Dear Editor and Reviewers,

Thank you for your helpful and in-depth revision of our manuscript. Below, you find our answers (in *italics*) to your raised issues.

Best regards
the Authors.

Reviewer 1

Review of the article entitled:

Ground penetrating radar on Rutor temperate glacier supported by ice-thickness modelling algorithms for bedrock detection

This study addresses the challenges of measuring ice thickness in temperate glaciers, such as the Rutor Glacier in the Southern Alps (Italy), in these glaciers the ice is at or near the melting point throughout its entire mass, including both the surface and deeper layers. This means the glacier contains both ice and meltwater, which makes it sensitive to temperature changes and contributes to faster melting. Meltwater then interferes with the clarity of Ground Penetrating Radar (GPR) signals. To improve the manual selection of bedrock profiles from GPR-based ice thickness measurements in such glaciers, the researchers combined GPR data with three open-source thickness inversion algorithms (GlabTop2, GlaTE, and OGGM), which estimate ice thickness based on surface topography and mass turnover. These models guided the manual selection of unclear or scattered GPR data for the Rutor Glacier. The study analyzed two new GPR datasets and produced a more accurate ice-thickness map using GlaTE (one of the algorithms, after selecting the correct bedrock profile with the aid of outputs from all three models). Authors then conclude that the glacier stored about 515 million cubic meters of ice in 2021, significantly higher than previous estimates. The authors claim that this methodology is replicable and can simplify future GPR surveys of temperate glaciers, particularly in noisy data conditions caused by meltwater.

Overall, the manuscript, methods, and results are well explained, however, I have several corrections to the current text. I find the study very creative and could have potential for the use of this type of data to validate and calibrate ice thickness inversion algorithms. However, my main concern lies with the novelty of the study and significant gaps in the methodology, such as the uncertainty quantification of model results and the use of OGGM in such a small-scale glacier-specific study, as well as not providing details of the set up used for the OGGM inversion. I could consider this study for publication, but only after the authors address my questions and make the necessary changes to the manuscript.

Major comments:

Novelty, Reproducibility, and Scalability

- After reading the manuscript, I find it difficult to see how this analysis effectively contributes to the broader challenge of providing ice thickness observations and distribution products that could be used to constrain, evaluate, or train model simulations, or new deep learning algorithms (e.g., The Instructed Glacier Model).
- Additionally, there is no discussion on how this method could be scaled to a regional level. Expanding the study across multiple temperate environments and numerous glaciers with GPR measurements (e.g., in Alaska, the Alps or South America) raises concerns about the efficiency of manually detecting multiple profiles. Such an expansion would likely require a more robust approach for parameter calibration, validation of ice thickness inversion by each algorithm, and the generation of a final thickness map using more than one algorithm.

  I am concerned about the scalability of this method, as the parameters used for this specific glacier may not be transferable to others. This approach heavily depends on both data quality and the accuracy of model outputs. The examples presented in the manuscript show that the three algorithms perform well on some profiles but less so on others. A sensitivity analysis of the algorithms, with varied parameters to assess their impact on the thickness profiles, would have been valuable. Additionally, a more detailed uncertainty estimation for the final thickness product is needed. This could have been addressed by combining the results from all three algorithms, not just GlaTE, and providing a standard deviation on the final ice thickness map, while also comparing the results to existing ice thickness inversions and volume products (e.g., Millan et al. 2022, Farinotti et al. 2019 and Cook et al 2023 – all available in OGGM).

  Thank you for this valuable analysis.
  Regarding scalability, it depends on the meaning of scalability at a regional level.
  If this means using this methodology with the same set of parameters and similar uncertainty on a bulk of glaciers, we do not think it could work effectively. The main problems are mainly related to the great variability in the GPR profiles available on different glaciers. The data quality of the GPR profiles depends on many intrinsic factors of the temperate glacier; it happens that many times the signal is not very clear, as reviewed by Rutishauser et al., 2016. Moreover, the spatial resolution (lateral) is often constrained by the spatial distribution of GPR profiles along the glacier because of logistical or economical constraints.
  The manual processing and picking of GPR profiles is a need, which often requires local knowledge of the specific glacier and its recent history.
  In Alpine regions, it could happen that the local environmental authorities could be more focused on some specific needs of specific glaciers, more than regional studies.

The scalability at a regional level of this methodology, therefore, it may surely be possible, but every glacier should be accounted for and analyzed manually and separately.
The strength of this methodology is to allow us to analyze a single glacier in a more effective way, and while scalability is certainly possible, it cannot be fully automated.

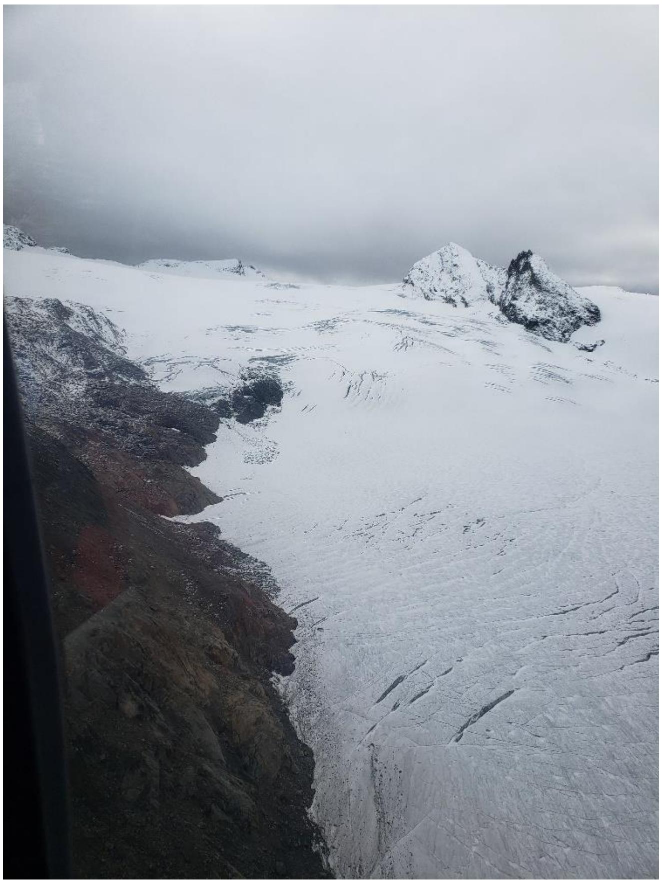
Regarding the sensitivity analysis, we fully agree with you. We will improve the study by including the analysis of a reasonable range in which the main parameters can change and make a sensitivity analysis.

Methodology:
Related to the data input used:

- Regarding the GPR survey conducted by helicopter, I wonder if the authors need to correct for signal reflection from the nearby mountain terrain and elevation changes - i.e., interference caused by the surrounding mountain slopes in the radargram?
- Is the outline from the Randolph Glacier Inventory (RGI)? If authors have used their own glacier outline this might significantly deviate from its RGI counterpart, which could introduce errors and the authors should have computed the calibration steps again in OGGM.
- In the introduction (L69) authors are using their own DEM to predict the ice thickness from all models. In that case, the authors should have re-processed the GIS task of OGGM. A detail on how they use OGGM is missing (see below).
- All data inputs and as well as the model's thickness inversion (glacier initial state) represent different timespans. Why not use the same DEM and glacier outline across all models? You can input your own DEM and glacier outline into OGGM and recompute all steps until the inversion. See the following tutorials.

- Using your own outline in OGGM
- Create local topography maps from different DEM sources with OGGM
- Step-by-Step guide to building preprocessed directories from scratch

Thank you for your comments. Regarding the GPR survey by helicopter, we considered the local morphology and the helicopter altitude above ground, but we did not notice interference caused by surrounding mountain slopes. We think that this is because the glacier sits on the top and only a few slopes are higher than it, as you can see by this photo we took recently.



For the other comments, we used our own outline and DEM, provided by a recent geomatic survey (in 2021). For the OGGM model only, we used the RGI (Randolph glacier inventory) and another DEM provided by OGGM (and the results were corrected by the differences between the two DEMs). This choice was because we were curious about the impact of different DEMs on the outcomes; however, we should have tested OGGM with both DEMs. We can do it as part of our sensitivity analysis.

Thank you for the links to the tutorials :)

Algorithms:

- Choice of input parameters in ice thickness inversion models: The authors should clarify that these parameters are not transferable between glaciers (see Zekollari et al. 2022). Additionally, a sensitivity study on the model parameters should have been conducted to assess the impact of parameter variation on ice thickness profiles computed by the models.
- How did the authors calibrate surface mass balance and ice thickness inversion in OGGM? or Did they use pre-processed directories? A specific workflow of the steps followed with OGGM is missing. The actual code repository of this study is not shared, thus is not possible to verify.

Results:

- It would be interesting to see a comparison of ice thickness differences between GlaTE and the other two models, along with a more in-depth discussion of the reasons behind these differences.
- The findings of the paper would be strengthened by comparing the resulting ice thickness map from GlaTE to existing ice thickness inversion and volume products (e.g., Millan et al. 2022, Farinotti et al. 2019, and Cook et al. 2023, all available in OGGM).

Thank you, they are two good ideas that we can implement for sure.

Discussion:

- I would encourage the authors to provide a stronger justification for how this methodology could be scaled to other glaciers and applied to existing GPR surveys in temperate glaciers. Additionally, it would be helpful to explain how this study could address the under-sampling problem of ice thickness in temperate regions (e.g., the Andes). However, caution is needed, as once models are used to improve observations, they are no longer pure observations and here there is a "human error" element also in place with this method. The authors could emphasize that GPR measurements provide a better representation than models, especially in areas like valley walls where models may struggle due to the simplification of glacier geometry (e.g., elevation flowlines and bed geometry assumptions in the case of OGGM).
- There is little mention about debris cover which is likely not accounted for in the ice thickness inversion algorithms.

Thank you. I agree with the need to improve the discussion you suggest here. For the issue of scaling to other glaciers, we would formulate some critical evaluation, starting from the previous comments (see the Novelty, Reproducibility section).

We did not consider debris cover, which is not crucial in our glacier (see the photo above, taken at the end of the ablation season). In the GlaTE model there is the possibility to account for it with a simple parameter, but we are confident that this could be skipped in the sensitivity analysis.

Conclusions:

- While the study is well-detailed and clearly explained, it could benefit from a stronger emphasis on its contribution to the broader challenge of ice thickness observations in temperate glaciers. The results, though valuable for this specific glacier, do not provide new insights beyond the updated GPR surveys and improved ice thickness map. To enhance the overall impact, the authors could explore a more quantitative interpretation of the results and better highlight how their findings address larger-scale issues in future research.

Thank you. A more quantitative approach will be our effort during this revision. For the larger scale issue, refer to our previous discussion. This methodology does not have a straightforward scalability in terms of automatic processing of many glaciers, but can surely be applied to other glaciers one by one. We could highlight here the main weaknesses and strengths of the methodology in this sense.

Minor corrections and suggestions:

Thank you for all your very detailed corrections and suggestions.
We do not reply one by one, but we will try to include everything in the manuscript, since we agree with each of them. In the event we fail to include some suggestions in the next revision, we will highlight them in the next revision comments.

Abstract

L1: Add an example of where temperate glaciers are located (i.e. not at the poles).

L10: Authors should explicitly state that they used model output to manually select the best bedrock profile from the GPR data in problematic survey sections, clarifying that the model output is used to fill gaps in the GPR observations along those profiles. This should be stated early on in the abstract and the introduction, to improve the objective of the manuscript.

Introduction

L29-30; replace "inner composition." with "present day ice thickness distribution and geometry"

L42; EM to Electro Magnetic.

L43; Suggestion: Rutishauser et al. (2016) analyzed a large set of GPR data acquire on Swiss glaciers and found that depending on the specific glacier, the bedrock interface could only be successfully detected in 12-69% of the GPR data due to this scattering issue.

L48 Remove "Also". Suggestion: "Air bubbles trapped in ice cause additional scattering of the GPR
signal, which helps differentiate between various types of ice…"

L51: replace "are reported in the Study site paragraph" by "are summarised in section X" L56: replace "paper" by "study".

L58: point to a figure to direct the reader to a GPR profile to indicate the issue.

L62: replace “help the analysist” with “aid”.

L64: I will just call it glacier models or ice dynamical models (they all are ice thickness inversion algorithms of some sort). Authors should pick a single definition throughout.

L67: Please cite the version of OGGM used in the study. See https://docs.oggm.org/en/latest/citing- oggm.html#software-doi

L77: statements like “it should be” introduces doubt on the results, try to avoid this type of language and quantify how much the ice thickness product improved via statistics.

Study site

This section is too long and I don’t see how past geomorphological events are relevant to this particular study. I would start by describing the site (from L97) and georeferenced so the readers know where the glacier is geographically.

L102: Add citation of DEM’s used to compute ice thickness losses.

Methods

L111-123: Remove all

“to”. L113: Remove “and

updated”.

L119: Replace “to perform the manual picking” with “Manually select reflexion events”

L123: Replace “to draw a final result…” with Produce a map of the glacier ice thickness (Figure 6)

L124-127: Suggestion:

“Some topographical adjustments were necessary to assist in analyzing GPR observations that span different time periods (2012 and 2022). A 2021 DEM of the glacier surface was used for the GlaTE and GlabTop2 algorithms, while the 2000 DEM was used for the OGGM algorithm. In other words, the GlaTE and GlabTop2 models represent the 2021 situation, OGGM represents 2000, and the GPR data corresponds to 2012.”

What about the glacier outline date?

L131: Why do the authors not use the same DEM (or the best DEM) for all models? See above.

L124-145: This text seems a bit misplaced, I would divide the text into sections for (i) pre-processing of input data for models and (ii) post processing of model output and the describe (ii) after describing the algorithms.

Sect 3.1 Explain if the GPR data collected from a helicopter needed to be corrected for altitude changes in the survey and the scattering effects caused by the nearby terrain. See Church, G. et al. (2018).

L154: Add - The GPR data was processed by the following method:

L170-175: These lines contain irrelevant text. The increase in usage and citations of a tool or model (e.g., OGGM) does not necessarily indicate it is the best tool for a particular study. A more thorough justification for the choice of tools should be provided here. The OGGM documentation clearly states that it is designed for large-scale or regional glacier modelling. Caution is advised when using OGGM for single glacier studies, and a detailed workflow for producing the thickness inversion should be included in such cases.

L177: Remove "ice flux mechanics" and replace: ice flow theory and

mass conservation.

L179: Replace all "picking" with manual selection.

Suggestion replace L181 – L184 with

"The thickness inversion models required specific input parameters to run. These were reviewed for consistency with the physical characteristics of the study area, but unless stated otherwise, default values from similar alpine glacier studies by the algorithm developers were used. See below a summary of all models".

Here, authors should state that these parameters are not transferable glacier to glacier and a sensitivity study on one profile at least should have been carried out on model parameters to see the impact of parameter uncertainty in ice thickness distribution.

Sect. 3.2

This section would benefit from a table comparing the parameters (and their values) used in all models, providing a quick overview of each model's setup, along with a column citing the publications from which these parameters were sourced.

L225: Cite OGGM version used.

L227-228: Replace "OGGM bed topography inversion algorithm" with "OGGM ice thickness inversion algorithm" … "which is based in ice flow dynamics and mass conservation (Farinotti, et al. 2009 and Maussion et. al 2019). The ice flux is computed as: … "

L234: "under the simple assumption of equilibrium". This is not correct in the case that the latest version 1.6.0 of OGGM was used. Please, note the version used in this study and how the ice thickness inversion was calculated. Do authors calibrate surface mass balance and ice dynamical parameters? Note that it is possible to calibrate OGGM to match geodetic mass balance data which removes the equilibrium assumption. In the latest version is possible to calibrate the glacier mass balance and ice dynamics parameters at the same time using a "dynamic spin-up" see Appendix A and Aguayo et al. (2023) for details and the following tutorials:

https://tutorials.oggm.org/master/notebooks/tutorials/observed_thickness_with_dynamic_spinup. html#dynamic-model-initialization-using-observed-thickness-data

Discussion

L276: "ice thickness"? do you mean ice volume (why is this not just stated in Km^3)

Section 5.1 Here ideally authors should have done a better analysis on the difference between the thickness maps computed by the different models and also show a flowline profile view. Also compare the resultant volume with previous studies and estimates (see references).

A lot of this section could be removed if the authors use the same DEM and there is no need to correct ice thickness changes over time.

L302-307: Suggestion

"This joint interpretation prevented the mistake of interpreting the first non-reflective layer (white in the GPR sections) as ice and the first reflective zone (scattered black) as bedrock. The deepening reflection on the right side of Figure 3 clearly shows that the ice-bedrock interface is not related to the scattered reflective zone observed at 20-40 m depth. Manually picking the ice-bedrock interface, guided by the estimates from the algorithms, was particularly helpful, especially below 50 m where the GPR signal was too attenuated."

L309 "This is not far from estimates without GPR data" Quantify such differences.

L329. "previous research" add citations.

(more comments below)

Figures

Figure 1.

This figure needs a map of the alps with the location of Rutor glacier. Add RGIID or GLIMS ID.

Replace "how many meters it has subsided in the past decade (from 2008 to 2021)" with changes in
ice thickness (m) from 2008 to 2021.
Add RGI outline as well as the outlines used in this study with different colours.
Add citations.

Figure 2.
Dotted survey lines could be thicker.

Figure 3.
I would add a point of first guess from authors of where the bedrock might be if they didn't know from

the thickness inversion algorithms.

Figure 4.
Another panel could be added to this figure looking into thickness profiles from models along the main flowline and two more figures showing the ice thickness differences between GlaTe and the other two models.

Figure 5. (and similar)
Add to the bottom panel the part of the profile that is taken or selected using the ice thickness inversion algorithm (i.e., fill the gap in the profile via another colour)

Figure 6.
Instead of displaying the GPR data on top of the thickness map, display thickness differences between GlaTE and the GPR. Or plot differences in profiles.

Appendix.
Authors should also compare their resultant thickness map with other estimates. See comments above, this could go in the appendix.

References
Aguayo, R., Maussion, F., Schuster, L., Schaefer, M., Caro, A., Schmitt, P., Mackay, J., Ultee, L., Leon- Muñoz, J., and Aguayo, M.: Assessing the glacier projection uncertainties in the Patagonian Andes (40–56° S) from a catchment perspective, EGUsphere [preprint], https://doi.org/10.5194/egusphere- 2023-2325, 2023.

Church, G. & Bauder, A. & Grab, Melchior & Hellmann, Sebastian & Maurer, H.. (2018). High- resolution helicopter-borne ground penetrating radar survey to determine glacier base topography and the outlook of a proglacial lake. 1-4. 10.1109/ICGPR.2018.8441598.

Cook, S. J., Jouvet, G., Millan, R., Rabatel, A., Zekollari, H., & Dussaillant, I. (2023). Committed ice loss in the European Alps until 2050 using a deep-learning-aided 3D ice-flow model with data assimilation. Geophysical Research Letters, 50, e2023GL105029. https://doi.org/10.1029/2023GL105029

Millan, R., Mouginot, J., Rabatel, A. et al. Ice velocity and thickness of the world's glaciers. Nat. Geosci. 15, 124–129 (2022). https://doi.org/10.1038/s41561-021-00885-z

Farinotti, D., Huss, M., Fürst, J.J. et al. A consensus estimate for the ice thickness distribution of all glaciers on Earth. Nat. Geosci. 12, 168–173 (2019). https://doi.org/10.1038/s41561-019-0300-3

Zekollari, H., Huss, M., Farinotti, D.,& Lhermitte, S. (2022). Ice-dynamicalglacier evolution modeling—Areview. Reviews of Geophysics,60, e2021RG000754. https://doi.org/10.1029/2021RG000754.

Reviewer 2

Review of "Ground penetrating radar on Rutor temperate glacier supported by ice-thickness modeling algorithms for bedrock detection" by Andrea Vergnano et al. (2024)

The manuscript presents airborne and ground-based GPR data collected in 2012 and 2022 over Rutor Glacier, a temperate glacier, which are known for challenges posed by high signal scattering and absorption. The study's novel approach combines three models (GlabTop2, GlaTE, OGGM) to help with the identification of the ice-bed interface, improving upon prior estimates that likely underestimated ice thickness due to misinterpreted scattering zones near the surface. The study concludes that incorporating the models improves the GPR interpretation in terms of ice thickness. Finally, a new ice thickness map is generated with the new GPR interpretations constraining the GlaTE model.

I think this study presents a creative approach to improve the interpretation of challenging GPR data over temperate glaciers. Overall, the paper fits the scope of the journal and has potential, but in my opinion, several major issues need to be addressed before publication. These include the need for clearer methodological explanations, particularly concerning the use of DEMs in the models. The introduction should more clearly highlight the true novelty of using models to improve GPR interpretation. Furthermore, a deeper analysis of model-assisted picking, including statistical comparisons between model-guided and unguided picks, is necessary to fully support the claim that the models "provided substantial help in manually picking the ice- bed interface". Finally, the manuscript requires substantial English language revision to improve clarity, as many sentences are awkwardly phrased or repetitive. I hope the authors find my comments useful and that they can help to improve the manuscript.

Major Issues

- **Language:** The manuscript would benefit from significant English editing. Many phrases are unclear or awkward, and the text could be more concise. Paragraphs often repeat information unnecessarily. I have made specific suggestions in the line-by-line comments.

Thank you for this comment. We will accept with thanks your revision about language and those of other reviewers, who also highlighted some unclear phrases.

- **Research focus**: The main purpose of this research as stated in the introduction is to "investigate the Rutor glacier thickness with two new GPR datasets" (L56). However, I believe that the manuscript could better highlight the key goal/innovation – using models to assist in identifying the glacier bed in GPR data. This is underemphasized in the introduction, results, and discussion sections.

Thank you. We will emphasize more the key goal and innovation, also taking into account the lack of discussion about regional scaling of this methodology, highlighted by Reviewer 1.

- **Abstract**: I find the abstract quite lengthy, and the primary goal and key findings are not clearly conveyed. I recommend revising the abstract after the manuscript has been edited to ensure the message is concise and focused on the main points.

Thank you! We will do it as the last thing after all the revisions.

- **Methods:**
    - **Ice thickness change:** It is unclear whether the ice thickness change (Figure 1) from the DEM differencing is original to this study or based on previous work. If new, the method should be explained

This is original of this work. It was a standard procedure, therefore, we did not emphasize it, but we could explain it in detail.

- **DEM use:** The rationale for using different DEMs for different models is unclear, especially why a 2000 DEM was used for OGM. I am not familiar with the models, but is it not possible to run the OGGM model with the 2021 surface topography? Additionally, why was a 2008 and 2021 DEM used for the GlaTE and GlabTop2?

Thank you, this is correct, it is possible to run the OGGM with the 2021 surface topography, and we will do it in the revision. Also Reviewer 1 is of the same opinion. We will also assess eventual differences in the outcomes due to the use of different DEMs, which can be interesting in this study.

The 2008 and 2021 DEMs were used because some of the GPR data were collected in 2012 and some in 2022, and we want to provide a picture of the ice thickness in 2021. Therefore, the 2012 data have to be corrected for the loss of ice between 2012 and 2021. To do so, we calculated an average annual ice loss by subtracting the 2021 and the 2008 DEMs. Maybe this process was not clear as explained in the methods sections, we think about how to clarify it.

- **Ice thickness vs bedrock topography:** I understand that the models output ice thicknesses, but why not compute a bedrock DEM instead? The bedrock topography is not expected to change over the study period, and could directly be compared to the GPR data from any survey time (i.e. 2012 and 2022). Ice thicknesses can still be extracted (subtracting the bed DEM from the surface DEM). This could reduce all the ice thickness corrections that currently need to be applied.

This comment sounds particularly interesting, indeed, one nice idea for future works is to test these models on a glacier in which we have the DEM in several years to check the robustness in the detection of the bedrock. It would be interesting to build a model that takes into account multiple surface DEMs collected in multiple years, and is forced to calculate always the same bedrock. It could be done on this Rutor glacier using the 2000, 2008 and 2021 DEMs, but this would require an important modification of the code. We believe it is out of the scope of this specific paper, as it may take time to assess it in a rigorous way and change the model code.
Regarding the GPR surveys, we do not think that the 2012 and 2022 surveys can be compared effectively in this sense, because they overlap only in the top part of the glacier, which remained almost unchanged in the last decades, since it is the coldest part.
I would report these points in the discussion section, prompting future research.

- **Results:**
    - **Ice loss map:** As the ice loss map supports the hypothesis of underestimated thickness, it should be included in the results.

I understand your point of view, We put it before because it seemed to me a good reading flow. We will reorganize the paper according to your comment.

- **Statistical analysis:** A more in-depth quantitative analysis is needed to assess how much the models aid in picking the ice-bed interface. This could include comparisons of ice thickness picks with and without the models, as well as how each individual model was used (e.g. for future recommendation, is there one model that stands out, instead of having to run all three?) The discussion includes some statistics (e.g. "20% of the GPR lines clearly identified the bedrock"), but it is unclear how these were calculated, and they are not included in the results.

Thank you for these interesting ideas on how to present the results more quantitatively. Reviewer 1 asked for a sensitivity analysis, for example. So we see the need to improve in this sense, and we find your suggestions very helpful, and we will discuss them all. Thanks.

- **Radargram interpretation:** The manuscript could more strongly emphasize how weak reflectors, identified with low confidence, are validated through model agreement, increasing confidence in identifying the ice-bed interface.

  That being said, I also think there are instances where the selected reflectors appear questionable, which may raise concerns about potential bias in the manual picking process when influenced by model outputs (e.g. picking noise). For example, I have difficulties identifying a reflector that was picked on
  - Profile 2012-7 between ~200-500 m
  - Profile 2012-8 between ~1500-1900 m
  - Profile 2012-9 between 500-1000 m
  - Profile 2012-10 between 300-1500 m

  This risk should be discussed explicitly (in the discussion section), as it is important to acknowledge the possibility of seeing patterns in noise when guided by models.

You are perfectly right, we want to discuss the subjectivity of the methodology *in a stronger way.*

- **Figures**

For this comment section and the minor comments, I reply just here, saying that I appreciate your revision and I will do my best to include all of your comments in the manuscript. Thank you again!

- A study area overview map to see where in the Alps Rutor glacier is would be useful (e.g. integrated in Figure 1 or 2)
- Consider increasing the font size in all figures and remove color scale name information in the figure caption.
- *Figure 1*: Add elevation contour lines (or on Figure 2) and a reference to the source of the glacier outline. Also consider labelling the glacier tongues as described in the text.
- *Figure 2*: Increase line width, and consider using markers instead of "start" and "end" labels to reduce text and improve readability.
- *Figure 3*: I suggest adding arrows to indicate the "clutter zone" and "true bedrock" so the reader can follow what is meant in the text (L256-259). Also, consider removing Figure 3 as it is repeated in Figure 5, or replace it with another example (e.g. Profile 2012-8).
- *Figure 5*: I suggest using different colors instead of line-styles to better distinguish the models.
- *Figure 6*: I suggest using the same colormap for the GPR and model ice thickness for easier comparison. The GPR data can be surrounded with a white outline for contrast.
- *Appendix Figures:* I think that some of the description should be moved into the main results/discussion sections.

Minor Issues/Line-by-line comments

L3: I suggest removing the sentence with cold ice, it is

irrelevant here. L8-9: I suggest removing the sentence

"Besides, GPR…."

L31, L36, etc.: Consider replacing "meltwater" with "englacial water content" or "water", to avoid confusion with surface meltwater generation/runoff, englacial water may also result from rain.

L32: I believe it is "pressure-melting point", not "temperature-pressure melting point".

L35-36: This also reads a bit awkward, e.g. we wouldn't expect a sudden change in geothermal heat flux. I suggest rewording to "Temperate glaciers at the pressure melting point are primed for rapid meltwater production upon small energy or heat inputs…"

L37: Specify that while high-quality GPR surveys are possible (e.g. for snow/firn near surface studies),challenges lie in detecting the bed returns. Reword to "…can challenge the interpretation of bedrock returns from Ground Penetrating Radar (GPR) surveys."

L40: Clarify "smaller-scale heterogeneities", e.g. small fractures or sediment grains, smaller than the wavelength (or quarter wavelengths/range resolution)?

L42-44: Reword to clarify what was studied, e.g. "Challenges in detecting basal returns over temperate glaciers have been studied …" Additionally, I think it would be good to mention the studies on effects of antenna orientation on detection of the bedrock reflection e.g. (Langhammer et al., 2019).

L47-48: Rephrase to clarify that englacial debris may also originate from surface material, not just freeze-on at the bed.

L49-52: I think this sentence could benefit from directly referencing some of these studies. Also consider integrating the study site description here.

L52-55: Replace "resolution" with "spatial resolution". I suggest reformulating to "The spatial coverage of GPR surveys is limited by survey speed, time and access (e.g. crevasses), leading to discrete, limited sampling of the glacier bed. It is therefore possible that the maximum ice thickness remains unknown due to limited survey coverage."

L57-L59: Re-word for clarity, e.g. "These new datasets reveal high scattering of the radar signal over most parts of the glacier, demonstrating the difficulty in detecting the ice-bedrock interface."

L60: Include a reference for the "previous doubtful estimates of ice thickness".

L68: I believe the correct reference is (Langhammer et al, 2019a), verify other instances.

L68-70: "Thanks to … are extracted." I suggest rewording to "The ice thickness is predicted using the three models." (i.e. the DEM part belongs in the methods section).

L71-72: Rephrase to "… superimposed on the radargram to help identify the most likely ice- bedrock interface…"

L74: Replace "inner geometry of the glacier" with "bedrock topography"

L93-96: Instead of just mentioning multidisciplinary aspects/different perspectives, provide examples (e.g. glaciology, geomorphology, ecology, hydrology …?).

L96: misspelling of "multidisciplinary"

L97: reword to "… the Rutor glacier covers an area of 7.5 km^2 …" L100 and others: Replace "outline" with "margin"

L101-108: Moving the ice thickness change discussion to the methods/results sections, or reference to original source if from another study. L107: replace "extension" with "area".

L108-109: Move this sentence to the introduction for better context.

L116: Reword to "The results of this step are show in Figure 4.", or remove this sentence. L119: Replace "reflection events" to "reflectors"

L120: Replace "limit…" with "reduce the chance of mis-interpreted bedrock reflections" L121: Be more specific: "… surface topography and the GPR-derived bedrock topography."

L123: Step 6 does not contribute to the "overcome the difficulties in interpreting the GPR data…" as stated at the beginning of the methods section. I suggest removing this step.

L124-145: Address comments above and consider moving this section to 3.2. Clarify the glacier outline source (e.g. mentioned in L186)?

L150-151: This is repeated in Step 4, I suggest removing it here.

L154: What was the bandpass filter of for the ground-based survey? I assume it was lower than this.

L156: Clarify "correct max phase", e.g. is it a dewowing process? Also, avoid non-scientific language like "suggested by Reflexw".

L178: Replace "drive…" with "help identify the ice-bedrock interface during manual picking…"

L181-182: Reword to: "The modeling algorithms required additional input parameters (e.g. *xxx*). These were checked for consistency with the Rutor glacier study area, …" L202: Remove double citation.

L207: Clarify that known ice thickness/bedrock points, not GPR data itself, are used as input. Similarly, further down, I assume h_{GPR} is the GPR-derived ice thickness, not the GPR data.

L212: I suggest removing "outside"

L213: Clarify "gradient of outside terrain slope", i.e. is it the slope outside the glacier? L226: I believe this should be "meltwater runoff"

L228: remove the "is" before "equation" L233: precipitation~~s~~

(remove s)

L232-235: If a mass balance was used to estimate q, include the details on how this was determined for Rutor glacier and the value used.

L245-253: Instead of listing the figures at the start of the results section, I suggest integrating them into the text to improve the flow of the text.
L257: Replace “black reflection zone” with “strong backscatter zone” or “high amplitude zone”.

L257-258: “However, on the right side of the plot, the clearly submerging ice-bedrock interface shows…” I suggest rewording the interpretation of the submerging ice-bedrcok interface to make it less definitive and more interpretative (e.g. the contrast dipping towards the center on to the left also looks like a bed return, but is not picked as such).

L260-263: Move the comparison with other studies to the discussion section. Also, the Villa et al. (2008) study used GPR data from 2006, not 2008.
L270-274: There is a lot of repetition of methods within this section. I suggest focusing on results here only.

L277-282: This section is mostly a repetition of the methods part. Move any methods to the methods section and focus the discussion on e.g. how resolution affects the result (e.g. over- deepening being an effect of fine-resolution DEMs?)
L288: Explain how the ice thickness near the glacier margin was overestimated, e.g. was it compared to the GPR data?

L291: Replace “readability” with “…degree of visibility” or “strength of the ice-bedrock return.”
L298: “… more confidence was given…”, it is not clear how this was implemented. E.g., do the picks come with a confidence level?

L303-305: I suggest including a discussion on the possibility of off-nadir returns (e.g. from valley side walls).

L326: What about seismic surveys?

L329: I suggest adding this citation here (MacGregor et al., 2021) (relation between frequency and ice thickness)

L337: Can we quantify “reasonably comparable models” in the results section, e.g. what is the mean, maximum, standard deviation in the differences in ice thickness predictions?
L339: misspelling of minimizing

L340: It is unclear where these uncertainty estimates come from

L343-L360: This section mainly focuses on how the GPR data could be used in the future. However, I think there should be more focus on future applications of this methodology, including whether these models could assist in interpreting GPR data from other glacier surveys.

L376: "… one can choose a lower frequency antenna…", This conclusion is not supported by this study, as the 40 MHz data also did not show improvement regarding ice-bed returns.

References

Langhammer, L., Rabenstein, L., Schmid, L., Bauder, A., Grab, M., Schaer, P., and Maurer, H.: Glacier bed surveying with helicopter-borne dual-polarization ground-penetrating radar, J. Glaciol., 65, 123–135, https://doi.org/10.1017/jog.2018.99, 2019.

MacGregor, J. A., Studinger, M., Arnold, E., Leuschen, C. J., Rodríguez-Morales, F., and Paden, J. D.: Brief communication: An empirical relation between center frequency and measured thickness for radar sounding of temperate glaciers, The Cryosphere, 15, 2569–2574, https://doi.org/10.5194/tc-15-2569-2021, 2021.

Scanlan, K. M., Rutishauser, A., Young, D. A., and Blankenship, D. D.: Interferometric discrimination of cross-track bed clutter in ice-penetrating radar sounding data, Ann. Glaciol., 61, 68–73, https://doi.org/10.1017/aog.2020.20, 2020.

Reviewer 3

Review of "Ground penetrating radar on Rutor temperateglacier supported by ice-thickness modeling algorithms forbedrock detection"

November 2024

- **General**

The authors demonstrate a model-driven technique for picking points in radargrams corresponding to the glacier bed. They first ran three different models based on surface features, later used to guide the manual picking of Ground-Penetrating Radar (GPR) radargrams of 2012 and 2022. They then estimated the ice thickness in regions without GPR measurements by running the GlaTE model constrained by the GPR measurements.

The manuscript is well-written, and the subject of the work, the difficulty of retrieving the glacier bed, is a hot topic in glaciology, which deserves all the attention of the community. It is one of the most important sources of uncertainty for estimates of the future contribution to sea level rise. Dynamical glacier models are based on reconstructions of bed topography, which are themselves based on *in situ* measurements such as GPR and boreholes. The latter are reliable data, but they are not practical for surveying large areas. In this sense, GPR measurements are the foundation for glaciological studies. For this reason, the manuscript ”Ground penetrating radar on Rutor temperate glacier supported by ice-thickness modeling algorithms for bedrock detection” from Vergnano et al. is very important.

However, it is important not to turn the logic around. Since GPR measurements are an important source of *in situ* information, reversing the process and leaking the modeling data into the GPR measurements can be delusive. This is the most important comment I have for this work, and I would like to see it discussed further in the manuscript.

- **Major comments**

As mentioned previously, my main concern is related to the leakage of modeling data into measurement data. When inversion modeling is performed, it is crucial to have reliable data to constrain the model and evaluate its quality (see, for example, [Shahateet et al., 2023], where they show the impact of using different thickness maps for ice-discharge calculation and [Shahateet et al., 2024] where they show the importance of reliable thickness measurements). If the measurements are biased toward a specific model, it can highly impact everything that comes after, such as the inversion of the bed and the dynamical models that will use the inversion map.

The methodology is valuable, but the main point is to what extent you can use the picking drove by modeling estimations without data leakage. By analyzing Figure 5 and the appendix, I think you introduced too much bias. Some of the picks are not seen in the radargrams, only through the models.

I think that instead of having the model to then do the picks, the best approach would be to do several different picks and compare them to the models you have. In this case, you have less data leakage and more reliable measurements. In case where you have no reliable pick, leaving it without value is better than filling with model information, since in the future you do the inversion modeling of the ice thickness to cover all the domain. In this way, all the measurements you have are trustful and can be used broadly.

Thank you for your insight. We think this approach that you suggest, about making several different picks and comparing them to the models, can be done in our manuscript, and presented accordingly. Also yes, we could leave without value those with no reliable pick: Reviewer 2 raised a similar issue.

In this case, since you use models to support the picking of GPR measurements, you need independent data to validate your method. For this reason, it is desirable to use your method in another glacier with borehole measurements. In this way, you can have an independent validation method. I know it is easy to say and hard to do, but I think it is something important to keep in mind.

We would like to have a borehole on this glacier, but it is hard to do! We can discuss it better in the discussion section as a limitation of the study. Unfortunately, the goal of the paper is mainly related to this glacier and the effort of analyzing another glacier during the revision process, with little local knowledge about it, is very hard. We could think of it for further steps of research, where the ground-truth (ice-truth…) calibration is available.

In chapter 5.1 (comparison of the three ice-thickness modeling algorithms), you stated that the GlaTE and GlabTop2 had similar results, proving the consistency between the different algorithms. First, you do not provide an overall analysis of their agreement, except by the total volume. To say that, you at least need to show an overall metric to conclude that. Second, it is no surprise that they agree well, since they use the same perfect plasticity method. In my opinion, their agreement is not a proof of the consistency of the method.

Thank you. I understand what you mean, and probably this requires to include also OGGM with the same DEM as a comparison. We will also add your statement about the perfect plasticity method in the discussion section.

L287-288 is a warning that something may not be right. Why is the thickness overestimated near the outline of the glaciers? This is the region where you have reliable information from the GPRs, which shows that the measurements do not agree well with the models. Furthermore, L316 stated that 20% of the GPR data was used. Does it mean that 80% of the other points were taken from the models? In this case, it is no surprise that the total mass calculation of your method agrees well with the other models.

Thank you. We generally accepted that near the outline it is more difficult for the models to retrieve the correct thickness, as it is expected for them to provide a general shape of the glacier and not be very accurate in distinguishing if ice is thick 5 or 10 meters at a certain point near the outline. Anyway, We have to investigate this issue further during the revision process, playing with the model parameters.

- **Minor comments**

Thank you for all these minor comments and specific comments. We do not *reply one by one because we generally agree with all of them. If we fail to take some of them into account, we will highlight them in the revision comments.*

- The description of the homogenization of the different data sources is confusing and hard to follow with so many different years. Consider clarification and reduction of information.
- Why do you use the GlaTE as your final model? You never gave a complete reason for that. See my comment on L170-L175.
- In the Methods chapter, the figures are not presented in order. Furthermore, Figure 2 is not mentioned in the text except in the first enumeration of the Methods chapter. In the text, you mentioned Figure 1, and the next Figure to be mentioned is Figure 5. In general, I think it is important to improve the way you make references to the figures.
- Where do the other inputs from the OGGM model come from? You did not describe all the inputs.
- You don't need the enumeration from L245-253. This information is contained in the legend of the figures. Also, it is better to start talking about the figures before showing them out of the blue.
- You cite a personal communication twice. If you do not have a regular citation for that, rephrase it. For example, changing the word "considered" in L129 to "...showed to be..." avoids the need for a citation of a personal communication.
- For the OGGM model, you assumed that the glacier was in equilibrium to infer the ice volume flux (q), which according to the section of the study site is wrong. You can easily use a geodetic mass balance (the one you mentioned) to account for this mass change.
- Several times, you should change to "Rutor Glacier", with capital "G".

- **Specific comments**
  - L42: The acronym EM is not defined, and it is the first and only time that you use it. So, it is not needed.
  - L52: Change "paragraph" to "section".
  - L96: Change "multiisciplinary" to "multidisciplinary".
  - L118: I think mentioning the v.sample tool in this overview of the methodology is not necessary and can distract from the main point.
  - L123: The information in this line is not needed.
  - L151: The sentence "according to the following steps," made me get lost. It looks like you are going to explain the steps, but you start to talk about the software. Only in the next page you are actually explaining the steps. Consider passing the sentence to the end of the paragraph: "The raw data were processed using the commercial. . . open source software (Huber and Hans, 2018), according to the following steps:".
  - L170-L175: I think this paragraph is not necessary. It seems to me that you try to give a reason to use them because of their popularity.

I would try to address this question with a more objective reasoning.

- L177: ”Ice dynamics” instead of ”ice flux mechanics”.
- L183: Change ”writers” to ”authors”.
- L188-L190: How do you avoid the glacier flow line computation? Furthermore, in L190 you say that h_f is the mean ice thickness along the central glacier flow line. So do you actually not avoid it?
- L190: You say what is f , but no further explanation is given. What value did you use? It highly impacts the final result, since it accounts for lateral drag. I presume that in an alpine glacier, this value is important to discuss.
- L198-199: You can exclude this line and pass only ”Further details are provided in the appendix of Frey et al. (2014)” and a good reference of the code (see my next comment).
- L199: several times you wrote the URL link as reference. I think it is not the right way of referencing a webpage.
- L202: ”Clarke et al., 2013” should be ”Clarke et al. (2013)” and ”(Clarke et al., 2013)” is duplicated.
- L223: Same as L199.
- L228: ”is” should be removed.
- L238: Same as L199.
- L239: The data is not well cited. It is (NASA JPL, 2020). Also, the reference is wrong in L465.
- L240: Better ”(based on DEM differencing)”.
- L280: Same as L239.
- 311: How the bias can not be considered significant? You said that the interpretation of GPR measurements below 50 m was difficult and only 20% of the GPR data was clearly identified (presumably in shallow regions, considering the previous statement). It means that in 80% of the time you used ice thickness from the models, or at least driven by it (it is not clear to me when it is driven and when you simply used the same thickness), especially in the regions where it accounts more to the total volume (deep regions). For me, this bias is the major concern regarding the methodology used, and need to be addressed in more details.
- L337: ”from” is duplicated in ”. . . from starting from. . . ”
- L339: Change ”miimizing” to ”minimizing”.
- L357-360: It is a conclusion.
- L365: 17.5 m ”on average”.

- **Figures**
  - Figure 1: In the legend, change ”areas” to ”categories”. Furthermore, remove the parentheses from ”(Crameri, 2021)”.
  - Figure 2: The legend is confusing. Why not numbered from 1 to 5? Also, it is better to number at the end also (e.g.: end-1).
  - Figure 4: Same comment as in Figure 1 regarding ”(Crameri, 2021)”.
  - Figure 5: The legends of GlaTE and OGGM are indistinguishable. It would be clearer if you used different colors for the different models.
  - Figure 6: Same as in Figure 4.
  - All the Appendix Figures: Same as in Figure 5.
  - Is Figure A2 the same as Figure 5. If so, no need to show it again.

References

[Shahateet et al., 2024] Shahateet, K., Fürst, J. J., Navarro, F., Seehaus, T., Farinotti, D., and Braun, M. (2024). A reconstruction of the ice thickness of the antarctic peninsula ice sheet north of 70°s. EGUsphere, 2024:1–29.

[Shahateet et al., 2023] Shahateet, K., Navarro, F., Seehaus, T., Fürst, J. J., and Braun, M. (2023). Estimating ice discharge of the antarctic peninsula using different ice-thickness datasets. Annals of Glaciology.