Author Response to the RC1

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Response date: 24.06.2025 by Patil et al

Response to Specific Comments

Thank you for your positive feedback and review of our manuscript. We appreciate your thorough engagement with our work, constructive feedback and valuable questions. We agreed to implement most of your comments and have gladly integrated the majority of them into our manuscript. RC1 comments on the model tuning procedure, which is not part of our manuscript, so we refrain from responding in detail to related comments. We see a few repeated comments in specific, critical, major, minor and line-by-line comments. So we selectively responded to Specific comments. We addressed all comments and responded to them in the corresponding comment sections.

Specific comments

01. Scope — Does the paper address relevant scientific questions within the scope of The Cryosphere? *Yes. The manuscript directly addresses firn dynamics, glacier mass balance, and cryosphere–climate interactions on an Alpine glacier — all central topics within the scope of The Cryosphere. No concerns regarding scope.*

02. Novelty — Does the paper present novel concepts, ideas, tools, or data? Yes, with qualification. The primary novel contribution is the first multi-year, repeat CMP application for temporal firn density and compaction monitoring on a European Alpine glacier. Previous Alpine GPR studies (e.g., Sold et al., 2015, The Cryosphere, 9, 1075–1087, doi:10.5194/tc-9-1075-2015) used fixed-offset profiles for spatial snow water equivalent mapping but did not track year-to-year density evolution at depth. The integration of stable isotope and chemical impurity records for IRH dating

adds methodological rigour beyond prior Alpine studies. The quantification of elevation-dependent annual 2 density change (~130 kg m^{-3} a^{-1} at lower-elevation sites vs. smaller values at higher sites) is a novel empirical result. The CMP methodology itself is not novel (established in polar glaciology: e.g., Brown et al., 2012, doi:10.1029/2011JF002089; Meehan et al., 2021, doi:10.1017/JOG.2020.91), and the observation that compaction rates decrease with depth is consistent with established firn densification theory (Herron & Langway, 1980). The authors should more clearly delineate, in the Introduction, what is genuinely new relative to prior Alpine work.

03. Conclusions — Are substantial conclusions reached? Partially. The conclusions are broadly consistent with the data presented. However, several claims are not adequately supported:

a. The assertion that results constitute “an essential step toward improving firn-densification models and glacier mass-balance estimates” (Abstract, line 19–20) is not substantiated. The firn model tuning is described without specifying the optimisation procedure, objective function, or validation against independent data. Three CMP locations over two years are insufficient to rigorously constrain or validate community firn models.

b. The conclusion that CMP is “a valuable alternative” to invasive core drilling is reasonable but would be strengthened by a quantitative comparison (RMSE, bias) between CMP-derived and core measured density profiles.

c. The observation of “potential effect of glacier dynamics on firn stratigraphy” (Abstract, line 17) is presented as a conclusion but is not quantitatively supported in the manuscript body.

Recommendation: Moderate the impact claims; provide quantitative support for model-tuning claims; reframe the glacier-dynamics observation as a hypothesis for future investigation.

04. Methods — Are scientific methods and assumptions valid and clearly outlined? Insufficiently. This is the most critical deficiency in the manuscript.

What is adequate: The choice of CMP for velocity-based density profiling is scientifically valid and well-established. The use of the Looyenga mixing formula, cross-checked against Kovacs and CRIM, is appropriate. The combination of geophysical and geochemical methods for IRH dating is methodologically sound.

What is missing or unclear:

• CMP acquisition parameters are not reported: antenna frequency (MHz), offset range, number of traces per gather, trace spacing, recording time window, and number of stacks. These are essential for assessing data quality and for reproducibility.

• Processing workflow is described only in general terms. Specific parameters for bandpass filtering, gain functions, and the velocity analysis algorithm are not given.

• Semblance panels or velocity spectra — the standard quality-assessment output of CMP analysis — are absent. Their inclusion is necessary to demonstrate the reliability of velocity picks and the absence of cycle-skipping or noise-dominated picks.

• IRH tracking procedure is not described: manual vs. semi-automatic, continuity criteria, treatment of gaps, and how IRHs were matched between CMP sites and between years.

We appreciate your feedback. The detailed process for picking IRHs from Semblance analysis is described in our previous work (Patil et al., 2025). The same is cited in the manuscript, line 170. The CMP analysis quality assessment is discussed in our previous papers and provides details, such as the quality of CMP data with depth in the Appendix figures A1 and A2 (Patil et al 2025). We also provided the same in the supplement. We revisited the manuscript and provided missing descriptions on the CMP acquisition parameters, IRH tracking procedure and processing flow. Further, added more in detail in the supplement.

• Firn core analysis methods are incompletely described: which chemical species were measured by ion chromatography, analytical precision, and how seasonal signals were identified and used to define annual layers.
Thanks a lot for noticing. We added a recommended description within the main text.

• Firn model tuning is mentioned but not described: which parameters were adjusted, by what optimisation procedure, and how the tuned model was validated.
We did not mention any Firn model tuning within the submitted manuscript. The manuscript only focused on field observations.

• **Critical unaddressed assumption:** The manuscript assumes that downward displacement of IRHs between repeat surveys equals firn compaction. In a flowing glacier, this displacement also includes a contribution from vertical strain (thinning due to horizontal divergence and longitudinal extension of ice flow). At Grosser Aletschgletscher, surface velocities in the accumulation area reach ~30–60 m a^{-1} (see: Millan et al., 2022, Nature Geoscience, 15, 111–116,

doi:10.1038/s41561-021-00885-z), implying non-negligible vertical strain rates. This confound must be either corrected for or explicitly quantified and discussed.
We responded to these comments within the specific comments compiled below.

05. Results — Are the results sufficient to support the interpretations and conclusions? Partially. The qualitative patterns reported (density change decreasing with depth; compaction rate maximum near the surface; elevation-dependent density evolution) are plausible and internally consistent.
However:
• No uncertainty estimates are provided for any quantitative result. Without error bars, it is impossible to assess whether differences between sites, depths, or years are statistically distinguishable. Velocity uncertainty of ±5% from semblance analysis propagates to density uncertainty of ~8–10 kg m^{-3} via the Looyenga formula — non-trivial relative to the reported annual changes (Medley et al., 2015, doi:10.3189/2015AOG70A203).
We appreciate your detailed suggestions on uncertainties. However, we provided the semblance velocity picking (±0.005 m/ns) uncertainty in density estimations in line 591 within the subsection 6.5 “Conservation of mass and Uncertainties”. The same is explained in detail in our previous work (Patil et al 2025) as suggested by Booth et al. (2011). All plots related to density-depth or density-age profiles are plotted considering the semblance velocity uncertainty of 0.005 m/ns (Figures 7, 8, and 9) along with the uncertainty or error bars.

• The CMP-vs-core density comparison is presented qualitatively (“agreement”). No RMSE, mean bias, or correlation coefficient is reported, and no side-by-side figure with error bars is provided.
We appreciate your suggestion. We provided the RMSE and Bias information in Figure 7b in the revised manuscript. We also added a standalone figure of the CMP-vs-core derived density profile with RMSE and Bias information in the supplement.

• Compaction rates are reported as “maximum ~0.3 m a^{-1}” without specifying the depth interval, the year of measurement, or the uncertainty.
Thanks a lot for the feedback. We provided depth and year of measurement information on the maximum compaction rate.

• The firn model tuning is claimed to improve model performance, but no quantitative comparison (pre- vs. post-tuning RMSE) is shown.
We did not use any firn models in this study. The manuscript only focused on field observations.

06. Reproducibility — Is the description of experiments and calculations sufficiently complete to allow reproduction by fellow scientists? No — this is a critical deficiency. As detailed under criterion 04, the CMP acquisition parameters,

processing workflow, IRH tracking procedure, and firn model tuning procedure are insufficiently described for independent reproduction. The manuscript should provide either (a) complete parameter tables in the main text, or (b) a comprehensive supplementary methods section with all parameters and intermediate outputs (semblance panels, velocity-depth functions, IRH depth tables).
We appreciate your feedback. We agreed and provided detailed CMP acquisition parameters and processing workflow within the main text in the form of tables. The IRH tracking procedure is added in the revised manuscript. We provided the velocity-depth, including Vrms and interval velocity profiles, within the supplement, along with the IRH and depth information. The submitted manuscript focuses on field observations and does not provide any information on firn model tuning.

07. Credit and originality — Do the authors give proper credit to related work and clearly indicate their own new/original contribution? Adequately, with minor gaps. The reference list is broad and generally appropriate. The authors cite key relevant works in Alpine firn studies (Sold et al., 2015), polar CMP applications (Brown et al., 2012), and firn densification modelling (Herron & Langway, 1980; Kuipers Munneke et al., 2015). **However:**

• The Introduction does not explicitly state what is novel in this study compared to Sold et al. (2015) and other Alpine GPR work. A direct comparison sentence would help readers assess the incremental advance.
• Stevens et al. (2024, Journal of Glaciology, doi:10.1017/jog.2024.24) — cited in the reference list — reports direct multi-year firn density measurements at Wolverine Glacier, Alaska, and represents a close methodological analogue that should be discussed in the context of the current study's novelty.

• The discussion does not sufficiently compare the reported compaction rates (~0.3 m a^{-1}) with values from polar studies (Medley et al., 2015: ~0.33 m a^{-1} in Antarctica; Kruetzmann et al., 2011, doi:10.5194/TC-5-391-2011: ~0.05–0.25 m a^{-1} near Ross Island) to contextualise whether Alpine rates are anomalously high, low, or consistent with global patterns.
We responded to similar comments within the critical, major, and minor comments compiled below.

08. Title — Does the title clearly reflect the contents of the paper? Adequately, with a suggested refinement. The current title, "Annual firn pack variations in the context of the climate settings: Example from the Grosser Aletschgletscher using multi-year radar observations," is descriptive. **However:**

• "firn pack variations" is somewhat vague; "temporal firn density and compaction" would be more precise.

• “in the context of the climate settings” is awkward phrasing; “in response to Alpine climate forcing” or “under Alpine climate conditions” would be cleaner.

• The colon structure is acceptable but the subtitle “Example from…” slightly undersells the contribution.

Suggested alternative: “Temporal evolution of firn density and compaction at Grosser Aletschgletscher: first multi-year CMP radar and firn-core observations for a European Alpine glacier.”
We appreciate the suggested changes in the title. We changed the title to improve clarity and the scientific reach of our study.

09. Abstract — Does the abstract provide a concise and complete summary?
Partially. The abstract adequately covers the objectives, methods, and main results. **However:**

• **Line 14: typographical error —** “CMP measurements are & valuable alternative” (should be “a valuable alternative”).
Thanks a lot for noticing an error. We corrected for this.

• **Line 11: ambiguous phrasing —** “changes in firn density over a year decrease with depth and age” (does “over a year” modify “changes” or “decrease”?). Suggested revision: “annual changes in firn density decrease with depth and age.”
Thanks for noticing possible ambiguity in phrasing. We accepted the suggestions and corrected them accordingly.

• The abstract does not quantify the uncertainty on the key result (~130 kg m^{-3} a^{-1}), which is important for readers to assess the robustness of the finding.
Thank you for the feedback. We added this information in the abstract.

• The claim that results are “an essential step toward improving firn-densification models” (line 19) overstates the contribution relative to the study scope (see criterion 03). This should be moderated.
We appreciate your suggestion. We made the required changes.

• The abstract could be shortened by ~15% without loss of information (currently ~230 words; target ≤200 words for this journal).
We appreciate your suggestions. We consider making the needful changes.

10. Overall presentation — Is the overall presentation well structured and clear? Adequately structured, with important gaps. The manuscript follows a logical IMRaD structure (Introduction, Methods, Results, Discussion, Conclusions) appropriate for The Cryosphere. The writing is generally clear. **However:**

• **Essential figures are absent:** (a) semblance panels or velocity spectra demonstrating CMP data quality; (b) a side-by-side figure correlating GPR radargrams with core stratigraphy (density, $\delta^{18}O$, chemical impurities) with IRHs annotated; (c) a quantitative CMP-vs-core density comparison figure with error bars; (d) a figure showing compaction rate vs. depth with uncertainty bounds and comparison to model predictions or polar observations.
We respond to these comments within the specific comments compiled below in detail. Our current study does not focus on any firn model; therefore, we can not provide any figures related to model comparison with polar observations.

• A summary table of key results (density change rate, compaction rate, accumulation rate) by site and year, with uncertainties, would substantially improve clarity.
We respond to these comments within the comments compiled below.

• A conceptual schematic of the study area, CMP geometry, and firn layer structure would aid non-specialist readers.
We appreciate your suggestions. However, we refrain from providing a conceptual schematic of the study area as we already have a real-world aerial image in Figure 1. We added other basic information on CMP geometry within the supplement.

• **The Results section lacks a clear narrative hierarchy:** key findings are not distinguished from secondary observations.
Thanks a lot for the suggestion. We revisited the manuscript and made changes wherever necessary.

11. Language — Is the language fluent and precise? Generally yes, with minor issues. The English is fluent and technical terminology is used correctly. **Specific issues:**
• "Or" capitalised mid-sentence (Introduction, line 25): "survived at least one summer Or melt season."
We appreciate such detailed suggestions. We corrected the grammatical mistake.

• **"& valuable alternative" (Abstract, line 14):** typographical error. • Inconsistent hyphenation: "firn-core" vs. "firn core" used interchangeably throughout.
Thanks a lot for noticing the typographical errors. We made the required changes to be consistent with the hyphenation in the manuscript.

• Several long sentences in the abstract and methods could be split for clarity.
We appreciate your suggestions. We made changes in splitting long sentences wherever necessary.

• The phrase “functionally related to temporal changes” (Abstract, line 6) is vague; consider “controlled by” or “directly linked to.”
Thanks a lot for the detailed commenting. We changed the phrasing as suggested.

12. Mathematical formulae, symbols, abbreviations, and units — Are these correctly defined and used? Mostly, with gaps. The Looyenga mixing formula and its variables are cited but not written out explicitly in the manuscript. Given that this formula is central to converting CMP velocities to density, it should be stated explicitly with all variables defined. The abbreviations CMP, GPR, IRH, and CRIM are defined on first use. Units are generally correct, but axis labels on several figures are missing units — this must be corrected systematically. The decimal separator usage appears consistent (period), in line with journal style.
We respond to these comments within the specific comments compiled below.

13. Clarification, reduction, or elimination of parts — Should any parts be clarified, reduced, combined, or eliminated? **Several suggestions:**

• **Clarify:** The firn model tuning section should either be expanded with full methodological detail or removed if it cannot be adequately described and validated within the scope of this paper.

• **Clarify:** The section on glacier dynamics effects on stratigraphy (comparison of 2024 and 2025 GPR profiles) should be clearly labelled as preliminary/observational, with a quantitative estimate of the expected strain effect or an explicit statement that this is a hypothesis for future work.
We appreciate the much-needed suggestion. Yes, this interpretation is preliminary; we need additional observations to support our interpretation. We added the suggested statement explicitly.

• **Reduce:** The introduction contains some general background on firn processes that could be condensed, as it is well known to the target readership of The Cryosphere.
Thanks for the suggestions. We agreed and reduced or condensed some parts of the introduction related to firn processes.

• **Add:** A dedicated Limitations subsection in the Discussion would strengthen the manuscript by explicitly acknowledging: (i) single-site scope; (ii) two-year temporal baseline; (iii) three CMP locations; (iv) absence of ice velocity data; (v) lack of independent compaction validation.
We appreciate your suggestion of adding a dedicated limitation section in the discussion. We agreed and added suggested information within subsection 6.5.

14. References — Are the number and quality of references appropriate? **Largely yes, with minor issues.** The reference list (~90 entries) is appropriate in scope and covers key literature in firn physics, GPR methodology, Alpine glaciology, and firn modelling. **However:**

• Williamson et al. (2020) appears twice with apparently identical DOI (lines 915–919 of the manuscript). One entry should be removed, or the two entries should be differentiated if they are genuinely distinct publications.

• **DOI formatting errors:** Multiple DOIs use "https:lldoi.org" (capital "I" instead of lowercase "l"), which will generate broken links. All DOIs must be standardised to "https://doi.org/…".
We responded to these comments in the line-by-line comment section compiled below.

• **Missing comparison reference:** Stevens et al. (2024, Journal of Glaciology, doi:10.1017/jog.2024.24) is cited in the reference list but not discussed in the text despite being a highly relevant analogue study (direct multi-year firn density measurements at an Alpine-type glacier).
We appreciate your suggestions. Yes, we mentioned Stevens et al (2024) study on direct measurements to derive firn density measurements. We consider comparing our study with Stevens et al (2024) results and discuss in section 6.3.

• **Suggested addition:** Vandecrux et al. (2020, The Cryosphere, 14, 3785–3810, doi:10.5194/tc-14 3785-2020) — the RetMIP firn model intercomparison — should be cited when discussing firn model tuning, as it provides the community benchmark for model evaluation.
Thanks for the suggestion. However, our current study does not focus on any firn model tuning. Therefore, we do not discuss Vandecrux et al. (2020) in the submitted manuscript.

15. Supplementary material — Is the amount and quality of supplementary material appropriate? Supplementary material is not mentioned in the manuscript. Given the extent of methodological detail that is currently missing from the main text (acquisition parameters, processing workflow, intermediate outputs), the authors may consider preparing a comprehensive supplementary methods section to include such items as:

• CMP acquisition parameter table (per site and campaign).
• Processing workflow diagram with parameter values.
• Representative semblance panels for each CMP site and survey year.
• Velocity-depth functions derived from semblance analysis, with uncertainty bounds.
• IRH depth tables for each site and year.

• Firn core data tables (density, $\delta^{18}O$, chemical impurity profiles).
• Firn model tuning procedure and parameter values.

We appreciate the suggestion to prepare a comprehensive supplementary material, including the above-mentioned points in detail. We agreed and provided the supplementary material consisting of CMP acquisition parameters, processing workflow, representative semblance panel for each test site, velocity depth profiles with Vrms and interval velocity with uncertainty in semblance picking of ±0.005 m/ns, and IRH-depth table for all three CMP test sites. We provide firn core data, including all CMP and GPR profile data, once the manuscript is accepted for publication by creating a DOI for the dataset. Our current study does not discuss or provide any results related to the firn model tuning procedure.

Placing the raw data in a publicly accessible repository, accompanied by a data availability statement—a practice recommended by The Cryosphere, to the best of my knowledge—can also be carried out.
Thanks for the suggestions. We already provided the statement within the data availability section in the manuscript, lines 667-669.

Here is an ordered summary of specific comments compiled from above

First, the critical ones:

1. **Uncertainty quantification:** Provide full uncertainty propagation for all key results (CMP velocity → density → compaction rate → accumulation). Present all results with error bars or ± values. State the dominant uncertainty sources explicitly.
We appreciate your detailed suggestions on quantifying uncertainties. However, we provided the semblance velocity picking (±0.005 m/ns) uncertainty in density estimations in line 591 within the subsection 6.5 “Conservation of mass and Uncertainties” and also mentioned the error sources explicitly. The same is explained in detail in our previous work (Patil et al 2025) as suggested by Booth et al. (2011). All the plots related to density-depth or density-age profiles are plotted with error bars considering the semblance velocity uncertainty of ±0.005 m/ns (Figures 7, 8, and 9), except for the compaction rate vs age figure 10 in the submitted manuscript. We revisited all figures and added missing information as suggested.

2. **Methodological completeness and reproducibility:** Add a comprehensive methods description or supplementary methods section including: CMP acquisition parameters, processing workflow with parameter values, semblance panels, IRH tracking procedure, firn core analysis details, and firn model tuning procedure.
We appreciate the suggestion of preparing a comprehensive supplementary material, including the above-mentioned points in detail. We agreed and provided the supplementary material consisting of CMP acquisition parameters, processing

workflow, representative semblance panel for each test site, velocity depth profiles with Vrms and interval velocity with uncertainty in semblance picking of 0.005 m/ns, and IRH-depth table for all three CMP test sites. We will provide firn core data, including all CMP and GPR profile data, once the manuscript is accepted for publication by creating a DOI for the dataset. Our current study does not discuss or provide any results related to the firn model tuning procedure; therefore, we refrain from describing the same in the manuscript.

3. Strain vs. compaction separation: Either (a) obtain and present ice velocity data to estimate and correct for vertical strain, or (b) include a quantitative estimate of the strain contribution to IRH displacement and discuss its implications for the reported "compaction rates." A worked example: "Assuming a vertical strain rate of $\dot{\varepsilon} \approx X\ a^{-1}$ (consistent with surface velocities of ~Y m a^{-1} and a depth of Z m), the strain contribution to annual IRH displacement is estimated at ~W m a^{-1}, compared to the observed total displacement of V m a^{-1}."
Thanks for bringing the importance of strain rate on compaction rate. We appreciate your suggestions. We looked at S. Leinss and P. Bernhard (2021) velocity map, which suggests a negligible velocity gradient at our measurement locations. For this reason, we did not provide the strain rate impact on compaction rate in our submitted manuscript. However, we agreed to estimate the vertical strain rate using Millan's 2022 dataset. We also provide a quantitative estimate of the strain contribution to IRH displacement when the estimated values are significant; otherwise, we provide the details in the supplement.

4. IRH-core correlation figure: Provide a figure showing side-by-side GPR radargrams and core profiles (density, $\delta^{18}O$, SO_4^{2-}) with IRHs explicitly annotated and matched to core annual layers. Quantify core dating uncertainty.
We appreciate your suggestions. We agreed and provided a figure showing the GPR radargram and core profiles similar to Figure 5, with an annotated GPR radargram in the supplement. We also added information on quantifying the core dating uncertainty.

5. Quantitative CMP-vs-core comparison: Report RMSE, mean bias, and correlation coefficient for the CMP-vs-core density comparison. Provide a side-by-side profile figure with error bars.
Thanks for the suggestion. We added RMSE and mean bias information in Figure 7b and provided the standalone figure in the supplement.

<u>Then some major comments:</u>

6. Moderate conclusions: Replace "essential step toward improving firn-densification models" with language reflecting the case-study scope: "These observations provide site-specific constraints that can inform future calibration of

firn-densification models for Alpine accumulation areas." Reframe the glacier-dynamics observation as a hypothesis.
We appreciate detailed feedback. We agreed and made changes in phrasing and reframed the suggested conclusion parts.

7. Related with meteorological context: Present air temperature and precipitation data for the study period (from Jungfraujoch station or ERA5 reanalysis) and compare to the 1991–2020 climatological mean.
Thanks for the suggestions. We already provided the present and past climatological air temperature in lines 113-114 and 526-528 from the nearby weather station. Jungfarujoch research station does not record precipitation data; we provided the annual and seasonal accumulation as in Figure A1. We also added the comparison of mean annaul air temperature and accumulation over a suggested climatological period with our measurement period.

8. Dedicated Limitations subsection: Add an explicit Limitations section acknowledging: single-site scope, two-year temporal baseline, three CMP locations, absence of ice velocity data, and lack of independent compaction validation.
We appreciate your suggestion. We already have an uncertainty subsection; we added suggested information within the same section.

9. Missing figures: Add semblance panels, IRH-core correlation figure, compaction-rate-vs-depth figure with uncertainty and model comparison, and a summary results table.
We appreciate your feedback. We agreed to provide semblance panels for the remaining CMP datasets, similar to Figure 2 in the supplement. We also provide a compaction rate vs depth figure with uncertainty in the supplement. We do not have any model results to compare in this study. The summary results table is also agreed to be added to the supplement.

10. Data availability statement: Add a data availability statement and deposit raw data in a public repository (PANGAEA or equivalent). Or not…
Thanks for the suggestions. We already provided the statement within the data availability section in the manuscript, lines 667-669.

Finally, some minor recommendations:

11. Title revision: Consider: "Temporal evolution of firn density and compaction at Grosser Aletschgletscher: first multi-year CMP radar and firn-core observations for a European Alpine glacier."
Thanks for suggesting changes in the title to improve the scientific readability of this research and for a cleaner and more precise title. We agreed and made a change in the title as suggested.

12. Abstract corrections: Fix typographical error (“& → a”); resolve ambiguous phrasing (line 11); reduce length to ≤200 words; moderate impact claim. 13. Language corrections: Fix capitalised “Or” (Introduction, line 25); standardise hyphenation (“firn core” throughout); split long sentences.
We appreciate detailed comments on typographical and language corrections. We agreed and corrected the suggested changes to the revised manuscript.

14. Mathematical notation: Write out the Looyenga formula explicitly; add missing axis units to all figures.
We appreciate your suggestions. However, the Looyenga formula is well-known within the community, and explicit mention of the formula in this manuscript does not add valuable information to existing knowledge. Most of the figures presented have axis units in the submitted manuscript, except for Figure 11 (depth-age). We reviewed all figures and made the required changes.

15. Reference corrections: Remove duplicate Williamson et al. entry; fix all DOI formatting errors; add in-text discussion of Stevens et al. (2024) and Vandecrux et al. (2020).
Thanks for the suggestion. We removed duplicate citations and fixed the DOI formatting wherever necessary. We also agreed to discuss Stevens et al (2024) as suggested in line-by-line remarks. However, our study only focuses on observation-based firn densification and compaction; therefore, discussing Vandecrux et al (2020) is not suitable for the scope of this manuscript.

<u>And lastly —typos, tiny comments, and specific line-by-line remarks</u>

Abstract line 11: “changes in firn density over a year decrease with depth and age” — ambiguous scope of “over a year”
Agreed and changed the phrasing as suggested.

Abstract line 14: “CMP measurements are & valuable alternative” — typographical error : “CMP measurements are a valuable alternative”
Thanks for noticing. We corrected a typographical error.

Abstract line 19: “an essential step toward improving firn-densification models” —overstated: “a contribution toward future calibration of firn densification models”
We appreciate your suggestions. We made changes accordingly.

Introduction line 25: “survived at least one summer Or melt season” — erroneous capital: “survived at least one summer or melt season”
Corrected
Introduction general: Novel contribution vs. Sold et al. (2015) is not explicitly stated. Add one sentence: “Unlike Sold et al. (2015), who used fixed-offset GPR for

spatial SWE mapping, the present study employs repeat CMP surveys to track year-to year changes in firn density and compaction at depth."
We appreciate your feedback and suggested changes. We added the suggested correction and made the corresponding changes in the manuscript.

Methods: CMP antenna frequency not stated. Add: "CMP surveys were conducted using [X] MHz antennae with an offset range of [Y–Z] m and a trace spacing of [W] m."
Thanks for the suggestions. However, we already added this information in the submitted manuscript, lines 147-148. We consider adding details of the CMP acquisition parameters in the table format.

Methods: Looyenga formula not written out: State formula explicitly: ε^(1/3) = φ_ice · ε_ice^(1/3) + (1–φ_ice) · ε_air^(1/3), with all variables defined.
We appreciate your suggestions. However, the Looyenga formula is well-known within the community, and explicit mention of the formula in the main text of this manuscript does not add valuable information to the existing knowledge. We provided this information within the supplement.

Methods: IRH tracking procedure not described. Add: "IRHs were tracked [manually/semi automatically] using [software name], with a continuity threshold of [X] m. Gaps of more than [Y] traces were [interpolated/excluded]."
Thank you for this suggestion. We added this information to the revised manuscript.

Results: "maximum ~0.3 m a^{-1}" — depth interval and year not specified. Add: "~0.3 m a^{-1} at [X–Y] m depth during [year]"
We appreciate your suggestion to add depth and year. We agreed to add this information to the revised manuscript.

Results: CMP-vs-core comparison presented qualitatively only. Add: RMSE and mean bias; provide quantitative figure.
Thank you for pointing it out. We added RMSE and mean bias information in Figure 7b and provided the standalone figure in the supplement.

Discussion: "potential effect of glacier dynamics" — unquantified claim. Either quantify or reframe as: "We hypothesise that glacier dynamics may influence firn stratigraphy; quantification requires future ice velocity measurements."
Thanks a lot for the feedback. Agreed and reframed the sentence as suggested.

Discussion: No comparison of compaction rates with polar analogues. Add comparison: Medley et al. (2015) ~0.33 m a^{-1} in Antarctica; Kruetzmann et al. (2011) ~0.05–0.25 m a^{-1} near Ross Island.
We appreciate your comments on comparing the polar studies. As the study is focused on Alpine climatic conditions, we thought comparison with polar results is

not suitable for the intended focus of the manuscript. Nevertheless, we added the suggested compaction rate values to the revised manuscript.

References: Williamson et al. (2020) duplicated (lines 915–919). Remove duplicates; verify if two distinct papers.
Thanks for noticing our mistake. We rectified accordingly by removing the duplicate citation from the bibliography.

References: Multiple DOIs: “https:lldoi.org” (capital I). Standardise to “https://doi.org/…” throughout.
Agreed and corrected

Figure captions: Axis units missing on several figures. Add units to all axes; conduct systematic check.
Thanks for the suggestions. However, most of the figures have axis units in the submitted manuscript, except for Figure 11 (depth-age (years)). We reviewed all figures and made required changes wherever necessary.

Throughout: Inconsistent hyphenation: “firn-core” vs. “firn core”. Adopt “firn core” (noun phrase) and “firn-core” (attributive adjective) consistently.
We appreciate such detailed feedback and comments. We corrected for the consistent hyphenation, as suggested.

Throughout: Inconsistent citation format (some with DOI, some without). Standardise: include DOI for all references where available.
Thanks a lot for noticing the inconsistent citation format. We could not find DOIs for some of the papers that we cited in the manuscript. We have revisited the manuscript, corrected for the suggested consistency by adding missing DOIs or the last access date.

References:

Patil, A. M., Mayer, C., Seehaus, T., Groos, A. R., and Bauder, A.: Investigating firn structure and density in the accumulation area of the Grosser Aletschgletscher using ground-penetrating radar, The Cryosphere, 19, 5547–5577, https://doi.org/10.5194/tc-19-5547-2025. 2025b

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