Response to Reviewer 1, The Cryosphere Journal

From Snow Depth to Streamflow: Reducing Snowfall Uncertainty in Alpine Headwaters with Sentinel-1-based Snow Depth Retrievals

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1 Response to the Editor

Dear Editor,

We sincerely thank the Editor and reviewers for their careful and constructive comments. We address each of Reviewer 1's comments point by point below, outlining our planned revisions to the manuscript prior to resubmission.
We also noted the Editor's comment regarding the figures: "In the downloaded PDF file it appears that there are some boxes / parts of boxes / grey lines around Figures 1, 2, 3, 4, 5, 8 and 9 – please check / are these screenshots? Figure 5: 'Sentinel-1' instead of 'Sentine-1' in the legend)."
The figures are not screenshots; we will investigate and remove these artifacts in the revised figures, and correct "Sentine-1" to "Sentinel-1" in the Figure 5 legend.

Kind regards,
Shima Azimi on behalf of all authors

2 Reviewer 1

Summary This study aims to improve the GEOframe-NewAGE hydrological model by assimilating Sentinel-1 C-band snow depth observations to tackle the sparse distribution of precipitation gauges in mountainous regions. The approach is tested in two catchments in the Italian Alps. The methodology encompasses a probabilistic ensemble approach (particle filter batch smoother), in which the snowfall correction factor and other model parameters are varied to get optimal parameter settings through a probability distribution function and

subsequent weighting of these functions, utilizing the satellite data to calculate the likelihood function. The snow-corrected hydrological model is then validated against a kriging-only model, highlighting strong improvements in precipitation estimates, discharge biases and timings and their correlation to observations.

General Remarks & Decision The study presents an interesting approach for assimilating satellite data in hydrological modelling to substantially improve snow depth and, as a consequence, discharge modelling in alpine catchments. Applications for this methodology are widespread and could greatly benefit the community using semi-distributed hydrological models. While the underlying science is plausible and the major part of the methodology is adequately described, the manuscript text, general presentation, discussion, as well as the literature review (to a lesser extent) need substantial revisions and are unpolished as of now. I therefore recommend reconsideration after major revisions before publishing in TC.

Response to General Remarks & Decision We sincerely thank the reviewer for their positive assessment of our work and for recognizing the potential value of the proposed methodology for hydrological modelling and snow data assimilation. We also appreciate the constructive comments and suggestions, which will help us improve the quality and clarity of the manuscript.

We acknowledge the reviewer's concerns regarding the presentation, discussion, and literature review. In the revised manuscript, we will substantially improve these sections by refining the overall structure, expanding and strengthening the discussion, and revising the literature review where appropriate. We address each of the reviewer's points in detail in our point-by-point responses below.

Major Comments

Comment 1: State of the manuscript running text and figures: In the current state, the running text as well as some figure colorbars and font sizes need substantial improvement. I think the work you have done is quite interesting, and your underlying approach deserves a better presentation. I tried to highlight as much as possible in the minor comments, starting from rephrasing to placing some text blocks in different sections, etc.

Response to Comment 1 Thank you for your constructive feedback. We will carefully revise the manuscript to improve the clarity and flow of the running text, enhanced the readability of the figures by adjusting colorbars and font sizes, and addressed the suggested rephrasing and restructuring throughout the manuscript as indicated in the minor comments.

Comment 2: Unbalanced proportion of Methods and Discussion: Many sentences in the Results section should go in the Methods section. Doing so would highlight that the length of the Results & Discussion section is disproportionate compared to other parts of the manuscript. I recommend to deepen the Discus-

sion, the Results itself are adequately described. Some ideas on what to discuss are stated here:

- Include Fig. A2 in the manuscript: The KGE results, in my opinion, deserve a spot in the main manuscript. You could add similar boxplots of the validation period as well.
- Figure 5: Can you interpret the results? Why are some years overestimated and some are underestimated? Does it have something to do with the number of heavy precipitation days?
- Figure 6: How do these precipitation correction factors relate to other studies, e.g. Avanzi et al. (2021) or Herrnegger, Senoner, and Nachtnebel (2018). I think you are in good agreement, that is worth pointing out.
- Add a discussion about conversion from SWE to snow depth as potential limitation, as snow density assumptions are not trivial.

Response to comment 2

We thank the reviewer for this constructive suggestion and agree that the current balance between Results and Discussion should be improved. We split this comment to separated parts as follows:

Unbalanced proportion of Methods and Discussion We will move all methodological descriptions currently embedded in Section 4, including the kriging approach and the hydrological modeling framework, to a new subsection in Section 3 (Methods). This restructuring will streamline Section 4, improve the overall organization of the manuscript, and provide additional space for a more in-depth Discussion, as recommended.

Include Fig. A2 in the manuscript: The KGE results, in my opinion, deserve a spot in the main manuscript. You could add similar boxplots of the validation period as well. We agree that the KGE comparison between the baseline and DA-based models represents an important result and will therefore move Fig. A2 to the main manuscript (Section 4.2). We will also include boxplots for the validation period. The only concern is that the validation period considered in this study is not available for all hydrometric stations. We will therefore investigate an appropriate way to present the validation boxplots alongside the calibration results while ensuring a consistent and meaningful comparison.

Figure 5: Can you interpret the results? Why are some years overestimated while others are underestimated? Does this have something to do with the number of heavy precipitation days? We thank the reviewer for this valuable comment. We will clarify the interpretation of Figure 5 in the revised manuscript. Our framework employs an offline batch smoother, in which all available Sentinel-1 observations over the assimilation window are assimilated

simultaneously rather than sequentially in time. Consequently, the posterior estimate represents a compromise over the entire assimilation window, which can lead to underestimation in some years and overestimation in others. We will also acknowledge this as a limitation in the Discussion section, noting that the batch smoothing approach may provide suboptimal estimates for some individual years, while being more appropriate for others.
Regarding the reviewer's question on heavy precipitation days, we will investigate whether the interannual differences between the Sentinel-1 observations and the particle filter ensemble estimates are related to precipitation characteristics, particularly the annual precipitation and the number of heavy precipitation days. This analysis will help assess whether differences in precipitation forcing may contribute to the observed overestimation in some years and underestimation in others. We will report the results in the revised manuscript and discuss this relationship accordingly.

Figure 6: How do these precipitation correction factors relate to other studies, e.g. Avanzi et al. (2021) or Herrnegger, Senoner, and Nachtnebel (2018). I think you are in good agreement, that is worth pointing out. We thank the reviewer for this valuable suggestion. We agree that comparing our snowfall correction factors with those reported in previous studies is important in this context. We will add a discussion comparing our results with studies such as Avanzi et al. [2021] and Herrnegger et al. [2018], highlighting the consistency of our findings with previously reported elevation-dependent precipitation patterns in the Alpine region. We will also clarify that, although these studies primarily focus on total precipitation gradients, their findings provide relevant support for the physical basis of the snowfall adjustment factors derived in our study.

Add a discussion about conversion from SWE to snow depth as potential limitation, as snow density assumptions are not trivial. We thank the reviewer for this valuable comment. We will add a discussion addressing the uncertainty associated with the conversion from SWE to snow depth, which depends on the representation of snow density. Snow density exhibits substantial spatial and temporal variability and therefore represents an important source of uncertainty when relating SWE to snow depth, particularly in complex environments such as the Alps. We will support this discussion with relevant literature, for example Jonas et al. [2009] and López-Moreno et al. [2013].

In our framework, snow density is dynamically updated within the GEOframe-NewAge snow module using an iSnobal-type compaction formulation. The density evolution accounts for the simulated SWE, snowfall, liquid water, and snowpack temperature, together with the model parameters governing snow densification and compaction. The resulting time-varying snow density is then used together with the simulated SWE to derive snow depth.

Nevertheless, uncertainties associated with the density and compaction parameterization remain a limitation of the approach, particularly because the density formulation is not explicitly perturbed in our ensemble framework. We

will acknowledge this source of uncertainty explicitly in the revised manuscript.

Comment 3: Literature and Undercatch section in the Introduction: At the current manuscript state, the introduction lacks proper citation in critical statements. I tried to refer to those statements in the minor comments and recommend to enhance your references. I further recommend to add one paragraph of (solid) precipitation measurement errors in gauges (undercatch) and how your approach can also help mitigating that problem. See works of e.g. Kochendorfer et al. (2017) and others.

Response to Comment 3 Thank you for this valuable comment. We will strengthen the statements throughout the Introduction by adding appropriate references, and we will consider the references and suggestions highlighted by the reviewer in the minor comments. In addition, we will add a dedicated paragraph discussing uncertainties in solid precipitation measurements from gauges, including wind-induced undercatch and the effects of complex terrain and site-specific exposure conditions, supported by relevant literature such as Kochendorfer et al. [2017], Wolff et al. [2015], Smith et al. [2020]. We will also clarify how our snowfall adjustment framework, which uses satellite-derived snow depth observations to constrain snowfall estimates, can help reduce uncertainties associated with gauge-based snowfall measurements, particularly in high-elevation and complex Alpine environments where gauge undercatch can be substantial.

Comment 4: Missing section on kriging methodology: I think how you generate spatial data from ground-observed precipitation deserves either a section in the Methods or in the Appendix. This is not a straightforward step and needs proper description, and potentially even further analysis.

Response to Comment 4 Thanks for the comment. We will add a dedicated subsection in the Methods (or Appendix material) describing the kriging procedure used to interpolate gauge-based precipitation, including the variogram model, the selected parameters, and the assumptions underlying the interpolation approach.

Comment 5: Appendix or Supplement: The Appendix is added directly to your published article, whereas a Supplement will be provided as a separate document. Given the amount of figures in their Appendix, it seems like the authors rather wanted to provide Supplementary material instead of an Appendix. I recommend to change that throughout the manuscript. Further, a reordering of the Supplement should be done, in the order of mentions in the manuscript.

Response to Comment 5 We appreciate this suggestion regarding the organization of the additional material. We prefer to retain the current Appendix format because we consider these figures and tables to be directly relevant to the interpretation of the manuscript and would like them to remain attached to the published article. Additionally, some of the figures will be moved to the

main body of the manuscript, thereby reducing the overall number of figures included in the Appendix. However, we will improve the organization of the Appendix by adding more detailed descriptions for the figures and tables and ensuring that they follow the order of their mention in the manuscript.

If, during the revision process, we find that the amount of material remaining in the Appendix is still too extensive, we will reconsider its format and follow the reviewer's suggestion to provide the material as Supplementary material.

Line-by-line comments

We thank the reviewer for the careful reading of our manuscript and for the constructive comments. We will address all of the minor comments in the revised manuscript. Below, we provide detailed responses only to those comments that require further clarification, while the remaining comments will be incorporated directly into the revised version.

- Figure referencing: In the main text, Figure panels should be mentioned like "Fig Xa" and not "Fig X(a)", so without the brackets.

  We thank the reviewer for this suggestion. We will revise the figure panel references throughout the manuscript to follow the requested format (e.g., "Fig. Xa" instead of "Fig. X(a)").

- Equation layout: Equations are part of the main text and should have a comma or period after stating them.

  We will revise that accordingly. Thank you for the suggestion.

- L24: Remove "The" before "high-quality".

  We will consider that.

- The sentence "However, precipitation data..." requires a citation. What about other data sources like gridded precipitation data?

  To support this statement, we will add the reference Sun et al. [2018] to the text.

  Gridded precipitation datasets derived from ground-based observations generally provide more reliable estimates of precipitation than remotely sensed or reanalysis products, particularly in regions where sufficient gauge observations are available. However, compared with point-scale gauge measurements, these datasets still contain uncertainties associated with station density, spatial interpolation methods, grid resolution, and the representation of local precipitation variability. These uncertainties become particularly relevant in complex mountainous terrain, where strong elevation gradients and small-scale spatial variability are often difficult to capture. Previous studies such as Merino et al. [2021] have shown that gauge-based gridded products generally are not free from interpolation-related uncertainties, especially in areas with sparse observations and strong orographic gradients.

We will add the above-mentioned information on gridded precipitation datasets and the relevant references to the main text.

- L28: The sentence "Despite its strengths..." also needs citations, ideally more than one.

  We will add relevant references to support this statement, including Phillips et al. [1992], Hevesi et al. [1992], Prudhomme and Reed [1999], Goovaerts [2000]. Thanks for the comment.

- L31ff: The introduction would benefit in naming and describing some gridded precipitation products, which stem from such kriging methods.

  Response: We will name and briefly describe representative station-based, interpolation-derived gridded precipitation products, such as the E-OBS [Cornes et al., 2018] and EMO-5 [Gomes et al., 2020] datasets, to illustrate how spatial interpolation methods are commonly used to generate gridded precipitation fields from gauge networks.

- I think you should also comment on model spatial resolution being one of the reasons why precipitation is not accurately captured in mountainous regions. You hint at it by stating "capturing orographic effects", but this deserves a more prominent position.

  The reviewer is completely right. We will revise the text to explicitly highlight the spatial resolution of the models underlying reanalysis products as an important factor contributing to precipitation underestimation in mountainous regions. The relatively coarse model resolution limits the representation of complex topography and associated orographic processes, resulting in a smoothed representation of elevation and precipitation gradients and potentially leading to systematic precipitation underestimation, particularly at high elevations.

- Remove "s" from "Earth observations data".

  Thank you for the comment. We will modify that.

- L42: The sentence "Additionally,..." also needs citations.

  We thank the reviewer for this comment. We will add supporting citations, including Rott et al. [2010] and Rutter et al. [2022] for the proposed snow monitoring missions.

- L45ff: Split sentence.

  We will revise as suggested. Thank you.

- L53ff: Split sentence.

  We will revise as suggested. Thank you.

- L64: "states" instead of "summarizes"?

  Yes, we will modify. Thank you.

- L69ff: "Cold Continental Climate" should be all lower case.

  We will modify. Thanks.

- L70: °C and not °.

  We will modify. Thank you.

- L 74: "region's susceptibility" instead of "region susceptibility".

  We will revise as suggested. Thank you.

- L74ff: Citation of the data set necessary.

  The data were obtained from the Po Catchment Authority. We will add an appropriate citation for the dataset. Thank you for the comment.

- Figure 1: Increase size of the colorbar. Further, the bin size of 165 m seems arbitrary, so why not use more natural bin sizes, e.g. 250 m? Caption: Double notion of the red outline should be removed. The sentences "The headwaters...", "In this study..." and "The distribution..:" should go into the main text.

  Response: Figure 1 will be modified. Thanks for the comments on that.

- L79: Citation of the data required.

  We will add the appropriate citation. Thank you for the comment.

- L88: The link is leading to a non-existing website and should not be in the main text. Cite properly.

  We will contact the Po Catchment Authority to obtain the correct reference and will replace the link with an appropriate citation in the revised manuscript. Thank you for the comment.

- L90: Move "S1A and S1B" after "mission".

  We will modify.

- L95: Remove "it uses"

  We will remove that. Thanks for the comment.

- L100: Space between "500" and "m".

  We will modify that. Thank you.

- Remove Link from main text.

  We will remove the link from the main text as suggested. Thank you for the comment.

- Figure 2: Increase colorbar size substantially, I think you could put all panels in one row by removing the axis labels as the projections is irrelevant here.

  Thank you for the suggestion. We will modify the figure.

- L108: What components?

  Response: The sentence will be changed to "The GEOframe-NewAGE modeling system is a semi-distributed hydrological model that integrates snow, canopy, soil, groundwater, and runoff generation components to simulate the main processes of the hydrological cycle.".

- L112: Change "delineates the allocation" to "separates"?

  We will change that. Thank you.

- Fig 3: Not all variables are declared properly: Please note, what T (temperature obviously, just for good measure) and the symbol in the triangle in Fig 3c mean. Also, what do the black dots and does the empty circle in Fig 3c try to symbolize?

  We thank the reviewer for the helpful comments regarding the text and Figure 3. These suggestions are appreciated. We will revise both the text, Figure 3 and the figure caption accordingly to improve their clarity and presentation.

- L122 and L123: Add comma after the equations.

  We will add it. Thanks.

- L128: Move the sentence "For a detailed..." after the equations.

  We will move the sentence as suggested. Thank you for the comment.

- Figure 4: Great flowchart! "Assimilation" should be lower case in the legend.

  Thank you. We will modify the legend accordingly.

- L148: Insert "the" before GEOframe model.

  We will add "the" as suggested. Thank you for the comment.

- L149: Change to "with the key difference, that data assimilation...".

  We will change that.

- L155: "100 particles of α_S".

  We will modify the sentence as suggested. Thank you for the comment.

- L155: Past tense - "indicated".

  We will modify that as suggested. Thank you for the comment.

- L162: Comma after equation.

  We will modify this as suggested. Thank you for the comment.

- L167: I think you can cut this sentence and then just add rephrase the sentence before: "The weights are determined by comparing the predicted snow depth state of the particle to the observed Sentinel-1 snow depth retrievals."

  We will remove the sentence and rephrase the preceding sentence as suggested. Thank you for the comment.

- L168: "...where Z are Sentinel-1...".

  We will modify that. Thanks for the comment.

- L174: Remove (Eq. 5) and write ":".

  We will modify that. Thanks for the comment.

- L175: Period after the equation. I think Nobs was never defined.

  We will add the missing period after the equation and define N_{obs} in the revised text. Thank you for your careful reading.

- L176: You can already define wj+ here, so you don't need to do it in L179. The likelihood function and Nens is also already defined.

  We will consider defining w_j^+ at this point to avoid repeating the definitions of the likelihood function and N_{ens}. Thank you for the comment.

- L178: Comma after equation.

  We will modify that. Thank you.

- L181: "...snow depth values using Sentinel-1 retrievals, as illustrated by Fig. 4." Then you can delete the following sentence.

  We will modify the sentence as suggested. Thank you.

- L185: HRU is never used again, you can delete the abbreviation.

  Thank you for pointing this out. We will remove the abbreviation as suggested.

- L187: "...model's snow component..."

  We will modify that. Thank you.

- L189: How is the average catchment snow depth used in the assimilation?

  The model is subbasin-based rather than grid-based. Therefore, the Sentinel-1 snow depth observations are spatially averaged within each subbasin, and the resulting mean snow depth is assimilated into the corresponding model unit. We will clarify this point in the appropriate section of the revised manuscript.

- L191: I think you should replace "storms" with heavy snowfall events. Or you properly define it (like daily precipitation ¿ X mm).

  We will consider this suggestion during the revision and replace the term "storms" with a more appropriate term. Thank you for the comment.

- L196 - L198: I think these two sentences can be deleted.

  We will delete them.

- L203 - L206: Introductory sentences are not needed. Your motive on why you perform this analysis is well described in the Introduction.

  We will remove these introductory sentences from the manuscript as suggested. Thank you for the comment.

- L206ff: How did you compare ground measurements and satellite snow depth?

  We are aware of the challenges associated with validating spatially distributed snow depth products against point-wise ground observations. Nevertheless, to obtain an initial assessment of the performance of the Sentinel-1 snow depth retrievals in our study area, we compared the satellite-derived snow depth with the available ground-based observations using the Sentinel-1 pixel nearest to each ground measurement location. The comparison yielded RMSE values of 454.1 $\pm$ 216.4 mm over the Aosta Valley and 398.6 $\pm$ 193.6 mm over the Piemonte headwaters. We will clarify this comparison procedure in the revised manuscript.

- L209: Fig. 5 should be Figure 5 at the start of a sentence. Better wording: "Figure5 presents how..."

  We will modify that. Thank you.

- Figure 5: Error in the legend ("Sentine-1"). Tiny numbers next to the colorbar. I recommend to change storms for snowfall events. Further, you can streamline the caption by putting "for a subcatchment within the Aosta Valley catchment" at the end of the first sentence.

  Thank you for the careful review. We will correct the typo in "Sentinel-1", increase the font size of the colorbar labels, replace "storms" with "snowfall events", and modify the caption as suggested.

- Figure 6: The second sentence in the caption should be in the running text. I think this plot could also be single column.

  We will transfer the second sentence to the main text and revise the figure to fit a single-column layout, as suggested. Thank you for the comment.

- L211 - L212: Already stated in Fig 5 caption. Can be deleted.

  We will remove that. Thanks for the comment.

- L213 - L216: Should go in the methods section. Also, remove period before "(see Eq. 2)".

  We will move this text to the Methods section and remove the period before "(see Eq. 2)" as suggested. Thank you for the comment.

- L217: Which study area? Specify if Aosta or Piemonte.

  We meant both study areas, Aosta and Piemonte, and we will clarify this in the revised manuscript. Thank you for the comment.

- Figure 7: I think you cannot give one letter to one column. Better do a-c for the first column etc. Also, you could move the colorbars to a better position (e.g. horizontal on the bottom). In the caption, change "derived from (a) the kriging" to "derived (a) from the kriging". Also, the sentence ",highlighting that..." should go in the running text.

  We will revise the figure layout and caption as suggested, including the panel labels, colorbar positions, and caption wording. We will also move the sentence beginning with "highlighting that..." to the main text. Thank you for the comment.

- L221 - 222: Your kriging approach deserves a whole subsection in the Methods section and should not be stated here.

  We will add a dedicated subsection on the kriging approach in the Methods section and move all relevant descriptions to that subsection. Thank you for the comment.

- L227: "(see the dark red catchments in Fig. 7)".

  We will modify the sentence, as suggested. Thank you.

- L228: Replace "Owing" with "Due".

  We will modify that.

- L229: State explicitly, that Fig A1 shows a similar elevation trend as Fig 7.

  We will explicitly state that Fig. A1 shows a similar elevation trend to that presented in Fig. 7. Thank you for pointing this out.

- L232-L239: Rephrase the whole paragraph. You are essentially repeating L219ff.

  We will rephrase the paragraph to avoid repetition, as suggested. Thank you for the comment.

- Fig 8: Great results! Can you specify, on what time step you are validating the corrected snowfall? Is it on a daily basis?

  The validation of the corrected snowfall is performed on a daily time step. We will clarify this in the revised manuscript. Thank you for the comment.

- L249 - L259: Very good description of the hydrological model, which however belongs to the Methods section.

  We will transfer the methodological description to the Methods section and retain the relevant results in the Results section. Thank you for the comment.

- L263: "yield" instead of "yielded".

  We will modify. Thank you for the comment.

- L267: Insert "to observations" after "red and green time series".

  We will modify the sentence, as suggested. Thank you.

- L268: Remove space before period.

  We will remove the space before the period. Thank you for the careful reading of the manuscript.

- L270: Streamline to "The correlation between observed and simulated discharge during spring and summer...".

  We will revise the sentence as suggested. Thank you for the comment.

- L272: "baseline model"

  We will add the word "model" before "baseline" in the sentence, as suggested. Thank you for the comment.

- Section 4.3: The first part might fit better in the Conclusions, as it is already a summary of your study. It is very well written, though! Limitations can stay here.

  We will move the first part of Section 4.3 to the Conclusions section, while retaining the discussion of limitations in Section 4.3, as suggested. Thank you for the comment.

- L280: Remove "potentially", I think this is a very definite uncertainty, as you also included potential dates with wet snow.

  We agree with the reviewer and will remove "potentially" from the sentence. We will revise the text as follows:

  "One limitation of our proposed approach for snowfall correction is the increased uncertainty of Sentinel-1 C-band snow-depth estimates under wet-snow conditions, although these conditions were minimized in our analysis through the definition and selection of snowfall events."

- L282: Again, remove storm events or state a definition.

  We will do that. Thank you.

- L284: To my understanding, you did modify the total precipitation, as it is a sum of rain and snow? I think this sentence needs correction.

  We modified the snowfall component, while the rainfall component remained unchanged. We will clarify this in the revised manuscript. Thank you for the comment.

- L286: What do you mean with "snow model states?"

  By "snow model states," we refer to the simulated snow variables, including snow depth and snow water equivalent (SWE). We will clarify this in the revised manuscript to avoid ambiguity.

- L291: Add "...associated snow parameters in a particle filter batch smoother approach."

  We will add that to the sentence in Line 291. Thank you for the suggestion.

- L298: Remove Brackets.

  We will remove that. Thank you.

- L306: Replace ";" with ", where".

  We will replace that. Thank you.

References

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