Response to Reviewer 1

Dear Reviewer 1,

We sincerely appreciate the time and effort you have invested in reviewing our manuscript. Below, we address your comments (colour-coding: blue review comment, black answer statement).

Major Comments

1. **Clarification of Methods**
    a. **In Situ/Model Data Description**

I found the description of the in-situ (AWS data) and SNOWPACK model to be rather confusing. Are the IMIS stations assimilated into SNOWPACK? Does the SNOWPACK timeseries at station locations reflect the station data or if not, how has it been modified? Are the timeseries in Figure 2 observed or modelled data? Please see minor comments below for additional detail.

We acknowledge that the description of the in-situ AWS data and SNOWPACK model could be clearer. All data used in our study were extracted from SNOWPACK rather than directly from station measurements. SNOWPACK is forced by the meteorological measurements performed by the AWS and assimilates the snow height as measured at the station (ultrasonic snow height sensor). As a detailed energy balance model with an arbitrary number of layers, it is able to simulate the stratigraphy of the snow at the AWS (as necessary for avalanche warning applications) such as weak layers or the wetting of the snow (Wever et al., 2016)). We will revise the manuscript accordingly to ensure this distinction is clearly communicated. We suggest adding the following at line 104 in the manuscript to make it clearer:
"The snow cover model SNOWPACK simulates the detailed stratigraphy of the snowpack based on meteorological input data from an automatic weather stations. Specifically, the model uses local meteorological measurements, such as air temperature, snow depth or snow surface temperature, to describes the snow microstructure, density, temperature and liquid water content of the layers in the snowpack"

- **Wet Snow Ratio**

The wet snow ratio (ln 139) features prominently in the results but is fairly "hidden" in the methods. I suggest presenting this as a formal equation to help highlight it and then reference it elsewhere in the manuscript.

We agree that the wet snow ratio plays a central role in our study and should be highlighted more prominently in the Methods section. We will introduce a formal equation for its calculation ensuring a clear reference point throughout the manuscript.

2. **Impact of Sentinel-1 Overpass Timing (Morning and Evening) on Merged Product**

The manuscript describes that a key advance of this workflow is the use of LRW composites to overlook viewing geometries. However, snowmelt and LWC varies temporally over multiple temporal scales (diurnal to seasonal). What is the impact of including morning and evening overpasses in the LRW composites? What if a pixel is frozen during the morning acquisition but melting in the evening acquisition?

We recognize the importance of this point and appreciate the reviewer's concerns. However, we argue that if the impact of this issue were substantial, it would manifest as systematic differences between east- and west-facing slopes in steep terrain. This is because east-facing slopes receive more weight from the ascending (morning) acquisitions, while west-facing slopes are more influenced by descending (evening) acquisitions. No such systematic bias has been observed in our data (and was also not observed in prior studies performed by the authors, see Dasser (2021)), supporting our assumption that the impact is minimal.

Additionally, to rigorously assess this effect related to the overpass timing, we would require independent reference data that are both accurate and spatially representative of steep terrain. We focused on cross-correlation between station data and the LRW composites, demonstrating that the backscattered signal is indeed driven by snow wetness. Given that our study's primary goal is to assess the feasibility of using Sentinel-1 for wet snow avalanche preconditioning rather than validating the LRW product itself, we consider a more detailed analysis of Sentinel-1 acquisition timing beyond the scope of this manuscript. We have already mentioned the issue in the discussion section (lines 283-286)

3. **More Detailed Comparison to Previous Work**

The discussion starts out describing the advance of this work over prior methods (lines 220-224) but this comparison was not explicitly made in the manuscript. I suggest the addition of a rigorous comparison to existing workflows be included, as that would demonstrate this advance more clearly. This in regards to both temporal (lines 220-224) and spatial (lines 224-226) scales.

We acknowledge that the discussion in lines 220-224 could better compare our approach to previous studies. To address this, we will incorporate all four Sentinel-1 tracks into our dataset, further emphasizing the improvements in temporal coverage. Additionally, we will include the SAR Wet Snow data corresponding to Figure 5, enabling a clear visual comparison that also highlights spatial enhancements.

4. **Data Availability**

I strongly encourage the authors to archive the datasets in a publicly available repository rather than by request from an organization. At present, the manuscript is not compliant with TC data policy: https://www.the-cryosphere.net/policies/data_policy.html, “The best way to provide access to data is by depositing them (as well as related metadata) in FAIR-aligned reliable public data repositories, assigning digital object identifiers, and properly citing data sets as individual contributions.”

We recognize the importance of open and FAIR-aligned data sharing, in accordance with *The Cryosphere*'s data policy. To ensure compliance, we will make our code available via GitHub and data accessible through EnviDat (link) upon publication.

Minor Comments

2 – snow wetness has implications beyond avalanche release, as detailed later. A broader justification for this work would be appropriate in the abstract.

While we acknowledge that snow wetness has broader implications beyond avalanche release, we prefer to maintain a focused discussion on its relevance for wet snow avalanches. We will clarify this focus in the title and manuscript, as also suggested by Reviewer 2.

3- replace “allow us” to “facilitate”

Line 3 Done, thanks.

4- replace “show how” with “utilize”

Line 4 Done, thanks.

4 – delete “can be used”

Line 4 Done, thanks.

5 – state the number of seasons/years

Line 5 Done, thanks.

5 – I suggest using evaluate rather than validate here and elsewhere (ln 50, for example)

Line 5 Done, thanks.

10 – briefly define wet snow ratio here

Line 10 Explicitly define the wet snow ratio as the amount of pixels per elevation band that were classified as wet snow over the amount of all pixels present in corresponding elevation band.

14 – simplify “operative monitoring application” to operational monitoring

Line 14 Done, thanks.

15 – include specifics on why wet snow avalanches are still difficult to predict

Line 15 This difficulty can be attributed to the limited availability of in-situ measurements of liquid water content, as well as the incomplete understanding of how liquid water influences the mechanical properties of the snowpack. (Hendrick et al., 2023). We will explain this better in the manuscript.

23-34 – I found this paragraph to be somewhat confusing, as background on the use of SAR for SWE retrievals and snowmelt detection is presented. I suggest revising to clarify which application is being discussed.

Lines 23-34 We will improve clarity in the discussion of SAR applications and focus on snowmelt detection.

26 – what does “compare Lievens et al 2020” mean?

Line 26 We will revise ambiguous phrases such as “compare Lievens et al. 2020” for better clarity

30-34 – I was surprised to not see the inclusion of relevant literate like Lund et al. 2020 (https://www.frontiersin.org/journals/earth-science/articles/10.3389/feart.2019.00318/full) and Gagliano et al. 2023 (https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2023GL105303), both of which utilized Sentinel-1 for snowmelt detection

Line 30-34 Thanks for pointing out these additional references. We will evaluate if they are relevant to our study and include them accordingly.

48 – I suggest including details on the Karbou et al. 2021 products rather than just the citation here.

Line 48 We will describe details on the Karbou et al. 2021 products

Figure 1 caption - revise: …of research at three spatial scales.

Done, thanks.

54-55 – check formatting of elevation values

Line 54-55 We will change formatting of elevation values (from 3’225 to 3225 m a.s.l. for consistency)

55 – provide more details regarding field site slope. I recognize that this is a large area, but a range and median value would provide a useful characterization.

Line 55 We will add range & median value for field site slope for a better feeling of the area.

55 – provide additional details on forest cover (tree types, canopy heights, % of study area, etc)

Line 55 We will provide additional details on forest cover (tree types, canopy heights, % of study area, etc)

58 – Does this range represent daily values over the entire year? Averaged over how many years?

Line 58 We will clarify origin of provided temperature values

67 – clarify: this would be reduced

Line 67 Rephrased to: "The revisit time in our dataset is six days; however, for current projects, it has extended to 12 days due to the Sentinel-1B outage in December 2021 (European Space Agency, 2022)."

80-81 – provide more details from the Nagler et al study on why this 2dB threshold was selected

Line 80-81 Explain why the 2 dB threshold was selected based on Nagler et al. (2000)

The selection of this threshold featured in the discussion section lines 241-247. As referenced in the manuscript we based our selection on Nagler et al., 2016, which is when the authors have published an adjusted threshold of 2 dB specifically for Sentinel-1 applications based on their histogram analysis (rather than from Nagler and Rott, 2000 where the threshold was set to 3 dB for ERS data). Since this is current state of the art and references are provided, we believe that further explanation in the manuscript is not necessary.

83 – revise sentence structure to not start with: As reference Nagler…

Line 83 Done, thanks.

94 – what percent forest cover was used for this mask? How sensitive were the results to this selection?

Line 94 We will clarify the forest cover threshold used for masking

133 – Please clarify and provide an example for what is meant by "entries occurring more than 25% of the time were ignored"?

Line 133 We will provide a clearer explanation of the 25% threshold for data exclusion

We can rephrase this to make the statement clearer. 0 and NaN values (depending on the parameter, NaN if 0 was a sensible value such as in temperature values and 0 when it did not naturally occur in the parameter) were overrepresented across space and time and drastically influenced the output statistics (e.g. 0 in snowheight, which was most of the time throughout the hydrologic year). Such values were discharged from the assessment.

136 – please describe this plot design in more detail for readers not familiar with Karbou et al. 2021

Line 136 We will add detailed description of this plot design rather than referring to Karbou et al. 2021

138 – Why were the temporal classes defined by the ascending rather than descending (or average) Sentinel-1 acquisitions?

Line 138 We have selected ascending for illustrating purposes, however we have adjusted for this in the matching process as illustrated in fig. A2.

138 – Was the sensitivity to masking by 28 degrees assessed? Given radar viewing geometries on steep slopes, could better results be achieved by assessing wet snow presence on slopes <28 degrees even though those don't coincide with avalanche starting zones?

Line 138 Our study focuses on using Sentinel-1 data for wet snow avalanche preconditioning. Slopes below 28° were excluded to maintain practical relevance, as they are less critical for avalanche release. Including them would suggest higher accuracy than what can be achieved in the more challenging alpine terrain relevant for our field of application, where spaceborne SAR faces greater limitations.

139 – I suggest referring to it as the number of pixels rather than amount of pixels.

Line 139 Use "number of pixels" instead of "amount of pixels"

153 – could add a reference to the wet snow ratio equation (see previous comments)

Line 153 add a reference to the wet snow ratio equation which will be newly implemented

159 – check formatting throughout regarding en-dashes

Line 159 Check formatting regarding en-dashes to follow the manuscript according to The Cryosphere guidelines: change 2019-20 to 2019–20 throughout.

Fig 2- what is the temporal resolution of the LWC plotted in Figure 2? 3 hrs or has this been smoothed to daily resolution? If smoothed, does the original time series include diurnal variability?

Fig 2 As mentioned in the text we have averaged the SNOWPACK data to best match the S1 LRW. We here calculated the mean between the data available closest to the acquisitions in asc and desc geometry – with an operational setup of SNOWPACK featuring 3h output interval. With this, we attempted to calculate the closest data that actually influenced the radar signal displayed in the upper part of the plot. We can attempt to rephrase in the text and mention correspondingly in the figure caption.

Fig 2 – in 2020, the LWC (blue) increases when HS increases in the spring? HS increases indicate snowfall with <0 C temperatures, so why would LWC increases occur simultaneously? This can also be seen in 05-2018.

The SNOWPACK model gets its mass input from two sources: either by assimilating the snow height or from rain gauges. When assimilating the snow height, by default an air temperature threshold of 1.2°C is used to discriminate between rain and snow (it is also possible to instead rely on a linear interpolation between -2°C and +2°C to produce mixed precipitation). When using data from rain gauges and if the rain gauges are not heated, their data will be discarded except when the conditions are such that liquid precipitation can occur (relative humidity high enough, difference between the air temperature and the snow surface temperature below a given threshold). This allows SNOWPACK to get accurate estimates of mass input (thanks to the snow height assimilation) while also being able to handle rain on snow events (by using rain gauge data in such conditions; Bavay et al., 2024).

Moreover, SNOWPACK uses an internal timestep of 15 minutes, although in its operational mode (as used for the operational avalanche warning) it only write its outputs once every 3 hours, thus sometimes blurring the picture of its handling of the various processes.

In the Spring, it can happen that the air temperature is hovering over the rain/snow temperature threshold and thus generating either rain or snow at each 15 minutes timesteps that will be seen as mixed precipitation when accumulated over 3 hours outputs. Moreover, the station's unheated rain gauges might also provide true mixed precipitation to SNOWPACK. If SNOWPACK is forced with mixed precipitation, both the snow height and the liquid water content might increase simultaneously.

We will Improve clarity in the Figure 2 caption, ensuring it distinguishes between model output and measured data (line 2)

176-77 – given the reference to the other stations, a similar time series to what is shown in Figure 2 should be included as supplementary figures.

Line 176-77 We will provide similar figures in the supplementary figures for the other two stations.

179 – LWC doesn't need to be capitalized when being defined in acronym.

Line 179 Done, thanks.

181 – "a time shift of a couple of days" is vague yet this offset is important to understand. I suggest quantifying this in a more rigorous manner.

Line 181 Quantify the time shift in snowmelt detection instead of using "a couple of days"

185 – capitalize Spearman's

Line 185 Done, thanks.

190 – insert comma after 2018-19, also replace dash with en dash

Line 190 Done, thanks.

193 – clarify: end of April to end of March. Is this meant to be end of May?

Line 193 Good catch! Corrected to "end of April to end of May"

200 – what is meant by hence not extra?

Line 200 This note was meant to indicate that, since water bodies are already excluded by the minimum slope mask of 28°, we did not include an additional subplot in the appendix to specifically assess their influence. However, this detail is not essential and can be removed.

257-260 – If the SNOWPACK model is assimilating the station data (which is what I understand is happening), what is the value in only using the model output at the station locations over the measured station data? Further, why not compare the model output over the full domain to the Sentinel-1 melt products through time?

Line 257-260 The stations only assimilate HS, and relies on meteorological forcings to simulate all snow properties. The stations don't measured LWC or SWE, we will make this clearer throughout the manuscript, so without SNOWPACK it would not have been possible to show the correlation with LWC. For HS, since the model output data at the station location is identical to the measured station data, there is neither a gain nor a loss in using it. We do not compare the model output to the full domain over time because the accuracy of the model decreases as the distance from the station increases. Consequently, comparing a remotely sensed dataset to a modelled dataset over the full domain would not provide meaningful insights, as it would be unclear which dataset is closer to the actual conditions.

265 – was the sensitivity to the selected 3x3 window evaluated? What if a 5x5 window was utilized? This might provide some insight to the previous statement regarding whether "stations having an impact on the radar backscatter."

Line 265 We have tested different window sizes (e.g., 5×5) and found minimal effects on radar backscatter. However, as no method is entirely free from spatial dependencies, we discuss this potential limitation while opting for the higher-resolution 3×3 solution. We will clarify this reasoning in the manuscript.

280 – see previous comment re: time lag

Line 280 Done, thanks.

294 - should this read perimeter rather than parameter?

Line 294 Yes! We have corrected to perimeter, thanks.

298 – revise sentence for improved clarity "this influenced the miss of the first…."

Line 298 Done, thanks.

326 – delete also

Line 326 Done, thanks.

Additional Comments

1. **Discussion on Avalanche Dynamics and Snowmelt Percolation**

I suggest the addition of a Discussion paragraph on avalanche dynamics related to meltwater percolation. Sentinel-1 is sensitive to surface to near-surface melt while wet snow avalanches initiate due to failure of a buried interface or at the bottom of the snowpack. The discussion would benefit from some insights regarding these differences.

We appreciate the reviewer's request to clarify Sentinel-1's sensitivity to different snowpack layers. We note that Sentinel-1 is not exclusively sensitive to surface or near-surface meltwater (Strozzi & Mätzler, 1998). Given the attenuation properties of the radar signal, a buried melt layer or basal meltwater can also act as a dominant specular reflector, resulting in significant backscatter loss. We will include a brief discussion of these effects in the manuscript. Also, while we agree with the reviewer on wet-snow avalanches release is cased due to water percolation deeper in the snowpack, the water has to be produced at the snow surface (Mitterer & Schweizer, 2013)

2. **Rain-on-Snow Events and Avalanche Frequency**

Another common trigger of wet snow avalanches is rain on snow. While it would be beyond the scope of the manuscript to add a significant analysis in this regard, a simple analysis comparing a re-analysis precipitation product (e.g., ERA5-Land) with the avalanche frequency might identify which events are melt related and which were precipitation related, and improve the comparisons presented in this manuscript.

We agree that rain-on-snow is a critical factor in wet snow avalanche formation and acknowledge that a comparison with a reanalysis precipitation dataset (e.g., ERA5-Land) could provide valuable insights. However, the relationship between rain-on-snow events and avalanche occurrence is complex and not as straightforward as suggested (Nander et al.; Würzer et al., 2017). Incorporating a new dataset introduces further, dataset specific uncertainties.

Instead, we will consider analysing the number of recorded wet snow avalanches in the reference catalogue in relation to the temporal distribution of all liquid precipitation averaged over the study area. Such an approach would provide an initial assessment of the potential influence of rain-on-snow events while minimizing additional data usage.

3. Data Availability

Data Availability: See major comment. Also provide a reference for the Gamma software program.

We will add the reference to the software version used and specifically to the Sentinel-1 implementation into the software (Wegmüller et al., 2016). Thanks.

References

Bavay, M., Wever, N., Fierz, C., & Lehning, M. (2024). Looking back at the last 15 years of operational avalanche warning with the snowpack model in Switzerland. In K. Gisnås, P. Gauer, H. Dahle, M. Eckerstorfer, A. Mannberg, & K. Müller (Eds.), *Proceedings of the international Snow Science Workshop 2024* (pp. 82-87). Norwegian Geotechnical Institute.

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Mitterer, C. & Schweizer, J. (2013) "Analysis of the snow-atmosphere energy balance during wet-snow instabilities and implications for avalanche prediction". *The Cryosphere*, 7, 205–216, doi:10.5194/tc-7-205-2013.

Strozzi, T. & Mätzler, T. (1998). "Backscattering Measurements of Alpine Snowcovers at 5.3 and 35 GHz." *IEEE TRANSACTIONS ON GEOSCIENCE AND REMOTE SENSING*, vol. 36, no. 3, may 1998.

Wegmüller, U., Werner, C., Strozzi, T., Wiesmann, A., Frey, O. & Santoro, M., "Sentinel-1 Support in the GAMMA Software", *Procedia Computer Science*, Volume 100, 2016, Pages 1305-1312, ISSN 1877-0509, https://doi.org/10.1016/j.procs.2016.09.246.

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Würzer, S, Wever, N., Juras R., Lehning, M. & Jonas, T. (2017). "Modelling liquid water transport in snow under rain-on-snow conditions–considering preferential flow." *Hydrology and Earth System Sciences* 21.3 (2017): 1741-1756