Reply to Reviewer H. Bogena

We would like to thank you for all the comments, which have helped us improve the quality of our research and submission.

For an easier interpretation of the contents of this reply we decided to adopt the following colour scheme

Reviewer comments

Authors reply

Proposed changes (lines refer to the updated manuscript)

This manuscript presents a network-wide parameterisation to estimate snow water equivalent (SWE) using cosmic ray neutron sensing (CRNS) across sites in the Italian Alps.

The topic is highly relevant and of significant interest to the cryosphere and hydrological communities, and the authors' effort to leverage network information to enhance SWE monitoring with CRNS stations represents a highly valuable contribution.

The manuscript is generally well written, and the approach is promising; however, several major issues related to the representation of the network and the methods, the clarity of the validation procedure, and the robustness of the conclusions need to be addressed before publication. I outline these points in the following major and specific comments.

Major comments

From the 26 sites, only 6 sites were used for calibration and 13 sites for validation. In its current form, the narrative risks implying broader validation than is actually demonstrated, e.g. from the title and the abstract. The authors should clearly and consistently distinguish between (i) the full network, (ii) the calibration subset, (iii) the validation subset, and (iv) sites to which the method is extrapolated. In particular, the abstract and conclusions should avoid wording that could be interpreted as network-wide validation. I recommend explicitly stating the number of sites used for calibration and validation wherever network performance is discussed.

We thank you for this comment. To address it we propose to change every instance where "network-wide" appears with "shared" (including in the title and abstract of the manuscript). We agree with your suggestions and, to improve the clarity of the manuscript, we propose to divide the data and results shown in the following subsets: (i) calibration data (6 sites), (ii) validation data from the same sites used for calibration, and (iii) validation data from (7) additional sites of the network. This modification will be applied both for the methodology description of Section 2 and the results of Section 3 as well as in Figure 2.

Proposed modifications:

Every instance of "sensors" substituted by "probes".

Every instance of "network-wide" substituted by "shared".

New title:

Brief communication: Shared parameterisation for estimating snow water equivalent through cosmic ray neutron sensors in the Italian Alps

Abstract changes:

L24-28: Further results show that correlations between SWE series from coupled monitored and unmonitored sites are strongly affected by elevation differences. ~~which can be extended to unmonitored sites if they have monitored counterparts at similar elevation. This finding overcomes the need for year-round accessibility and increases the number of potential sites for continuous SWE retrieval~~.

Main body changes:

L187-188: The validation dataset (Fig. S3) is divided as: (i) manual samples from the same sites chosen for the calibration, and (ii) manual samples from the 7 additional monitored sites of the network.

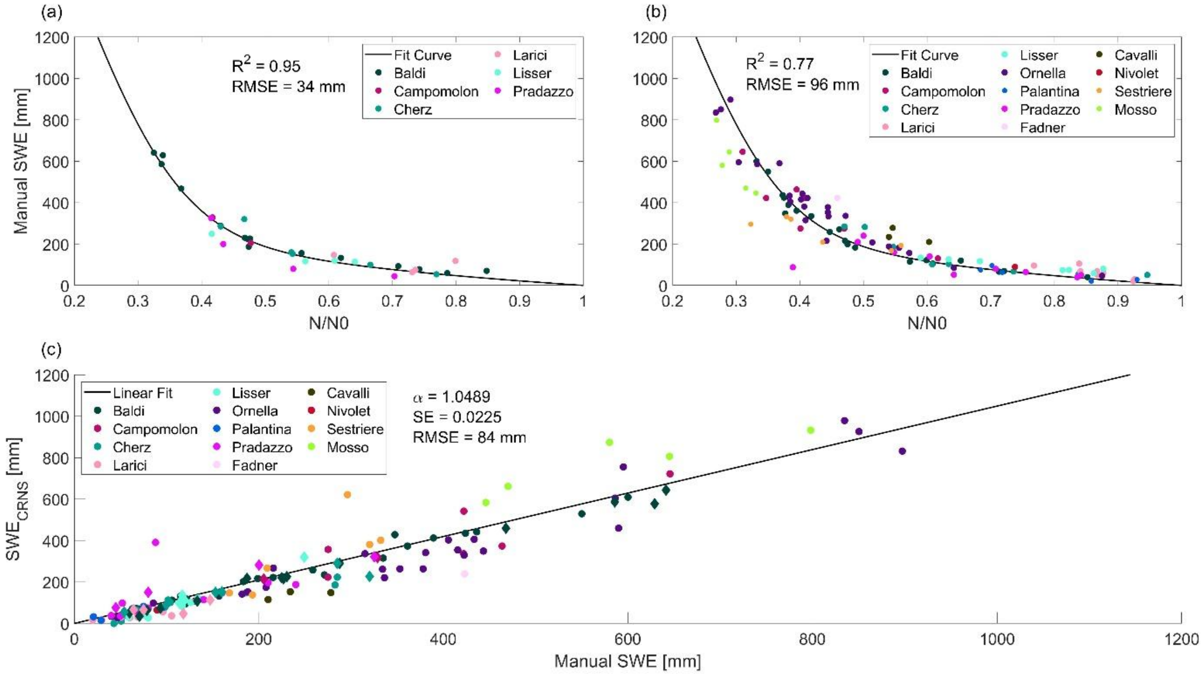
L220-221: R^2 values obtained for the calibration, validation at sites of calibration, and validation at additional sites are 0.95, 0.87, and 0.65 respectively.

L229-230: as in each of the three instances of linear regression the slope is close to the ideal value 1.

L236-239: Remarkably, both the slope and the SE obtained for the validation subset at the sites used for calibration (Fig. 2e) appear to perform better than the calibration subset (Fig. 2d). Nevertheless, RMSEs sensibly increase across the three subsets from 34 mm of the calibration subset to the 130 mm of the validation subset in the 7 additional sites. The latter subset shows also an α further from 1 (1.084) and an higher SE (0.1441).

L293-294: on the same sites chosen for the calibration (R^2 = 0.87, RMSE = 56 mm) as well as in seven additional monitored sites (R^2 = 0.87, RMSE = 130 mm). ~~(R^2 = 0.77, RMSE= 96 mm).~~

OLD FIGURE 2:



NEW FIGURE 2:

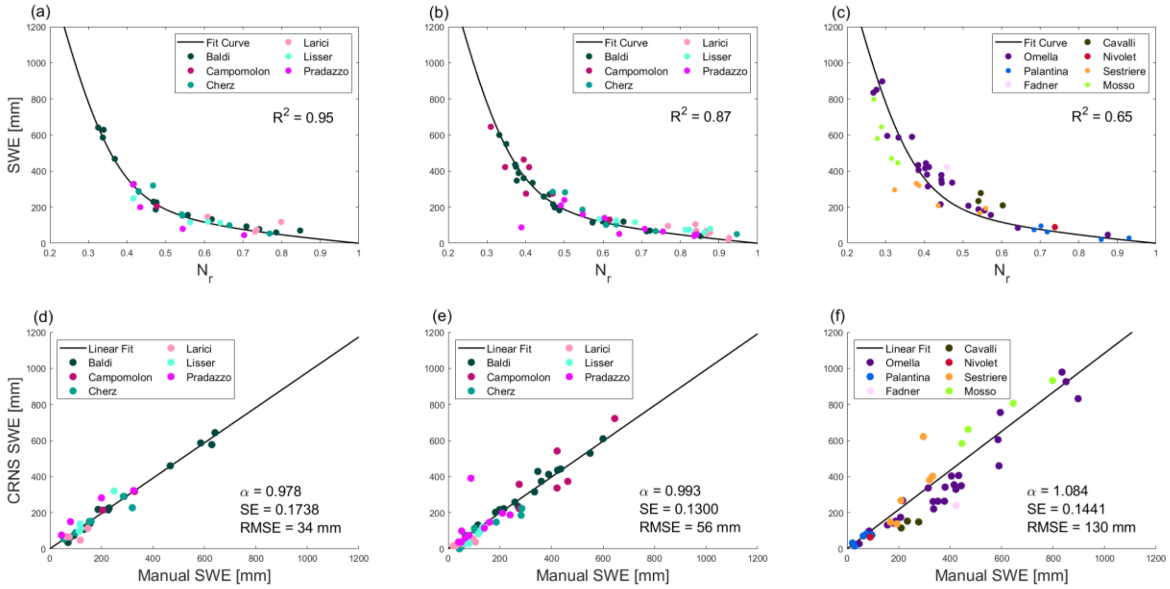


Figure 2: Normalised daily neutron count rate (x-axis) against SWE direct measurements (y-axis) for each site (coloured dots), and regression curve (black line) for the calibration dataset (a) and validation dataset divided between the six sites chosen for calibration (b) and the remaining seven sites(c). Manual SWE measurements plotted against SWE$_{\text{CRNS}}$; coloured dots represent the calibration (d), validation in the same sites as calibration (e), and validation at different sites (f) dataset respectively; the black lines illustrate the linear regression fit performed for each dataset.

The proposed method for converting neutron counts for SWE (Eqs. 1 and 2) introduces five free parameters (Λmax, Λmin, a1, a2, a3), which are calibrated using 35 SWE observations collected across six sites. While 35 measurements may appear sufficient in absolute terms, the effective degrees of freedom are substantially reduced when accounting for site-level clustering, potential temporal autocorrelation, and shared environmental conditions. This raises the question of whether the calibration is over-parameterised relative to the available independent information content. In particular:

1. With five fitted parameters and 35 observations, the nominal ratio is only seven observations per parameter. If measurements are not fully independent (e.g., repeated measurements at the same site or within similar snow conditions), the effective sample size may be considerably smaller.

2. The physical interpretability of each parameter is not entirely clear. If Λmax and Λmin are meant to represent physically bounded attenuation limits, are they sufficiently constrained during calibration?

3. The exponential structure in Eq. (2) already provides substantial flexibility; adding three additional empirical parameters (a1, a2, a3) may risk compensating for noise or site-specific effects rather than capturing generalizable physics.

Given that the study aims to propose a network-wide parameterisation, parameter stability and transferability are critical. I therefore encourage the authors to justify the choice of five free parameters explicitly, assess potential overfitting (e.g., via cross-validation or information criteria), and discuss parameter sensitivity and identifiability. If the goal is broad applicability across sites, a reduced or partially constrained parameter set (for example, fixing Λmax and Λmin based on physical reasoning or literature values) might improve robustness and interpretability. Addressing this issue would significantly strengthen the methodological foundation of the manuscript.

We thank you for this comment and apologise for the lack of clarity on this crucial point of our work. The adopted conversion formula is widely used in literature reporting SWE measurements with CRNS, in particular in the following papers published on The Cryosphere across the years:

- Howat et al., 2018 (https://doi.org/10.5194/tc-12-2099-2018)
- Gugerli et al., 2019 (https://doi.org/10.5194/tc-13-3413-2019)
- Jitnikovitch et al., 2021 (https://doi.org/10.5194/tc-15-5227-2021)
- Pokhrel et al., 2024 (https://doi.org/10.5194/tc-18-5913-2024)

We propose to add to the references the articles of this list that were not originally present (i.e. Howat et al. 2018 and Jitnikovitch et al. 2021).

The formula is grounded in neutron transport simulations; therefore, we opted to maintain that standard functional form of the conversion formula instead of trying to introduce a new arbitrary one. It is common in literature to see a site-specific adaptation of the parameters, but an interpolation on a large set of manual SWE samples like ours has never been presented. We started with the set of parameters described in Gugerli et al. (2019) due to the proximity and similarity of their study area (the Swiss Alps) with ours. Please note that in our interpolation we only let Lambda_min and a1 as free parameters, to avoid over-parametrization. We constrained Lambda_min to be positive and less than Lambda_max. The rationale for this is that the other parameters do not significantly affect the conversion when the amount of SWE is far from the saturation threshold (e.g. Jitnikovitch 2021). Moreover, we constrained Lambda_min to be positive and less than Lambda_max, and a1 to be positive. Nevertheless, we realise that this was not clearly stated in our manuscript and we apologise for this. To amend, we propose to modify the dedicated section to explain the fit procedure in greater detail.

Main body changes:

L134-170:

2.3 CRNS data processing and SWE computation

Each sensor retrieves raw particle counts that are integrated on a 1-hour time window. The neutron count rate measured by the ground detector represents the main signal, while the muon count rate measured by the mast detector provides the incoming flux reference. To correct the raw counts (C_{raw}), we adopted an atmospheric pressure correction from onsite atmospheric pressure measurements (p) and applied it to obtain the atmospheric pressure corrected count rates (C_{apc}) following Eq. (1):

$$C_{apc} = C_{raw} * \exp\left[\beta\left(p - p_{ref}\right)\right] , \quad (1)$$

Where p_{ref} is the reference pressure at each site elevation (H, in meters) derived as (Eq. 2):

$$p_{ref} = 1013.25\ hPa * \exp -\left(\frac{H}{8006\ m}\right), \quad (2)$$

and β is a correction factor that varies between neutrons (β_N) and muons (β_μ). Both β_N and β_μ values used in this study were provided by the manufacturer: β_N is fixed at 0.0076 hPa^{-1}, while β_μ scales with the site elevation.

While performing these processing steps, we discarded data that fell under at least one of the following criteria: (i) integration time lower than 500 s; (ii) null value of either air pressure, neutron counts, or muon counts.

For each site, we took the baseline (pressure corrected) neutron and muon count rates (N_0 and μ_0) during a period characterised by the following features: (i) minimum length of 24 hours, (ii) stable signal (i.e. without discarded data), and (iii) absence of snow cover. N_0 varies greatly from each site due to its dependence from elevation, soil composition, and morphology. At every station of the network, N_0 and μ_0 are assessed at the beginning of each season and their values are updated if needed.

Subsequently, to obtain the corrected neutron count (N) we applied to the pressure corrected neutron count rate (N_{apc}) a site-specific incoming correction factor given by the ratio between μ_0 and the atmospheric pressure corrected muon count (μ_{apc}) as proposed by Stevanato et al. (2022) and illustrated in Eq. (3):

$$N = N_{apc} * \frac{\mu_0}{\mu_{apc}}, \tag{3}$$

It is therefore possible to compute the normalised neutron count rate (N_r) according to Eq. (4):

$$N_r = \frac{N}{N_0}, \tag{4}$$

Then, we computed SWE adopting the widely used formula (e.g. Pokhrel et al., 2024; Jitnikovitch et al., 2021; Gugerli et al., 2019; Howat et al., 2018) reported in Eq. (5):

$$SWE = -\frac{10}{\Lambda} log N_r, \tag{5}$$

Where the attenuation length (expressed in cm^{-1}) Λ is (Eq. 6):

$$\Lambda = \frac{1}{\Lambda_{max}} + \left(\frac{1}{\Lambda_{min}} - \frac{1}{\Lambda_{max}}\right) * \left[1 - exp\left(\frac{a_1 - N_r}{a_2}\right)\right]^{-a_3}, \tag{6}$$

2.4 Calibration and validation against manual samples

We assessed the parameters of Eq. 6 through a calibration process that leveraged 35 direct SWE measurements taken from six sites in the Veneto region (Eastern Alps) between December 2023 and March 2024 (Fig. S2). To avoid over-parameterisation, we kept fixed the values of parameters Λ_{max}, a_2, and a_3. These values were taken from Gugerli et al. (2019) due to the spatial proximity of our respective study areas (the Italian and Swiss Alps). The calibration was performed on the two free parameters Λ_{min} and a_2. This first instance of an interpolation common to multiple sites suggested the possibility of adopting a shared parameterisation across the Italian CRNS network and prompted the study presented in this work.

The manuscript would benefit from a substantially more detailed description of the CRNS data processing workflow. At present, key preprocessing steps are either only briefly mentioned or not described in sufficient detail to ensure reproducibility and allow readers to evaluate the robustness of the SWE retrieval. In particular, the authors should clearly document:

- how incoming neutron flux variations were corrected (including data source, temporal resolution, and scaling approach);
- the atmospheric pressure correction procedure and coefficients used;
- atmospheric humidity corrections applied;
- quality control and filtering steps (e.g., temporal averaging, outlier removal, snow-free screening);

We thank you for this comment and agree on the fact that the preprocessing steps are only briefly mentioned since we believed that a technical and detailed description was not suited for a brief communication. However, we are glad to expand on the correction processes adopted.

The signals used for the computation of SWE were, for each station, the hourly neutron count rate from the ground detector and the hourly muon count rate from the mast detector.

Atmospheric pressure correction was applied to both signals separately. The correction factor applied is $\exp[\beta^*(p-p_{ref})]$ where β for neutrons was 0.0076 hPa^{-1} while beta for muons was scaled with the altitude H (in meters) according to a scaling formula provided by the manufacturer.

We thank the reviewer for pointing out the most recent developments regarding the scaling of beta with elevation and other factors. We believe that the data gathered from our network could be used for an extensive investigation on the empirical β_N scaling with elevation at northern Italy's latitude. However, this would require an extensive analysis, which is out of the scope of the current manuscript but may be object of throughout investigation in our future works.

Data were discarded by a set of filters: if the integration time was shorter than 500 s or if the value of either neutron counts, muon counts or pressure was null.

A daily average of the particles count rates was then performed, since a higher temporal resolution is not needed for the purpose of this study and manual SWE samples are generally assumed to be representative of daily values while comparing them with remote sensing data (e.g. Brodylo et al., 2025 https://doi.org/10.5194/tc-19-6127-2025), model output (e.g. Colombo et al., 2022 https://doi.org/10.1016/j.jhydrol.2022.128532) and, crucially, CRNS SWE estimates (e.g. Gugerli et al., 2019).

Finally, incoming correction was applied as proposed by Stevanato et al. (2022), by using the muon signal as a reference. The incoming correction factor is defined as μ_0/μ, being μ the (pressure-corrected) muon count rate and μ_0 the reference muon count rate, fixed contextually to N_0.

N_0 was determined before the start of the snow season, as the average count rate in a period (minimum 24 h) characterised by absence of snow and stable signal. μ_0 was taken as the average muon count rate in the same period of time. At each site, the setting of N_0 and μ_0 was reviewed and either confirmed or updated every year.

The changes proposed to address the previous comment cover this one and the next as well.

Given that SWE estimates derived from CRNS are highly sensitive to preprocessing choices, a transparent, step-by-step description is essential. I strongly recommend either adding a dedicated subsection in Methods that outlines the complete processing chain, or roviding a reproducible workflow (e.g., in the Supplement).

We propose to add a Subsection in Section 2 titled “CRNS data processing and SWE computation” with the step-by-step description of the preprocessing we adopted, including additional equations.

Chapter 2 would benefit from a clearer and more logical restructuring with subchapters as follows: 1) Manual SWE sampling, 2) station setup and 3) CRNS processing and SWE calculation including atmospheric pressure correction, incident neutron flux correction, detailed description of parameterisation and calculation of SWE from neutron counts. This reorganisation improves the logical flow of the chapter.

We acknowledge your comment. We propose to restructure Chapter 2 in four Sections, namely “2.1 Network and station setup”, “2.2 Manual SWE sampling”, the already mentioned “2.3 CRNS data processing and SWE computation", "2.4 Calibration and validation against manual samples", and "2.5 Correlation between time series of monitored and unmonitored sites". Contextually, we propose the restructuring of Chapter 3 into 2 Sections, namely: "3.1 Calibration and validation against manual samples", and "3.2 Correlation between time series of monitored and unmonitored sites".

The use of local muon flux measurements to correct for incoming neutrons has not yet been demonstrated to be highly accurate. I recommend that the authors provide a comparison with the standard correction approach to assess the validity and performance of this method.

We acknowledge your insights on this matter. The focus of this paper is the validation of SWE measurement by CRNS with a set of default settings and parameters. The muon-based incoming correction is a native feature of the CRNS system installed in the network. We understand the importance for the CRNS community of an assessment of performances of this correction specifically in comparison with the traditional method. However, we believe that such an assessment is beyond the scopes of the present paper and may be part of further and more detailed research.

Specific comments

L58: You should consistently use the term "sensor".

We thank you for pointing out the inconsistencies in the use of the terms "sensor" and "probe". To address it, we opt for consistently use the expression "CRNS probe", because the "S" in CRNS already stands for Sensor/Sensing.

Substituted the word "probe" at lines: 48, 50, 53, 72, 77, 126, and 287.

L68: It is unclear what the authors are referring to with the term "main Alpine watershed."

We adopted the same definition given in the cited Brugnara and Maugeri (2019). Alternative definitions may be "Alpine divide" or "main chain of the Alps". In any case, if this definition is deemed to be unclear, we are open to change it with "Alpine divide" or "main chain of the Alps".

L88: Please change "barometric factor correction" to "atmospheric pressure correction" to align with standard CRNS nomenclature. In addition, recent work by Davies et al. (2026) demonstrates that the barometric coefficient is strongly dependent on-site elevation. Given that the network in this study spans a wide elevation range (1422–2901 m a.s.l.), it is unclear whether elevation-dependent variations in the barometric coefficient were accounted for. In case a single coefficient values was used, please provide justification for why you are confident that this does not introduce systematic bias across the network. Addressing this issue is critical, as uncorrected elevation-dependent variations in the barometric coefficient could directly affect the accuracy and comparability of the SWE estimates across the network.

We propose to change "barometric factor correction" to "atmospheric pressure correction". We thank you again for pointing out recent developments regarding the elevation dependence of this factor as we have addressed this issue in the reply to one of the major comments.

L90: Please explain in greater detail how you determined the baseline neutron count rate. In addition, the current use of the variable name $\mathbf{N_0}$ may lead to confusion with the well-established $\mathbf{N_0}$ parameter used in standard CRNS soil moisture calibration. Because the present study defines a conceptually different baseline quantity, I strongly recommend to adopt a distinct symbol (e.g., *N_ref*, *N_base*, or similar).

The process used to assess the baseline neutron count rate is described in our answer to one of the major comments. Regarding the use of N0 to name such baseline, we adopted the most common name used in the existing literature on CRNS SWE measurements (e.g. Gugerli et al., 2019; Howat et al., 2018; Schattan et al., 2017 https://doi.org/10.1002/2016WR020234).

L147-151: For each site, we took the baseline (pressure corrected) neutron and muon count rates (N_0 and μ_0) during a period characterised by the following features: (i) minimum length of 24 hours, (ii) stable signal (i.e. without discarded data), and (iii) absence of snow cover. N_0 varies greatly from each site due to its dependence from elevation, soil composition, and morphology. At every station of the network, N_0 and μ_0 are assessed at the beginning of each season and their values are updated if needed.

L93: Please explain in greater detail how you determined the normalised count rate (Nr).

The normalised count rate Nr was determined by dividing the corrected neutron count rate by the baseline count rate (i.e. N/N0) as explained in the proposed additional Eq. (4).

L152-157: Subsequently, to obtain the corrected neutron count (N) we applied to the pressure corrected neutron count rate (N_{apc}) a site-specific incoming correction factor given by the ratio between μ_0 and the atmospheric pressure corrected muon count (μ_{apc}) as proposed by Stevanato et al. (2022) and illustrated in Eq. (3):

$$N = N_{apc} * \frac{\mu_0}{\mu_{apc}}, \qquad (3)$$

It is therefore possible to compute the normalised neutron count rate (N_r) according to Eq. (4):

$$N_r = \frac{N}{N_0}, \qquad (4)$$

L124-130: In this case these stations need to be excluded from the analysis.

We completely agree. In fact, as we stated in L129-130 ("To avoid biases, we decided to not consider for the next steps of the analysis the 2023–2024 data of the two stations"), those two stations were indeed excluded from the analysis for the 2023-2024 season, when the assessment of a reliable N0 was not possible. However, we included the data of the 2024-2025 season because by then an updated baseline neutron count was determined. In any case, if you or the Editor believe that the aforementioned statement of L129-130 may be misinterpreted, we are open to rephrase it in a clearer way.

L149-152: Please refer to Figure S1.

Thank you for pointing that out, we propose to cite it at the end of the sentence. Given the addition made to the Supplementary Materials, that figure is now referred to as Figure S3.

L216: (Fig. S3)

L155: The current validation procedure includes both calibration and non-calibration stations. While this provides an overall assessment of performance, it can potentially overestimate the method's predictive skill because the calibration sites have already influenced the parameterisation. Therefore, I recommend separating the validation sites from calibration site explicitly.

We acknowledge that and have chosen to modify Figure 2 to explicitly separate the sites of the validation dataset.

L173: Given that you are using a buried CRNS sensor, whose footprint is already very small, the explanation provided does not seem physically sensible.

We appreciate your comment on this. The given explanation was mainly driven by what was already stated in Gugerli et al. (2019). Nevertheless, we propose to drop this part from the manuscript to avoid statements that are not rigorous and physically sensible.

L243-245: ~~This phenomenon could be linked to the footprint reduction caused by high snow depth. The uncertainties arising from the increases in the snowpack thickness are well documented (Gugerli et al., 2019) and may lead to an increased sensibility of the sensors to the small-scale spatial variability of snow depth.~~

L193: The manuscript cites Gottardi et al., 2013, but this reference appears to be inaccessible. Ensuring that all references are accessible is essential for reproducibility and for readers to follow the methodology or contextual background.

Thank you for pointing that out. We propose to add the URL where this document can be found. Despite not having a DOI assigned, the reference can be found online and is freely accessible (https://arc.lib.montana.edu/snow-science/objects/ISSW13_paper_O2-08.pdf). Unfortunately, there is little literature about the EDF CRNS network, but we believe it is important to acknowledge its existence.

Addition to references:

- Gottardi, F., Carrier, P., Paquet, E., and Laval, M. T.: Le NRC: une décennie de mesures de l'équivalent en eau du manteau neigeux dans les massifs montagneux français, International Snow Science Workshop 2013, 33, 926–930, https://arc.lib.montana.edu/snow-science/objects/ISSW13_paper_O2-08.pdf, 2013.

L197: It is unclear which variable is being correlated (e.g., SWE, neutron count rate), which stations are included in the analysis (all 26 network sites, only calibration sites, or only validation sites), and whether the correlation refers to site-averaged values, individual measurements, or temporal series. The authors should clarify these points explicitly in the text and in the figure caption.

Thank you for pointing out this lack of clarity. We propose to modify Figure 3 description so that it explicitly says that the correlation refers to the coupled monitored-unmonitored sites snow seasonal time series.

Figure 3: (a) Heatmap of the average correlations of the SWE_{CRNS} time series classified by the horizontal (x-axis) and vertical (y-axis) distances between unmonitored and monitored stations. The black dots represent each pair of monitored-unmonitored stations for which r was computed for a total of 78 pairings. Average r values computed for each ~~depending on~~ vertical (b) and horizontal (c) distance~~s~~ classes. The x coordinates of each point represent the upper limit of its distance class.

L197-203: In my view, this correlation analysis is only meaningful if each station has been individually calibrated. Otherwise, the uncertainties introduced by transferring the parameterisation across sites may dominate the variability and artificially inflate or suppress correlation values.

We acknowledge your comment, however the same analysis performed using the Nr time series (which are independent from the subsequent parameterisation) showed similar results. We are open to include the figure obtained from the mentioned Nr analysis in the main body of the manuscript but we currently propose to include it in the Supplementary Materials.

L275-276: An analogous analysis conducted on the Nr time series instead of the SWE_{CRNS} ones showed similar results (Fig. S4).

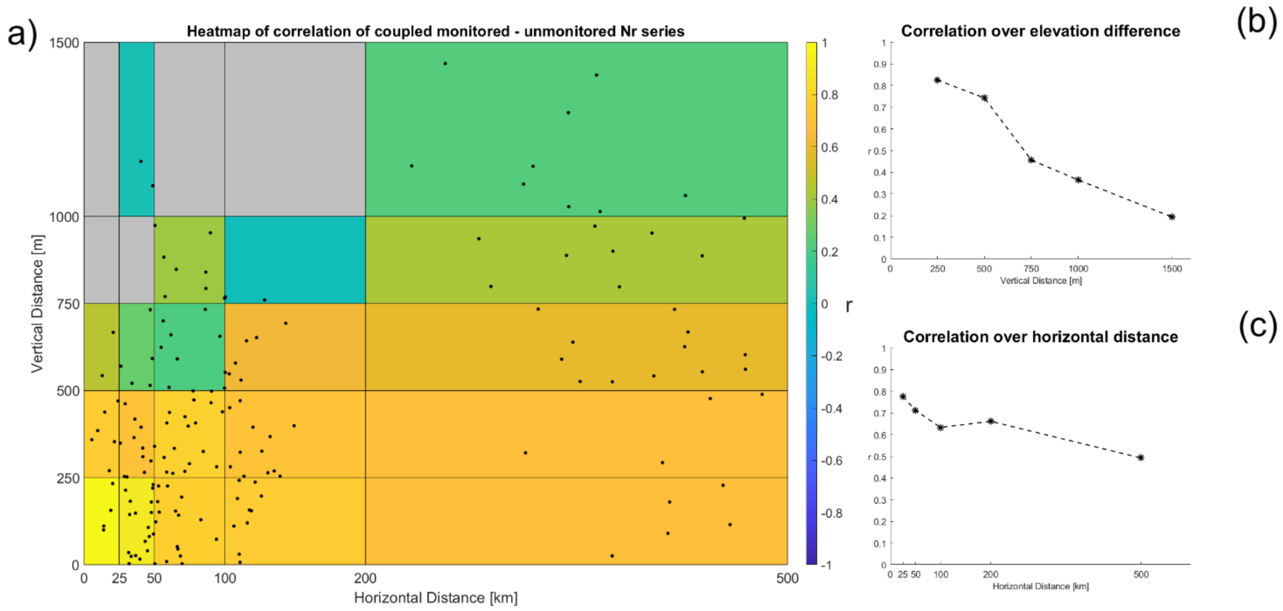


Figure S4: **(a) Heatmap of the average correlations of the N_r time series classified by the horizontal (x-axis) and vertical (y-axis) distances between unmonitored and monitored stations. The black dots represent each pair of monitored-unmonitored stations for which r was computed for a total of 78 pairings. Average r values depending on vertical (b) and horizontal (c) distances. The x coordinates of each point represent the upper limit of its distance class.**

Addition to the references

- Colombo, N., Valt, M., Romano, E., Salerno, F., Godone, D., Cianfarra, P., Freppaz, M., Maugeri, M., Guyennon, N.: Long-term trend of snow water equivalent in the Italian Alps, Journal of Hydrology, 614(A), 128532, doi:10.1016/j.jhydrol.2022.128532, 2022.
- Gottardi, F., Carrier, P., Paquet, E., and Laval, M. T.: Le NRC: une décennie de mesures de l'équivalent en eau du manteau neigeux dans les massifs montagneux français, International Snow Science Workshop 2013, 33, 926–930, https://arc.lib.montana.edu/snow-science/objects/ISSW13_paper_O2-08.pdf, 2013.
- Jitnikovitch, A., Marsh, P., Walker, B., and Desilets, D.: Snow water equivalent measurement in the Arctic based on cosmic ray neutron attenuation, The Cryosphere, 15, 5227–5239, doi:10.5194/tc-15-5227-2021, 2021.
- Lopez-Moreno, J. I., Leppänen, L., Luks, B., Holko, L., Picard, G., Sanmiguel-Vallelado, A., Alonso-González, E., Finger, D. C., Arslan, A. N., Gillemot, K., Sensoy, A., Sorman, A., Ertaş, M. C., Fassnacht, S. R., Fierz, C., and Marty, C.: Intercomparison of measurements of bulk snow density and water equivalent of snow cover with snow core samplers: Instrumental bias and variability induced by observers. Hydrological Processes. 2020; 34: 3120–3133. doi:10.1002/hyp.13785, 2020a.

Sincerely on behalf of all the co-authors,

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