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.
- **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.
- **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.
- **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

- **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?
- **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.

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

- **Figures**
  - 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 "…<u>can</u> challenge <u>the interpretation of bedrock returns from</u> 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.