Review of manuscript (https://doi.org/10.5194/egusphere-2025-615) by Akash M. Patil and colleagues entitled **"Investigating firn structure and density in the accumulation area of Aletsch Glacier using Ground Penetrating Radar"** submitted to The Cryosphere.

19 May 2025, Michael Zemp

Summary

Akash Patil and colleagues investigated the snow and firn structure of Grosser Aletschergletscher, Switzerland, based on snow pits, firn cores, Ground Penetrating Radar (GPR), and Common Mid-Point (CMP) measurements from field campaigns carried out between February and May 2024. They used these field observations and firn compaction models to reconstruct the accumulation history over the past 12 years and validated (or compared) their results against snow water equivalents from a long-term glaciological point mass-balance program run by Glacier Monitoring Switzerland.

Evaluation

Akash Patil and colleagues have conducted extensive fieldwork and investigated their observations in combination with process understanding, firn modelling, and existing measurements. This combination of methods provides new insights into the processes of snow/firn accumulation and densification in the accumulation zone of the largest Alpine glacier, which is changing from a dry zone to a percolation zone under current climatic conditions. The manuscript presents a valuable and very interesting study that fits well into the scope of The Cryosphere. Still, major revisions are required to improve the structure and readability of its text and figures, and to elaborate and discuss its key findings better. As such, it would be nice to add a direct comparison of their results from 2024 with an earlier survey from 2021 by Bannwart et al. (2024). My feedback is summarized as general and specific remarks outlined below.

General remarks

+ Structure: While the sections of the manuscript are generally well structured, the text would benefit a lot from better structuring, i.e., explaining the more general before going into details. This applies especially to the Abstract, Discussion, and Conclusions, as well as the captions for the Figures and Tables. I strongly recommend rewriting all captions, starting with (i) a short title, followed by (ii) a description of the content, (iii) explanations of axes, acronyms, and labels, (iv) notes or reading examples (if required), and (v) sources.

+ Readability: In its current form, the paper is hard to read, especially for "fast-food readers" who focus on the abstract, here-we-show-statement, figures, tables, and conclusions. To improve the readability, I encourage the authors to improve the structure and figure captions (see above), reduce the acronyms to the absolute minimum, and review the terminology (see below).

+ Terminology: The paper is not very consistent in its use of terms. Given the different Swiss place names (cf. Fig. 1), I suggest consistently using "Grosser Aletschgletscher". Write "Alpine" when

referring to the European Alps and “alpine” when referring to more general alpine environments. The (few essential) acronyms (e.g., GPR) should be introduced at their first use (only), and maybe written out in the captions. More questions related to terminology are listed in the specific remarks.

+ Key findings: Better emphasize the novelty and key findings of the study. From the Abstract and Conclusions, it is not clear (to me) which methods or combination thereof are novel and which findings are key for future research. Also, you mention a validation of your results against glaciological stake measurements in the abstract, while Figs. 6, 13, and 14 are instead a comparison.

+ Discussion: The discussion of the results remains relatively descriptive, and I see considerable potential for emphasizing the relevance of the findings. As such, you could discuss in more depth (and with the support of meteorological data) the presence (or absence) of seasonal and annual layers. Also, it would be interesting to discuss in more depth the impact of the increasing occurrence of summer melt in these formerly cold zones and the extreme summer 2022, which resulted in a net mass loss and erased an entire snow/firn layer. Finally, the authors mention that their GPR profile was a repeat measurement of the survey by Bannwart et al. (2024) from March 2021. It would be great to compare their GPR profiles (Bannwart et al. 2024, Fig. 5c) and firn cores (Bannwart et al. 2024, Fig. 6) from Ewigschneefeld, especially given the extreme years 2021/22 and 2022/23. Can you link the layers between the studies? Do you see any changes in the snow/firn densification profile? Figure 3 in Machguth et al. (2016) and Figure 4 in Sold et al. (2015) provide good examples of firn core comparisons.

The data from Bannwart et al. (2024) is temporarily available from Switch* and will later be added to the Zenodo repository related to the paper (https://10.0.20.161/zenodo.11071899).

*https://filesender.switch.ch/filesender2/?s=download&token=934552bd-6550-4398-a2ec-5837b0006f0e

+ Discussion & Figures: Your figures are all placed before the Discussion section. This is fine, but it would help to add (more) labels or reading examples that emphasize the topics discussed. As such, it would be interesting to see your age interpretation of the reflectors (in Figs. 2, 3, 4, 15, 16) and of seasonal/annual layers (Figs. 8, 9, 10, 11, 12).

+ Data availability: I strongly support publishing the dataset in a public repository such as Zenodo (https://zenodo.org/) or Pangaea (https://www.pangaea.de).

+ Methods: I note that GPR data processing and Common Mid-Point semblance analysis are outside my expertise. Here, I refer to the other reviewers and suggest considering their feedback on velocities picked from the semblance analysis (https://doi.org/10.5194/egusphere-2025-615-RC1).

Specific remarks

Title

L0: The present title is fine. However, if your firn modelling is a key finding of the study, you might consider reflecting this in the title.

Abstract

L1: Consider rewriting to improve structure and to emphasize key findings better.

L10: Remove line break in abstract.

Introduction

L18: Consider rewriting to improve the structure: background, state of the art, problem, "here we show…", general aim, and specific approach.

L35: Fix reference style of "Jordan et al., 2008".

L75ff: The study on Findelengletscher, by Sold et al. (2015), was mainly in temperate firn, while your study is located in cold firn. Does this difference matter when it comes to the consideration of radar velocity to get the internal reflection horizons? If so, please clarify.

L77-79: From the formulation of these lines, I would expect that your study will discuss the results compared to Huss (2013), and would not expect a comparison to Sold et al. (2015). I suggest rewriting the motivation part and better formulating the aim of your study.

Study area and data acquisition

L94: Concerning the largest glaciers, you might cite Windnagel et al. (2023).

L102: Instead of "validate", I would write "as available from GLAMOS (2024) and WGMS (2024)."

L116: Under the title "Glaciological investigations", I would also expect to find information about the point mass-balance measurements from GLAMOS that you used for validation/comparison to your results.

Methods

L158: Remove space in (V_{firn}).

L166: You have only one sub-section (3.3.1). Consider merging with Section 3.3. This would also reduce redundancies in the current title.

L177ff: Please provide more details on how the "tuning" was done.

L192: Would it be helpful to include these parameters in the sensitivity experiment (Section 5.3)? Also: replace ":" by ".".

L201: Check and adjust your term (e.g., "seasonal melt factor", "snowmelt rate value", "melt factor") to be consistent within your paper and, ideally, also with related key literature (e.g., Cogley

et al., 2011; Hock, 2003). Also, be careful when comparing point with glacier-wide, or seasonal to annual degree-day factors.

L208ff: The scaling of precipitation data includes major assumptions and comes with significant uncertainties. It would be good to add a corresponding discussion, and you might consider including it in your sensitivity experiment.

L224-225: Do you find a similar “trend” and/or “variability”? Please clarify.

L225: Figure 6 is a “comparison” rather than a “validation”. Please clarify.

L228: Avoid acronyms in the title.

L229ff: Maybe something for the discussion concerning this Method section: How well are annual firn layers (or end of summer horizons) detectable at high-altitude sites? Possibility of complete melting of firn layers in extreme years 2022/23/24? Disturbance & mass transfer through strong melt events?

L262: Consider adding the R^2-value (0.88) to Figure 7.

Results

L285: “… to a depth of 5 m”. From Figure 9, I would rather say at 4m at Ewigschneefeld (Site 1); for Mönchsjoch (Site 2), the fluctuations continue to the end around 5.5 m. Please clarify.

L292: “precipitation rate” or “accumulation rate”? Please clarify.

L295: What is the “effect of elevation difference”? Spatial variability or precipitation-elevation gradient? What about the temperature-elevation gradient?

L300ff: The difference between the SWE (420 mm vs 740 mm) is mainly due to the different depths of the snow pits, right? It might be better to compare the values at the common maximum depth. Please clarify.

L307-309: What influences the maximum depth of the reflection pattern? Mainly density? Please clarify.

L315ff: Could the change in density in Fig. 11 also originate from the percolating and refreezing meltwater from the intense summer melt of recent years?

L319: Instead of “testing and calibration”, I would have expected a “calibration and validation” of the firn compaction model. Do you use these terms instead because you do not trust your glaciological and geophysical observations enough? Or is it related to missing uncertainties? Please clarify.

L340: Does the difference in density between model and glaciological observations indicate a process (e.g., refreezing) not included in the model? Please clarify.

L347: Avoid acronyms in titles. Write “accumulation” with a lowercase "a".

L350: Is “lowest winter precipitation” correct, or should it be “lowest winter accumulation”?

L355: The average of a summer balance that varies between accumulation and ablation might be misleading. Consider rewriting with a focus on the change from summer-accumulation to summer-ablation regime.

L370: Based on what evidence/observation/indication did you expect some remaining firn at Mönchsjoch and Ewigschneefeld? Please clarify.

L386ff: Can you provide more details on how you estimated SWE within each layer? Simply by the geometry of layers and density within layers? Does this estimate consider meltwater penetration through layers? Please clarify.

L388: "suggesting higher precipitation and lower melt": AND/OR?

L399: "…leading to lower accumulation as elevation decreases." I think lower annual net accumulation could also result from similar winter accumulation, but a less positive or negative summer balance with lower elevation. Consider and maybe rephrase.

L390: I think the uppermost layer (above the last summer horizon) is a special case since you only have winter accumulation but no summer balance (yet).

Discussion

L401: What are you referring to with "extreme weather" – "extreme" in a statistical sense, or just "extreme" with respect to "normal" lowland weather conditions? Please clarify.

L431ff: This section about firn densification modelling remains a bit fuzzy. Can you be clearer about lessons learned and conclusions for future use?

L447: From Fig. 12, I would not say that "the offset at shallower depths disappeared". Instead, I would say the offset could be reduced. Check and consider reformulation.

L457: "…the tested models consider …, liquid water percolation and refreezing…" What could be learned from the model on the effect of the extreme melt events of the past few years? Please clarify.

L456ff: The section on "Sensitivity of field results" seems valuable. However, I found your conclusions difficult to understand. Are there any other relevant parameters that should/could be checked? Or do you consider velocity picking to be the main uncertainty?

L465: Do you consider a velocity picking uncertainty of 0.005 m ns^{-1} to be a typical or maximum uncertainty? How does Fig. 14 show the effect of an uncertainty of 1 ns? Please clarify.

L473-474: "Therefore, it is practical to use the mean TWT to estimate SWE along the GPR transect for the identification of the annual firn layer." Is this a justification for your approach or a conclusion for other studies? What is the corresponding state-of-the-art? Please clarify.

L475ff: The section on "Accumulation history and spatial firn distribution" is very interesting, but it is difficult to understand your main findings. As such, it would be interesting to be more specific about the advantage of your approach compared to that of Sold et al. (2015). Can you simulate the difference?

L475ff: The comparison to the earlier study (on the same GPR tracks) by Bannwart et al. (2024) is limited to one qualitative statement. It would be great to see a quantitative comparison of the results from both studies if feasible. Is it possible to link the GPR profile from the Ewigschneefeld? Do we see similarities or differences in the density profiles from the firn cores?

L478: "…it should be noted that not all IRHs necessarily represent annual firn layers." What else could they represent? Please clarify.

L484: "We assessed the role of extreme events…". How is your modelling affected by these extreme events? Do you expect some misinterpretation? Or do the models open the possibility for a detection & attribution of such events? Please clarify.

L491: "providing evidence for the survival of the 2022 firn layer." What evidence do you have? Please clarify.

L510: "The lack of CMP data at the lower part…". What was the reason of not having CMP data for Site 1?

Conclusions

L540ff: The Conclusions would benefit from rewriting, providing more structure, and highlighting key findings better: what was done;, what are the key results with respect to the accumulation history of Grosser Aletschgletscher, and from a methodological point of view; (what did we learn from a comparison to the earlier survey by Bannwart et al., 2024); what are recommendations for future work.

Appendix

L563, Fig. A1: I do not see a need for an appendix for one single figure and, hence, would rather integrate it into the paper.

L564ff: Data availability: For your own results, I strongly support publishing the dataset in a public repository such as Zenodo (https://zenodo.org/) or Pangaea (https://www.pangaea.de). For external input data, you can provide corresponding references (e.g., GLAMOS, MeteoSwiss).

L567ff: Author contributions: Who was responsible for the Community Firn Model runs and analysis?

Figures and Tables

All: Please improve the structure of the caption (see general comment).

Table 1: For the readability of the table, I would explain the acronyms (GRP, CMP) in the caption.

Fig. 1: Consider adding a note explaining why there is no CMP at Site 1. Regarding the background image, information on the platform, sensor, and date would be more relevant than the format. I suggest complementing Figure 1 with an additional Table summarizing the different observations per Site (1, 2, 3, 4), including locations, elevations, and survey dates.

Fig. 2: Consider adding the temporal interpretation of the internal reflection horizons (red lines). Indicate locations of other measurements (e.g., SP3, CMP3, SP1). It might be helpful to add a

comment on the elevation range from left to right of the profile and on prominent features, e.g., the merger of reflection horizons at a Distance of 1500m (melt of layers at lower elevation?) or the interpretation of the reflection horizon at a Time of 125ns between red lines.

Fig. 3: Consider adding the temporal interpretation of the internal reflection horizons (red lines). Add information on the location of this CMP(3?) with a reference to Fig. 1. Consider showing all CMPs in one figure for comparison.

Fig. 4: Explain all (colored) elements in figure, i.e. red lines (left), blue-green-yellow-red color range (right); xxx (right). Add information on the location of this CMP(3?) with a reference to Fig. 1.

Fig. 5: The caption does not seem consistent with the labels in the figures: “summer mass balance” (y-axis) versus “ablation” (caption)? “Degree-day” or “melt” factor? How does the width of the bars correspond to the (calendar or hydrological) years of the x-axis? Interestingly, there seems to be a correlation between summer balance and degree-day factor, maybe due to a feedback mechanism? What is the survey period of the summer balance? Was this consistent for all years?

Fig. 6: Provide information about the two graphs' trend, bias, and correlation.

Fig. 7: Consider adding a note on the density jumps at 3-5m, 12-17m, 23-27m.

Fig. 8: Consider adding the thickness of the ice lenses as values to the graph (e.g., next to the left y-axis). Consider adding a note on the density jump between the end of the red and the start of the brown line.

Fig. 9: Consider adding a note on the location of the end-of-summer horizons.

Fig. 10: Consider adding the data from Site 1 to this plot, too. Brown and orange horizontal bars are hard to differentiate. Consider adding the thickness of horizontal layers as values to the plot (e.g., right side).

Fig. 11: Avoid or explain the use of acronyms in the caption. Consider adding a note on the break in the velocity and density profiles at a depth of about 15 m.

Fig. 12: There seems to be an offset between snow pits/core and CMP values at common depths. Consider adding a corresponding note to the caption and/or cover in Discussion.

Fig. 13: Improve readability of the figure by separating bars of summer and annual balance. Add a horizontal line at zero balance. As a source, I would add a reference to GLAMOS (2024), and thank A. Bauder in the Acknowledgements.

Fig. 14: Does the x-axis provide calendar or hydrological years? Correct text to “43-72 mm w.e.”. Consider adding a note explaining the lack of markers, e.g. red in 2021/22, red and orange before 2014. Add a horizontal line at zero balance. Consider labeling the years/dates of the estimated reflection horizons in Figs 2,3,4.

Fig. 15: Does the white at the bottom of the graph refer to ice (density >850 kg m-3) or the maximum GPR depth? Consider adding year/date labels to the identified firn layers.

Fig. 16: Is “Accumulation” the correct label for the color legend, or should it be “SWE”?

References

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