Referee #2 – Authors reply

In the following, we provide a point-to-point answer to the referee's comments. The referee's comments start with RC:*, authors replies begin with AR: and are formatted italic with light-blue color.*

A markup of manuscript changes are shown in boxes with new text in dark blue and ~~removed text in red.~~

RC: This brief communication on the ‚Application of a muonic cosmic ray snow gauge to monitor the snow water equivalent on alpine glaciers' by Gugerli et al. gives a comprehensive introduction to a new cosmic ray sensor to monitor SWE at a point scale. The manuscript is well structured and gives comprehensive information on the applied methods and results. Moreover, the authors try to discuss their results carefully and point out potential uncertainties and further steps. Of course, it would be nice to get more detailed information on the method itself, however, for the chosen type of manuscript (brief communication) the length and amount of given information is well suited. In general, I see a great need in investigation of new sensor systems as presented here, as we still lack continuous in situ SWE measurements in alpine areas for various applications. I only have some minor points:

AR: We thank the Referee #2 for the time dedicated to our manuscript and the positive and constructive feedback, which will significantly improve it.

RC: Was the glacier surface already covered by snow at the date of installation (6 December 2020)? If yes, the natural snow cover was most likely destroyed by shovelling, which could have an impact on the results, especially at the beginning of the winter period. Please state on this.

AR: Unfortunately, we were not able to deploy the muon detectors before the snowpack started building due to logistical constraints. At the time of deployment of the muon detectors, the snowpack was already 140 cm deep (snow depth). In addition, the snow was very powdery and manual measurements were challenging.

The referee is right that it could influence the results of the µ-CRSG. As the n-CRSG was already deployed prior to the first snowfall, this instrument is not influenced. Comparing the inferred SWE from the n-CRSG with the µ-CRSG at the beginning of the season, the evolution is very similar. Due to the nature of the derivation of the conversion function, which uses the first manual measurement that is strongly underestimated by the n-CRSG, a bias is to be expected. We added a paragraph discussing this point.

[Section 4.1]

When the muon detectors were deployed in December 2020, the snowpack had a depth of 140 cm with a SWE of 393±98 mm w.e. (16 December 2020).

[Section 4.2]

Furthermore, the deployment of the µ-CSRG on 16 December 2020 disturbed the snowpack above the sub-snow µ-CSRG. This disturbance does not seem to have a significant influence on the estimated SWE as the evolution in SWE agree well at the beginning of the season. In addition, the bias between the two devices could also be related to the strong underestimation of the first manual field measurements (16 Dec 2020) by the n-CRSG

RC: What is the distance [m] between the buried neutron comic ray sensor and the buried muonic cosmic ray sensor? At what distances where the manual measurements carried out? I agree with Reviewer 1 on his point 2 – referring the measurements to a common snow depth should be applied if available (if not, please discuss this issue carefully).

AR: Concerning the distances between the n-CSRG and µ-CRSG, we added a photo in the supplement. The manuscript type "Brief communication" is restricted to three figures (see responses to Referee #1)

Concerning the validation of the SWE estimates by the n-CRSG, we adapted the validation of the n-CRSG as also suggested by Referee #1. The adapted validation is based on SWE derived by the manually obtained bulk snow density multiplied with the autonomous snow depth estimates. It generally improves our results.

RC: Please add the RMSE (besides R^2) to describe the accuracy between manual SWE measurements and n-CRSG-derived SWE (Section 3.1.2).

AR: We added the RMSE value (see manuscript excerpt above).

The 22 manual measurements are significantly and highly correlated with a coefficient of determination of 0.969 (Fig. 1a). On average, then-CRSG agrees with the manually obtained SWE with an underestimation of ~~-1~~ -2% and an uncertainty of ~~±12~~ ±10% (one standard deviation, Fig. 1b). The root mean square error amounts to 112 mm w.e. Please note that 50% of the manual field observations are obtained in snowpacks deeper than 1130 mm w.e.

RC: The two-part or eventually also three-part conversation function needs more explanation and background information (Section 3.2.2).

AR: In general, we agree. But we would also like to point out that this is a brief communication of a study with limited funding. We wish to show that results are promising enough to justify continued research on the method, and that the remaining questions are tractable.

We added the following to the manuscript to provide more explanations and background information.

[Section 4.2]

In the conversion function presented here we account for this transition in the attenuation length of muons with increasing SWE. To the best of the authors knowledge, however, no other data is currently available to derive a conversion function that is suitable for this glacierized site. Thus, our conversion function relies on the manual field measurements. While this results in a good agreement between µ-CRSG SWE and n-CRSG SWE, some limitations remain. With the fit between relative muon count rates and manually obtained SWE, the condition of having 0mm w.e. for a relative muon count rate of 1.0 is not fulfilled. Either a third part of the conversion needs to be introduced, or the fit needs to be repeated with more manual measurements. The transition within the conversion function could be caused by a softer component of the ionizing radiation from secondary cosmic rays. The ratio of the soft and hard component could also be location and especially elevation dependent. Hence, a site-specific calibration could be necessary. Nonetheless, this remains highly speculative and further measurement experiments would be needed to investigate it in more depth.

A robust statistical evaluation of the presented conversion function is not possible nor representative because only two manual field measurements remain independent.

[Section 5]

In future studies, more manual measurements, further measurement experiments and simulations can improve our understanding of this measurement approach in addition to validate the presented conversion function.

RC: (How) does the footprint of this in situ measurements change with an increasing snowpack?

AR: The extent of the footprint of the n-CRSG remains subject to further studies, and thus only assumptions can be made. We believe that the footprint is cylindrical, and depends on the depth of the snowpack. Currently, a paper by colleagues, which investigates the footprint of the sub-snow n-CRSG with a modelling approach, is in preparation. However, we cannot refer to it yet.

RC: In addition, could you give an assumption how the accuracy of the novel method changes with an increase of SWE?

Concerning the accuracy of the µ-CRSG, we assume a similar behavior as for the n-CRSG, i.e., the precision is mainly defined by the statistical uncertainty of the count rate, which depends on the depth of the snowpack. Gugerli et al. (2019) estimate the precision of the n-CRSG with error propagation and an uncertainty assumption for each parameter used to calculate SWE from the neutron count rate. As we deployed two µ-CRSG, the same approach would only include the uncertainty of the count rates by the sensors propagated through the conversion equation.

We modified the following paragraph.

[Section 4.3]

Based on the theoretical precision estimation, the µ-CRSG promises to infer sub-daily SWE estimates with a higher precision than the n-CRSG. In addition, the hourly observations vary less around the daily mean for the µ-CRSG than for the n-CRSG (Fig. 3b). Nonetheless, the µ-CRSG contain some inter-daily fluctuations that are larger in the µ-CRSG estimates than the n-CRSG. To understand these, further investigations are needed.