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
The Cryosphere Discussion, doi:10.5194/tc-2019-106

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

Anonymous Referee #2

We would like to thank the anonymous referee #2 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 change 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 evaluates the snow accumulation on the Plaine Morte glacier by means of a buried cosmic-ray neutron probe (CRNS) and an approach based on the scaling of the precipitation records of nearby meteorological stations. The accuracy of the field data is assessed by the propagation of possible error sources. Together with the combined approach using different types of field data, this gives important insights into the evolution of the snow pack on the glacier. The language of the paper is appropriate, as are the figures and tables. Partly, the paper would benefit from considering a geographically broader view on the state-of-the-art as many references focus on Switzerland. In principle, the paper is suitable for publication in this journal. In particular, the added value of the paper lies in applying a buried CRNS together with other measurements for continuously monitoring the snow accumulation of a mountain glacier.***

AR: *Thank you for your valuable assessment and the interesting feedback. The state-of-the-art has many, but not only Swiss references. But, we admit that there has been a strong focus on the Swiss observational network. This is to make a direct comparability within the same region easier. Nevertheless, we broadened the state-of-art section by adding more non-Swiss references.*

RC: ***However, prior to further consideration for publication, the following two major concerns need to be addressed carefully:***

AR: *To address these two major concern in more detail, we split the following comment of referee #2 into smaller sections. That allows us to directly address each comment point by point.*

RC: ***(1) The story line of the paper needs to be clarified. The title and the final conclusions do not match well with the analysis made. Furthermore, the second part of the analysis is not (yet) connected to the rest of the paper. One could think of some logical links between the two parts, but it is important to state this***

more clearly, and to frame the rest of the paper accordingly. In addition, it would help the reader if the novelty would be more pronounced in the abstract and the conclusions.

AR: *The main focus of the paper is to assess the application of a CRS in combination with the sonic ranging sensor for continuous snow water equivalent (SWE) and snow depth (SD) measurements on glaciers, and to show the advantages of such a measurement setup. We discuss the advantages of such a measurement setup and show what kind of knowledge we can gain, also in regard to precipitation scaling at high altitudes. Applying a scaling factor on precipitation estimates is a common approach when no in situ measurements are available. We re-framed the story line of the paper accordingly, following this story line. In addition, we rephrased the end of the introduction explaining more clearly the links between the CRS measurements and the precipitation scaling.*

RC: ***(2) While the error propagation of the snow depth, snow density and the meteorological measurements is reasonable and covers all important sources of uncertainty, this is not the case for the CRNS data. Most notably, the instrument's precision is most likely largely overestimated.***

AR: *We would like to point out that we differ between precision and accuracy, which we both call an uncertainty. With the error propagation, we calculate the precision of the instrument. With the field data, we could validate the CRS measurements and show that it slightly overestimate SWE amounts in average within ±13%. So our accuracy is rather ±13% than what the precision analysis showed. In addition, we believe that the comparison to the independent field data is more valuable than the propagated precision of the CRS. We will emphasize this point more strongly in the paper. In addition, we calculated an error propagation taking into account all relevant sources of uncertainty. More information is provided with the following comments.*

RC: ***Furthermore,a decrease of the error with increasing SWE is highly unlikely with mostly likely the opposite behaviour being the case. Currently, only the uncertainty of the neutron count rate is considered, and a constant error is added despite the high non-linearity of the signal. The latter is probably the reason why the relative accuracy seems to increase with higher snow accumulation values.***

AR: *Fig. 2 shows that the absolute uncertainty σ_{crs} increases with higher SWE amounts. However, the rate of increase changes which affect the relative uncertainty. We also point out that in the discussion we wrote "Generally higher neutron counts and lower SWE values place Howat et al. (2018) on a steeper part of the calibration curve which results in more precise results." Howat et al. (2018) use the same measurement device with the same empirical function and parameters. Since we redid the error propagation and removed the constant factor, we also replaced Fig.2 accordingly.*

RC: ***The statistical error of neutron count rate itself is an important element of measurement uncertainty, but it refers to uncorrected variations only. The uncorrected count rate includes variations not only of the accumulated SWE but also variations of incoming neutrons, atmospheric pressure, and in atmospheric moisture.***

AR: *In the new error propagation, we consider the effect of incoming neutrons and pressure. However, we expect the effect of atmospheric moisture on the count rate to be minimal (once the probe is buried). Work with the CRNS as a soil moisture sensor suggests that atmospheric moisture may affect N_0 by some small amounts. But this is actually not known (Rosolem et al., 2013).*

RC: ***An error propagation should thus include the uncertainty of (1) the neutron count uncertainty as already done, (2) the uncertainty of the measurements used for the corrections (Jungfraujoch neutron monitor***

data, atmospheric pressure, atmospheric moisture), (3) the uncertainty in the parameterisation of the correction functions (e.g., the value for the attenuation length, which may vary in space and time), and (4) the uncertainty in the (not well documented) empirical function relating neutron counts to SWE. In total, from figure 2 the error seems to be rather in the range of 10 to 20% (and thus around ten times larger than estimated in the paper!), with an increasing trend for high SWE values. Also the comparison with the manual measurements (figure 3) shows that the SWE from CRNS is mostly only touching the uncertainty bands of the manual measurements, while is partly entirely off.

AR: *We added the following part to the manuscript taking into account not only the uncertainty of the neutron count itself, but also of the measurements used to correct that neutron count. We admit that the precision is not equal to the accuracy of the CRS, and that claiming such an high accuracy as we have a precision would be too optimistic. However, we believe that a proper uncertainty estimate of the empirical function and its parameterisation would provide enough material for a paper on its own. Therefore, we consider it to be too much for the scope of this paper. But, we added a section in the discussion, where we critically discuss all sources of uncertainties, mainly points (3) and (4) given by referee #2. With this approach, we hope to address this major concern appropriately.*

The calculated SWE amounts depend only on the relative neutron counts as the empirical equation is fitted for relative neutron counts. Therefore, we base our error propagation on all corrections applied to the raw neutron count up to the calculation of the relative neutron count. For the corrections we use

$$N_{\mathrm{rel,i}} = \frac{N_i}{N_0} = N_{\mathrm{raw,i}} \cdot (\beta \cdot (\frac{F_{\mathrm{inc,i}}}{F_{\mathrm{inc,0}}} - 1) + 1) \cdot exp\left(\frac{p_i - p_0}{L}\right) \cdot \frac{1}{N_0} \tag{1}$$

The raw neutron counts N_{raw}, the incoming neutron flux ($F_{\mathrm{inc,i}}$) and air pressure (p_i) change with time, but remain independent from each other. Following the rules of error propagation of a non-linear equation, we approximate the uncertainty of $N_{\mathrm{rel,i}}$ as

$$\begin{aligned}\sigma^2_{N_{\mathrm{rel,i}}} \approx \left(\frac{\partial N_{\mathrm{rel,i}}}{\partial N_{\mathrm{raw,i}}}\right)^2 \cdot \sigma^2_{N_{\mathrm{raw,i}}} + \left(\frac{\partial N_{\mathrm{rel,i}}}{\partial N_0}\right)^2 \cdot \sigma^2_{N_0} \\ + \left(\frac{\partial N_{\mathrm{rel,i}}}{\partial F_{\mathrm{inc,i}}}\right)^2 \cdot \sigma^2_{F_{\mathrm{inc,i}}} + \left(\frac{\partial N_{\mathrm{rel,i}}}{\partial F_{\mathrm{inc,0}}}\right)^2 \cdot \sigma^2_{F_{\mathrm{inc,0}}} + \left(\frac{\partial N_{\mathrm{rel,i}}}{\partial \beta}\right)^2 \cdot \sigma^2_{\beta} \\ + \left(\frac{\partial N_{\mathrm{rel,i}}}{\partial p_i}\right)^2 \cdot \sigma^2_{p_i} + \left(\frac{\partial N_{\mathrm{rel,i}}}{\partial p_0}\right)^2 \cdot \sigma^2_{p_0} + \left(\frac{\partial N_{\mathrm{rel,i}}}{\partial L}\right)^2 \cdot \sigma^2_{L}\end{aligned} \tag{2}$$

The uncertainty $\sigma^2_{N_{\mathrm{rel,i}}}$ is then propagated through

$$SWE_i = -\frac{1}{\Lambda} \cdot \ln N_{\mathrm{rel,i}} \tag{3}$$

to estimate the uncertainty σ_{crs}

$$\sigma_{\mathrm{crs}} \approx sqrt\left(\frac{\partial SWE_i}{\partial N_{rel,i}}\right)^2 \cdot \sigma^2_{N_{rel,i}} \tag{4}$$

For each variable, we attributed an uncertainty to the best of our knowledge and supported by literature. The uncertainties are not always known, therefore we assume rather generous estimates for the uncertainties. Where possible, we base our estimates on literature values. Table 1 gives an overview of these values.

For all neutron counts ($N_{raw,i}$, N_0, $F_{inc,0}$, $F_{inc,i}$), we assume the square root for the uncertainties (σ) (e.g. Zreda et al., 2012, Schrön et al., 2018). With the integration over a time period t, the uncertainty is reduced by $t^{-0.5}$ (Schrön et al., 2018). While the relative uncertainty of N_{raw} varies between 1.5%-5.3% for hourly observations, it varies between 0.3%-1% for the integrated daily estimates.

The incoming radiation has a low uncertainty because its precision is with around 190 counts per second very high. However, incoming radiation needs to be corrected for different sites. This is done with β. Our study site is located less than 40 km (air line) from the Jungfraujoch and is around 900 m lower. Hence, this correction factor (β) is rather small for our site (0.95) and so is its uncertainty (σ_β, 0.03).

The uncertainty given by air pressure (σ_{p_i}, σ_{p_0}) is based on the instruments precision which is 0.1 hPa (Lufft, 2019). For the mass attenuation length L, we use 132 hPa with an uncertainty of $\pm$2 hPa (σ_L). This uncertainty corresponds to the difference of shielding depths from latitudes north and south of Switzerland as shown in Fig.1 of Andreasen et al. (2017).

To render the error propagation more robust, we calculated σ_{crs} using three setups with each the observations and with a dataset where the time dependent variables ($N_{raw,i}$, p_i,$F_{inc,i}$) are uniformly sampled within boundaries defined over their minma and maxima values. This semi-artificial dataset encompasses 4.8$\cdot$10^8 data points.

In the first setup (Fig. 1a,d), the uncertainty is calculated for an hourly resolution. In a second setup (Fig. 1b,e), we consider the integrated daily observations with their given uncertainties (Table 1). In Fig. 1c,f, we limited the uncertainties of the neutron counts ($\sigma_{Finc,i}$, $\sigma_{Nraw,i}$) to a minimal uncertainty of 0.5%. Fig. 1d,e,f show the relative contribution of each parameter to the propagated uncertainty. The contribution is quantified as the relative contribution of the uncertainty terms to the overall uncertainty. The uncertainty terms are defined as the squared derivative multiplied by the squared uncertainty (see also Eq. 2). Fig. 1 shows that the main uncertainty is given by the neutron count uncertainty. The almost equal contribution of several parameters in Fig. 1f is a result of the limited minimal uncertainty. Nevertheless, the neutron count uncertainty clearly dominates also in this setup for higher SWE amounts.

Table 1: Table with all given values and uncertainties. The units cph and cpd stand for counts per hour and day, respectively. Brackets show the minimum and maximum within the time series.

Variables	hourly observations	σ (hourly)	daily observations	σ (daily)
$N_{\mathrm{raw,i}}$	[354; 4450] cph	$\sqrt{N_{\mathrm{raw,i}}}$	[8.5$\cdot$10^3; 1.1$\cdot$10^5] cpd	$\sqrt{N_{\mathrm{raw,i}}}$
N_0	4143 cph	$\sqrt{N_0}$	9$\cdot$10^4 cpd	$\sqrt{N_0}$
$F_{\mathrm{inc,i}}$	[6.6$\cdot$10^5; 7.0$\cdot$10^5] cph	$\sqrt{F_{\mathrm{inc,i}}}$	[1.6$\cdot$10^7; 1.7^7] cpd	$\sqrt{F_{\mathrm{inc,i}}}$
$F_{\mathrm{inc,0}}$	6.9$\cdot$10^5 cph	$\sqrt{F_{\mathrm{inc,0}}}$	1.6$\cdot$10^7 cpd	$\sqrt{F_{\mathrm{inc,0}}}$
β	0.95	0.03	0.95	0.03
p_i	[708; 747] hPa	0.1 hPa	[708; 747] hPa	0.1 hPa
p_0	739 hPa	0.1 hPa	739 hPa	0.1 hPa
L	132 hPa	2 hPa	132 hPa	2 hPa

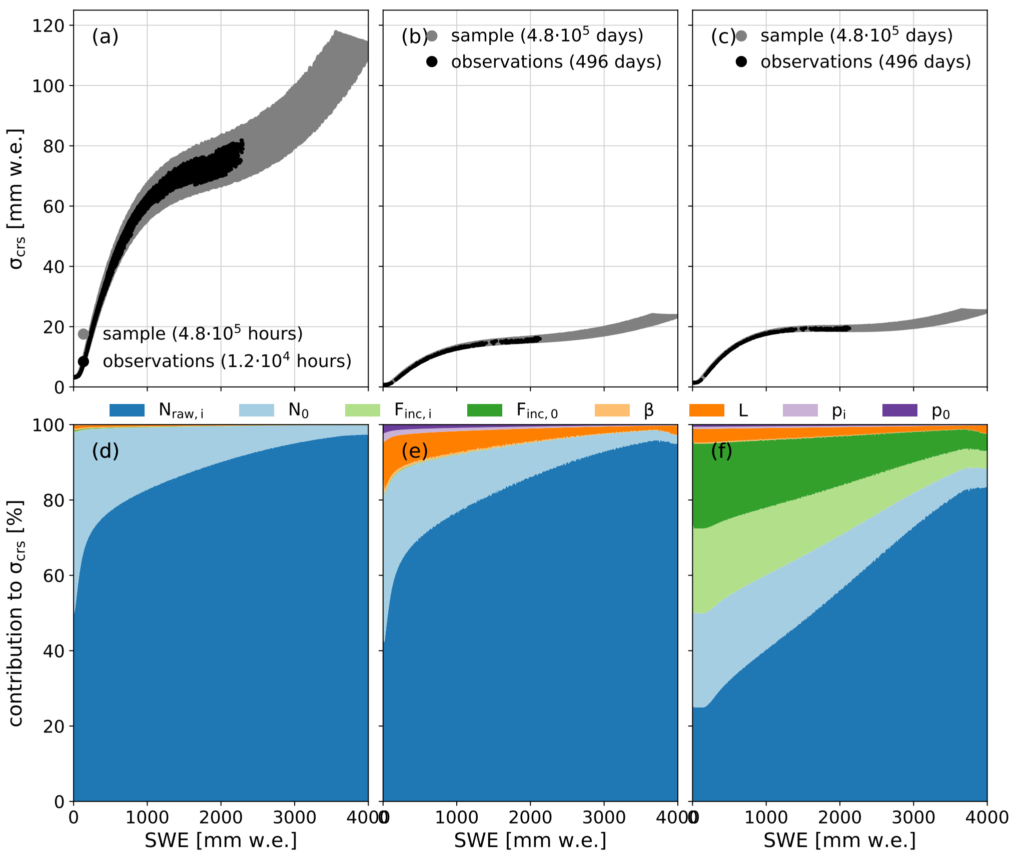

Figure 1: (a)-(c) show the absolute uncertainties as a function of SWE amounts. The grey dots represent a sample data and the black dots the observations. (e)-(f) show the relative contribution of each parameter to the overall uncertainty. (a) and (d) present the results based on an hourly temporal resolution, (b) and (e) show the results of integrated daily values and (c) and (f) integrated daily values with a limited minimal uncertainty of 0.5 %.

RC: ***With the current focus of the paper the lack of a proper error propagation of the CRNS data constitutes a severe issue, as the evaluation and the precision of the CRNS are stated prominently in the title and conclusions. Still, it is interesting to see the application of CRNS for glacier monitoring and I agree with the authors that it constitutes a very promising technique for continuous accumulation measurements on glaciers. Existing uncertainties should, however, be kept in mind instead of propagating an unrealistically high precision of the SWE estimate. I believe there are two equally legitimate strategies on how the authors could address this. One is a true and rigorous error propagation with regard to all relevant uncertainty sources of the CRNS SWE estimate. Another could lie in drawing the reader's attention to the***

fact, that the uncertainty range could be substantially (up to ten times) larger, combined with reframing the paper towards the application rather than the error propagation.

AR: *We integrated a more robust error propagation (see above). We also discussed the accuracy of the CRS with regard to the field data more critically in the coresponding section. Furthermore, we changed the title of the paper to emphasize the focus more on the application.*

Specific comment

RC: ***Page 3/ Line 33-34: Check the sentence ("..define three different scaling factors, one for...“?).***

AR: *We adapted the sentence as follows:*

> *~~In a more elaborate approach, we define three different scaling factor for each weather stations.~~ In a more elaborate approach, we define three different scaling factors, one for liquid precipitation only, one for solid precipitation only and one for mixed-phase precipitation. These scaling factors are defined for each weather station and grid cell individually and depend on in situ hourly temperature measurements.*

RC: ***Page 4/ Line 2: It would be helpful when the elevation of the glacier and the surrounding mountain peaks would be added here.***

AR: *We added the following sentence in the section "Study site".*

> *Our study site is located on the Glacier de la Plaine Morte (in the following: Plaine Morte), where we deployed a CRS along with an automatic weather station (46° 22.8’N, 7°29.7’E, 2690 masl). This glacier is situated on the ridge between two Alpine regions of Switzerland, the Bernese Alps in the North and the Rhône valley in the South (Huss et al., 2013). The glacier is surrounded by mountain peaks from 2926 masl (Pointe de la Plaine Morte) up to 3244 masl (Wildstrubel, see Fig.1)*

RC: ***Page 5/ Line 18: Can you add a few key facts on how the gridded products is produced. Does it contain station data? If so, how reliable is it when the nearby stations have data gaps?***

AR: *We added the following paragraph to address the comment and the question.*

> *RhiresD is based on data from around 400 automatic as well as manual non-realtime quality checked precipitation measurements. In a first step, the climatological mean precipitation measurements for the calendar month of a given day are spatially interpolated. Thereby, regionally varying precipitation - topography relationships are applied. With this interpolation, relative anomalies for a station are calculated for the given day. Adopting a weighting scheme, the relative anomalies are spatially interpolated prior to multiplication with the climatolgocial mean field. Main sources of uncertainty are given by the interpolation, rain-gauge measurements, grid spacing and its effective resolution and the temporal variation of the number of stations. For further information, the reader is referred to the technical document provided by MeteoSwiss (MeteoSwiss, 2013).*

RC: ***Page 6/ Table 2: Think of readers that are not familiar with the Swiss coordinate system. I would recommend converting the station coordinates into a globally used system like UTM or WGS84 (lat/lon). In any***

case, add also the EPSG-code of the coordinate system.

AR: *We added the WGS84 coordinates, but also kept the Swiss coordinate because it is easier to identify the location in the map of Fig.1. Additionally, we added a cross in the lower left corner of Fig.1 with the corresponding WGS84 latitude and longitude coordinates.*

RC: ***Page 7 Line 1: The reliability of the CRNS is one of the objectives, thus could cannot be claimed beforehand.***

AR: *With "reliable" we meant "technically reliable". We adapted the sentence as follows:*

> *Once deployed, the CRS measured ~~reliably~~continuously over the two winter seasons with one exception.*

RC: ***Page 23/ Line 2: the effect is related to SWE not to density.***

AR: *We revised this paragraph carefully, also in regard to all the additional points we added (see above).*

RC: ***Page 23/ Line 8: Here, too much confidence is set into CRNS.***

AR: *In the discussion, we point out all potential influences that could lead to overestimated SWE observations. However, it is also possible that there was a problem with the SD measurements. We tried to give a neutral exposition on both possibilities without pointing towards one or the other instrument. But, it still seems to have been slightly biased towards one direction and therefore, we changed part of that sentence as follows:*

> [..] Therefore, not all these effects would be identifiable, and explanations remain speculative. ~~Despite all potential explanation for errors by the CRS, it could also be a problem with the SD measurements rather than the SWE measurements. In our study setup, several reasons could cause erroneous SD measurements.~~ Given our study setup, erroneous SD measurements cannot be excluded either.

To underline this statement, we show a photo from the mast taken in June 2019 below. We are not intending to add the photo to the paper manuscript. Between the last field work in April 2019 and this one, the site was not visited, and we encountered it with the large depression around the mast itself.

Figure 2: Photo of the mast installation taken in June 2019.

References

Andreasen, M., Jensen, K. H., Desilets, D., Franz, T. E., Zreda, M., Bogena, H. R., and Looms, M. C. (2017). Status and Perspectives on the Cosmic-Ray Neutron Method for Soil Moisture Estimation and Other Environmental Science Applications. *Vadose Zone Journal*, 16(8):0.

Howat, I. M., De La Peña, S., Desilets, D., and Womack, G. (2018). Autonomous ice sheet surface mass balance measurements from cosmic rays. *Cryosphere*, 12(6):2099–2108.

Huss, M., Voinesco, A., and Hoelzle, M. (2013). Implications of climate change on Glacier de la Plaine Morte, Switzerland. *Geographica Helvetica*, 68(4):227–237.

Lufft (2019). Technical data. ventus-umb ultrasonic wind sensor. Technical report, Mess- und Regeltechnik GmbH.

MeteoSwiss (2013). Documentation of MeteoSwiss Grid-Data Products Daily Precipitation (final analysis): RhiresD. Technical Report August.

Rosolem, R., Shuttleworth, W. J., Zreda, M., Franz, T. E., Zeng, X., and Kurc, S. A. (2013). The effect of atmospheric water vapor on neutron count in the cosmic-ray soil moisture observing system. *Journal of Hydrometeorology*, 14(5):1659–1671.

Schrön, M., Zacharias, S., Womack, G., Köhli, M., Desilets, D., Oswald, S. E., Bumberger, J., Mollenhauer, H., Kögler, S., Remmler, P., Kasner, M., Denk, A., and Dietrich, P. (2018). Intercomparison of cosmic-ray neutron sensors and water balance monitoring in an urban environment. *Geoscientific Instrumentation, Methods and Data Systems*, 7(1):83–99.

Zreda, M., Shuttleworth, W. J., Zeng, X., Zweck, C., Desilets, D., Franz, T., and Rosolem, R. (2012). COSMOS: The cosmic-ray soil moisture observing system. *Hydrology and Earth System Sciences*, 16(11):4079–4099.