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Interactive comment on "Evaluating continuous and autonomous snow water equivalent measurements by a cosmic ray sensor on a Swiss glacier" *by* Rebecca Gugerli et al.

Anonymous Referee #1

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General comments

This paper presents the application of a sub-merged cosmic ray sensor (CRS) on a Swiss glacier to derive daily snow water equivalent (SWE) values for two winter seasons. An additionally installed snow depth (SD) sensor was used to calculate the snow density by CRS SWE and SD. For validation, some manual field measurements were conducted within the two years and precipitation recordings from nearby weather stations as well as a gridded precipitation product were scaled to compare them with the measured CRS SWE. The measurement results derived by CRS are very plausible for snow accumulation, densification and ablation phases. In general, this paper is well

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written and is, in my opinion, a good contribution to this journal. All measurements are well described and indicated by potential uncertainties and illustrated by significant figures. However, the main focus/objective of this paper has to be better defined. Are you rather interested in gaining better snow density information or are you mainly focusing on using and validating CRS measurements especially on such a glacial test site, or both? Please emphasize on this – maybe also the title has to be changed accordingly. In some paragraphs, references should be added or revised. Below, I indicated some other moderate to minor issues.

Specific comments

Please use the same units throughout the paper. SWE is usually given in mm (or kg/m^2), not in cm w.e.

Abstract

- p.1, l.12-16: The aspect of the comparison of the cosmic ray SWE values and the scaled precipitation is represented quite dominant in the abstract. I think this aspect can be reduced to two 2 sentences and the abstract should better include also a statement on the general applicability.

1. Introduction

- p.2, l.2: Not only the cold and windy conditions are a big challenge for in situ snow measurements in high mountains; please add that they are also often limited by difficult accessibility, complex terrain etc.

- p.2, l.13-21: The statements in this paragraph should be revised carefully as some statements are not correct. Some explanations are given in the following: Schmid et al. (2014) combined the upGPR with a snow depth sensor to additionally derive the liquid water content in snow. The main reasons for combining upGPR travel time with GPS signal strength in Schmid et al. (2015) were to eliminate an overestimation in snow depth during wet snow conditions, which would be the case by using only upGPR

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measurements, and to be independent of poles as both sensors were buried beneath the snowpack, which could be useful, e.g., in avalanche prone slopes. Moreover, with this upGPR-GPS sensor combination it was possible for the first time to derive SWE, snow height and liquid water content simultaneously. Schmid et al. (2015) is not suitable as reference in l.20 and Heilig et al. (2009) not for SWE measurements. Besides citing Steiner et al. (2018), Henkel et al. (2018, TGRS) and Koch et al. (2019, WRR) should be added as references in l.20. Besides snow accumulation, the GPS techniques derive snow properties under snow ablation/melt conditions. Additionally, in the latter reference, it was possible to derive three snow cover properties (SWE, snow depth and LWC) simultaneously with only one sensor setup.

- In general, a statement on remote sensing approaches to derive snow cover properties in alpine areas is missing (e.g. l. 31ff) – please give a short overview on such techniques.

- p.3, l.23: I would not name it 'in a second application'. This is rather a further type of validation (besides your manual SWE measurements) for CRS SWE.

2. Study site & 3. Data

- I would suggest to merge sections 2 and 3.

- p.4, l.2: Although you have mentioned the altitude of your study site in the introduction, this should definitely also be mentioned in this section.

- p.4, l.10f: How fast does the glacier move? Is there an effect on the measurements (e.g. on the SD sensor installed on a pole)?

4. Methods

- I would suggest including Subsection 4.1 in Section 3.

- The title of Subsection 4.2 might be misleading – it would be better to directly refer to CRS SWE and generally separate between SWE and snow density derivation.

- p.7, l.26: Please insert a reference for the empirical parameters.

- p.8, Table 3: Not sure if it really makes sense and is sound to use for the gap filling different meteorological parameters from different stations (e.g. temperature from station a, humidity from station b etc.). In my opinion, rather one station with an overall best fit of all parameters should be used. Please state on this.

- p.8, l.1: Please use just one unit for SWE (either mm or kg/m^2). Regarding SD – in the figures, you use [cm] and here you define SD in [m] – this should be uniform throughout the paper.

- p.9, Fig.2.a: Actually, no red or black crosses are visible in the figure (only red and grey horizontal lines) – please state on this and/or correct. Moreover, the error bars are not really readable. A revised version of this figure would be helpful (it could make sense to display the error bars in a separate figure).

- p.10, l.8: Please introduce N or do you mean Ni?

- p.10, l.10: Why did you chose +/- 1cm? Can this be underlain with a reference?

- p. 10, l.19: In an earlier section you mentioned 4.8 m instead of 4.75 m – please unify.

5. Results

- p.14, Fig.3: Please describe the vertical dashed lines in the figure caption or in a legend. In general, this figure would benefit to be displayed larger (if possible).

- p.15, Fig.4: I really like this figure!

- p.17, l.22: You should underlie the statement of rain gauge undercatch with a reference.

6. Discussion

- Please add the following points in the discussion: Is there a general SWE limit by using CRS? How big is the footprint of the sensor and which shape does it have (e.g.

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conical)?

- p.22, l.12: Please specify why there might be problems between 90 and 120 cm.

- p.22, l.26-30: Please insert references in this paragraph.

7. Conclusion

- As this study investigates to a quite big extent the development of the snow density at your study site, this should also be mentioned more prominently in the conclusions section.

Appendix A

- In my opinion the appendix should be integrated in the methods section.

- p.25, l.12: Please introduce N also in the text.

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