Referee comments to:

Manuscript: Annual firn pack variations in the context of the climate settings: Example from the Grosser Aletschgletscher using multi-year radar observations

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The overall quality

(see *The Cryosphere* Rating Scale: 1 = Excellent · 2 = Good · 3 = Fair · 4 = Poor)

Principal Criterion	Rating	Justification
Originality (novelty): Does the manuscript represent substantial progress beyond current scientific understanding (new insight, concepts, methods, or data)?	**2 – Good**	The study provides the first multi-year, repeat CMP-based characterisation of temporal firn density and compaction on a European Alpine glacier — a genuine and well-motivated contribution. The CMP methodology itself is established in polar settings, so the novelty is primarily regional and temporal rather than conceptual. The multi-method validation framework (CMP + geochemistry + stable isotopes) exceeds the rigour of most previous Alpine firn studies.
Scientific quality (rigour): Is the purpose clearly articulated, methodology adequate, and evidence compellingly presented? Are methods valid and suitable? Are results discussed in a balanced way with appropriate references?	**3 – Fair**	The scientific premise is sound, and the multi-method approach is appropriate. However, critical methodological details are missing (acquisition parameters, processing workflow, semblance panels), uncertainty quantification is entirely absent, independent validation of compaction rates is lacking, and the potential confound of vertical glacial strain on "compaction" estimates is not addressed. Discussion of related work is present but insufficiently critical.
Significance (impact): Does the manuscript substantially change	**2 – Good**	The work addresses a recognised gap relevant to Alpine mass balance modelling, firn densification

scientific understanding or introduce new practical applications of broad relevance?		model calibration, and climate-change monitoring. Impact is currently limited by the single-site, two-year scope and the absence of quantitative links to downstream applications (e.g., specific corrections to geodetic mass balance). With revisions, the significance rating could improve to Excellent.
Presentation quality: Are results and conclusions presented clearly, concisely, and well-structured? Are figures/tables adequate? Is English appropriate?	**3 – Fair**	The manuscript is logically structured, and the English—insofar as I can judge as a non-native speaker—is generally fluent. However, essential figures are absent (semblance panels, IRH-core correlation diagram, quantitative CMP-vs-core comparison), the abstract contains a typographical error ("& valuable alternative"), and axis units are missing from several figures. The abstract could be made more concise.

Overall comment: Major Revisions Required. The manuscript has genuine scientific merit and addresses an important knowledge gap. It can be recommended for publication in *The Cryosphere* after revisions addressing the methodological and presentation issues identified below.

Specific comments

(I tried to put it in accordance with The Cryosphere Review Criteria, Items 01–15)

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

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:

- 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.
- 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.
- 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.
- **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.
- **Firn model tuning** is mentioned but not described: which parameters were adjusted, by what optimisation procedure, and how the tuned model was validated.
- **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.

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).

- **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.
- **Compaction rates** are reported as "maximum ~0.3 m a^{-1}" without specifying the depth interval, the year of measurement, or the uncertainty.
- **The firn model tuning** is claimed to improve model performance, but no quantitative comparison (pre- vs. post-tuning RMSE) is shown.

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).

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.

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."*

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").
- 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."*
- 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.
- 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.
- The abstract could be shortened by ~15% without loss of information (currently ~230 words; target ≤200 words for this journal).

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.
- **A summary table** of key results (density change rate, compaction rate, accumulation rate) by site and year, with uncertainties, would substantially improve clarity.

- **A conceptual schematic** of the study area, CMP geometry, and firn layer structure would aid non-specialist readers.
- The Results section lacks a clear narrative hierarchy: key findings are not distinguished from secondary observations.

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."*
- "& valuable alternative" (Abstract, line 14): typographical error.
- Inconsistent hyphenation: "firn-core" vs. "firn core" used interchangeably throughout.
- Several long sentences in the abstract and methods could be split for clarity.
- The phrase *"functionally related to temporal changes"* (Abstract, line 6) is vague; consider *"controlled by"* or *"directly linked to."*

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.

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.
- **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*.

- **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.

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:Ildoi.org"* (capital "I" instead of lowercase "l"), which will generate broken links. All DOIs must be standardised to *"https://doi.org/…"*.
- **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).
- **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.

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.

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.

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.

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.

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}*."*

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.

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.

Then some major comments

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.

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.

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.
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.
10. **Data availability statement:** Add a data availability statement and deposit raw data in a public repository (PANGAEA or equivalent). Or not…

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."*
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.
14. **Mathematical notation:** Write out the Looyenga formula explicitly; add missing axis units to all figures.
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).

And lastly —typos, tiny comments, and specific line-by-line remarks

Location	Issue	Suggested Correction
Abstract, line 11	*"changes in firn density over a year decrease with depth and age"* — ambiguous scope of "over a year"	*"annual changes in firn density decrease with depth and age"*
Abstract, line 14	*"CMP measurements are & valuable alternative"* — typographical error	*"CMP measurements are a valuable alternative"*
Abstract, line 19	*"an essential step toward improving firn-densification*	*"a contribution toward future calibration of firn-densification models"*

	models” — overstated	
Introduction, line 25	*“survived at least one summer Or melt season”* — erroneous capital	*“survived at least one summer or melt season”*
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.”*
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.”*
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
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].”*
Results	*“maximum ~0.3 m a^{-1}”* — depth interval and year not specified	*“~0.3 m a^{-1} at [X–Y] m depth during [year]”*
Results	CMP-vs-core comparison presented qualitatively only	Add RMSE and mean bias; provide quantitative figure
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.”*
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
References	Williamson et al. (2020) duplicated (lines 915–919)	Remove duplicate; verify if two distinct papers

References	Multiple DOIs: *"https:Ildoi.org"* (capital I)	Standardise to *"https://doi.org/…"* throughout
Figure captions	Axis units missing on several figures	Add units to all axes; conduct systematic check
Throughout	Inconsistent hyphenation: "firn-core" vs. "firn core"	Adopt "firn core" (noun phrase) and "firn-core" (attributive adjective) consistently
Throughout	Inconsistent citation format (some with DOI, some without)	Standardise: include DOI for all references where available