Author Response to Reviews of

Evaluating continuous and autonomous snow water equivalent measurements by a cosmic ray sensor on a Swiss glacier

Rebecca Gugerli, Nadine Salzmann, Matthias Huss and Darin Desilets

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RC: ***Reviewer Comment***, AR: *Author Response*, ☐ Manuscript text

Anonymous Referee #1

We would like to thank the anonymous referee #1 for his/her time and the thoughtful and constructive review, which significantly improves our manuscript.

Following the suggestions by referee #1 and #2, we decided to adapt the title of the paper to "Continuous and autonomous snow water equivalent measurements by a cosmic ray sensor on an Alpine glacier."

General comments

RC: ***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 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.***

AR: *Thank you for your careful assessment and your constructive feedback. We have investigated the application of the cosmic ray sensor for measurements at challenging sites such as a glacier. The cosmic ray sensor (CRS) has been previously evaluated in the Alpine region (Schattan et al., 2017) and on the Greenland ice sheet (Howat et al., 2018) . To complement these studies, we assessed the application of this device on an Alpine glacier. The primary focus on this study lies on the measurement setup and what new knowledge we gain from such observations. To state this more clearly, we re-wrote the end of the introduction.*

Specific comment

RC: ***Please use the same units throughout the paper. SWE is usually given in mm (or kg/m2), not in cm w.e.***

AR: *We changed the units for snow water equivalent (SWE) to mm w.e., but kept the unit for snow depth (SD) as cm.*

Abstract

RC: ***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.***

AR: *We reduced the concerned part in the abstract as follows.*

> *~~Moreover, we compare daily SWE amounts to precipitation sums from three nearby weather stations located at lower elevations, and to a gridded precipitation dataset. We determine the best-possible scaling factor for these precipitation estimates in order to reproduce the measured accumulation on the glacier. Using only one scaling factor for the whole time series, we find a mean absolute error of less than 8 cm w.e. for the reproduced snow accumulation. By applying temperature-specific scaling factors, this mean absolute error can be reduced to less than 6 cm w.e. for all stations.~~ The continuous SWE measurements can be used, for example, to validate scaled precipitation measurements from nearby rain gauges at lower elevations. With these, we can reproduce snow accumulation with a mean absolute error of less than 80 mm w.e.*

1. Introduction

RC: ***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.***

AR: *We included a paragraph on remote sensing approaches.*

> *Besides the in situ manual and autonomous measurements, spaceborn sensors can estimate snow cover, SWE and SD. While these sensors have a large spatial coverage, their resolution is coarse. In addition, estimates of SWE are strongly affected by snow properties such as the snow crystals and the liquid water content which make accurate estimations challenging (Clifford, 2010, Dietz et al., 2012).*

RC: ***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.***

AR: *We added a further sentence to explain the limited accessibility and complex terrain.*

> *Cold and windy conditions pose the main challenge for accurate measurements (Sevruk et al., 2009, Rasmussen et al., 2012, Kinar and Pomeroy, 2015). The complex topography and limited accessibility add further challenges in high mountain regions.*

RC: ***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 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.

AR: *We revised this paragraph carefully, and changed it as follows.*

> *~~Ground-penetrating radar (GPR) is another method to determine snow accumulation and has been used in various studies (e.g. Heilig et al., 2009, 2010). Schmid et al. (2014) combine a snow depth (SD) sensor with an upward looking GPR (upGPR) installed within the ground below the snowpack. This combination results in continuous estimates of liquid water content, SD and SWE at a high temporal resolution. SWE derived from this method lies within ±5% discrepancy from manual measurements. In a follow-up study, Schmid et al. (2015) combined an operational upGPR with a low-cost GPS to render the approach independent from additional sensors (e.g. SD). Despite the good agreement with manual measurements of SWE, the underlying algorithm to derive SWE from the upGPR is still prone to errors. For instance, a deviation of 10% in SD may lead to an over- or underestimation of 30-40% of the resulting SWE (Schmid et al., 2014). Furthermore, erroneous identifications of the reflection horizons affect the resulting SWE (Heilig et al., 2009; Schmid et al., 2015).~~*
> *Ground-penetrating radar (GPR) systems, which are installed below the snowpack and look upwards, provide information about the snow stratigraphy (Heilig et al., 2009) and SD (Heilig et al., 2010, Schmid et al., 2014). Combined with a low-cost GPR, Schmid et al. (2015) derived the liquid water content, SD and SWE without additional information and independent of installation poles which makes it suitable for avalanche prone slopes. In more recent studies, Steiner et al. (2018) and Henkel et al. (2018) present sub-snow low-cost GPS as a promising method to continuously derive SWE. Koch et al. (2019) extend these studies by using the GPS signals to additionally derive SD and liquid water content. However, the processing of the GPS signal is relatively complex and different for dry- and wet-snow (Koch et al., 2019).*

RC: ***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.***

AR: *In general, we have more confidence in the CRS SWE than in the scaled precipitation measurements. For this reason, we scaled the precipitation events to fit the accumulated snow on the glacier and validate it with the CRS SWE measurements.*

2. Study Site & 3. Data

RC: ***I would suggest to merge sections 2 and 3.***

AR: *We added the section "Study site" under 3. Data.*

RC: ***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.***

AR: *We agree and added the altitude of the installation location. In addition, we added the elevation bands of the glacier in the text as follows.*

> *Plaine Morte is particular in that it has almost no elevation gradient. In fact, most of the glacier surface is located between 2650 masl and 2800 masl (GLAMOS, 2017). With a surface area of 7.4 km^2 it is the largest plateau glacier in the European Alps.*

RC: ***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)?***

AR: *Due to the flatness of the glacier, the surface velocity is small (in the order of 2-5 m per year, Huss et al., 2013). Especially at the site of installation, glacier movement is negligible and does not affect the measurements.*

4. Methods

RC: ***I would suggest including Subsection 4.1 in Section 3.***

AR: *We understand this point, but we decided against including subsection 4.1 into Section 3 because we consider it a method rather than data.*

RC: ***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.***

AR: *We split this section into two sections. The first one is about calculating SWE from neutron counts and its uncertainties, and the second one is about calculating the bulk snow density and its uncertainties.*

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

AR: *The empirical function and its paramteres have been previously used by Howat et al. (2018). We added this reference accordingly.*

RC: ***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.***

AR: *We absolutely understand this point of view. With regard to physical consistency, it makes sense to only use* *one station. Because we have the independent SWE measurements, the physical consistency of the gap fill is not that important here. Snow depth is the most important parameter with missing data. Thus, we wanted the best-possible correlation for snow depth (SLFGA2). The correlation for temperature and relative humidity does not differ greatly between SLFGA2 and SLFDIA. But it differs for wind speeds. Therefore, we decided to use temperature and humidity from SLFDIA, while using wind speeds from SLFGU2. In general, wind components are more variable in complex terrain than temperature and relative humidity. Given the good correlation of SD with SLFGA2, the effects of wind speeds on the snow dynamics do not seem that important. In conclusion, we assume that the best choice for this study is to use different stations for the gap filling. Concerning the results, the results in Fig.7 a, b would remain similar because the correlation is in the similar range. For Fig.7d, it does not change because the gap is not presented due to the missing wind direction (where we decided not to fill the gap due to the high variability).*

RC: ***p.8, l.1: Please use just one unit for SWE (either mm or kg/m2). Regarding SD – in the figures, you use [cm] and here you define SD in [m] – this should be uniform throughout the paper.***

AR: *We adapted the units to mm w.e. for SWE and cm for SD. To make the equation consistent with the given units, we added a conversion constant (c) with a value 100 cm m^{-1} to Eq.3.*

RC: ***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).***

AR: *The crosses are not visible because the scale is too large for the uncertainties which are given by the raw neutron count. We replaced Fig.2 with the following figure. The uncertainties are discussed separately.*

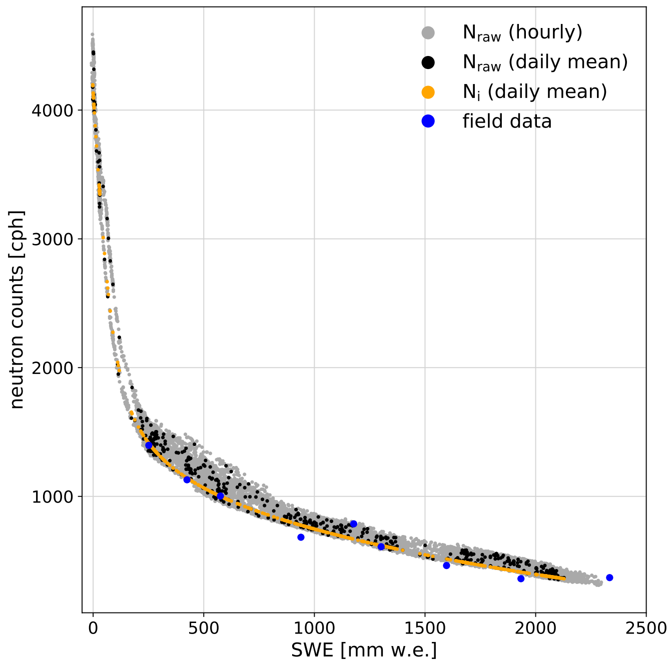

Figure 1: Grey dots are the uncorrected hourly neutron counts and black dots the uncorrected daily means. The orange dots represent the corrected daily means. Blue dots show SWE from the field data and the corresponding neutron counts of the field work days.

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

AR: *N refers to N_i. We will correct it in Eq. 6. and Eq. A.1*

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

AR: *This +/- 1 cm originates from an analysis during snow free conditions (not presented here), so it cannot be underlain with a reference. Nevertheless, we changed the uncertainty estimate of the CRS SWE as suggested by referee #2 to make it more sound. In the new approach, no systematic bias is added.*

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

AR: *We changed it to 4.8 m consistently.*

5. Results

RC: ***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).***

AR: *We added a sentence describing the dashed and dash-dotted line. We also revised this figure to improve the layout.*

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

AR: *Thank you.*

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

AR: *We added a reference of a study that aims at quantifying the undercatch of rain gauges as proposed in the following.*

> *As to be expected, precipitation sums are significantly lower than snow accumulation on the glacier. This is mainly due to orographic effects but could also be caused by snow drift, or undercatch of the rain gauge (e.g. Pollock et al., 2018).*

6. Discussion

RC: ***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. conical)?***

AR: *We added these points in the discussion as follows.*

> *The SWE limit is given by the exponential nature of the conversion equation (neutron counts to SWE). The uncertainty increases with lower neutron counts and consequently a lower N_i to N_0 ratio. At some point, the relative neutron count is no longer sensitive to SWE, and that corresponds to the limits of the device. Additionally, with decreasing neutron counts the noise level becomes large enough to loose the signal.*
>
> *The footprint of the CRS measurements are difficult to define because it is still not well understand how the neutrons are dispersed within the snowpack. Schattan et al. (2017) give an estimate of around 230 to 270 m, but their footprint is based on an above ground CRS. As the instrument in this study lies below the snow pack, the footprint is different. The CRS measures from all sides and with the dispersive nature of the neutrons, measures the surrounding snow pack. Most likely, the footprint is in the range of a couple of meters around the CRS, but further studies are needed to investigate this.*

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

AR: *Two field campaigns were conducted where SWE amounts were between 90 and 120 cm. Both field measurements differ by more than 15% from the CRS SWE. One of the field measurements is largely overestimated while the other one is underestimated. Because the spread of these two measurements is so large around the fitted curve, we assume that there might be a systematic bias in one of the corrections during one of the field campaigns rather than a misfit. We added this point in the discussion.*

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

AR: *We added some references accordingly.*

> *In general, one could argue that a snow scale or snow pillow would have been more suitable for such an analysis, especially given the higher temporal resolution during the accumulation phase. However, they require a large flat surface (e.g. Egli et al., 2009, Kinar and Pomeroy, 2015). This is not given at our study site because of the surface roughness of the ice, the lack of a large flat surface and the changing surface by ice melt during the summer season. In addition, ice bridging would have been problematic. For sub-snow GPS, potential problems might occur due to glacier ice flow or the surface melting which would affect the position of the GPS. In addition, data processing is different for dry and wet snow and is therefore more complicated (Koch et al., 2019).*

7. Conclusion

RC: ***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.***

AR: *We added the following paragraph about density evolution in the conclusions.*

> *With this measurement setup, we could show that all phases of the snow pack from accumulation over densification to ablation are distinguishable because of the pronounced relation between SD and SWE. Throughout the accumulation phase, snow densities are low with periodical cycles of snowfall and subsequent densification. Densities reach maximum values around 400 $\mathrm{kg\,m^{-3}}$. When the maximum in SWE is reached, the snow pack begins to densify continuously before it begins to melt. During the ablation phase, densities remain almost constant.*

Appendix A

RC: ***In my opinion the appendix should be integrated in the methods section.***

AR: *We agree and integrated it in Section 4.2.*

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

AR: *We will replace N with N_i to render the equations consistent.*

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