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 analysed 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).

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

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).

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 emphasise 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.

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.

Minor corrections and suggestions:

**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) analysed 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 analysing 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

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