to this and the above comments, we have replaced the Parula colormap with the Viridis colormap and adopted a discrete color scale. We have also unified the color scale limits across the panels to improve comparability and readability.

Figure 6: Use color palette that is more suited for color blindness and align scales between glaciers.

We thank the reviewer for this thoughtful suggestion. We have used Viridis colormap, which is highly colorblind-friendly. To improve readability of the figure, we have adjusted the contrast of the background imagery. We have tested the figure using a color blindness simulator to ensure accessibility. Same as noted above, we have retained individual color scales for each glacier, as they represent independent systems with different bed elevation ranges. Using a consistent color scale would reduce the visibility of spatial variations within each glacier.

Figure 7: Depending on which factors you want to emphasise in this figure, consider adjusting the y-scale of the different glaciers to better-visualise the differences in bed elevation along the profile (especially for panel (d)).

We thank the reviewer for this suggestion. We have adjusted the y-axis scale for the different glaciers to better visualise the variations in bed elevation along the profiles.

Table D1: SG is missing in this overview, why? Adjust northing and easting coordinate precision (decimals) according to GPS precision.

We thank the reviewer for this question. Table D1 presents only the dGNSS point elevations used for surface elevation calibration in this manuscript. As stated in the manuscript (Line 192), the ArcticDEM elevation was not corrected for SG due to the lack of dGNSS measurements in 2024. We have now clarified this in the caption of Table D1 as well. The coordinates were recorded in the SWEREF 99 TM system with three decimal places as provided by the dGNSS device during data acquisition. These values are therefore reported as measured. We have now stated the coordinate system in the table caption.

Figure E1: Do the same as for Figures 3-5 if you change the color palette.

We thank the reviewer for this suggestion. We have now changed the colormap to Viridis and changed the color scale to discrete.

Dataset:

The dataset, both raw and processed radar data including picks as well as distributed ice thickness and bed topography is nicely presented with clear explanations of what is what and how the data was derived.

Thank you!

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