Reviewer 2

This study used Sentinel-1 SAR data to map snow wetness in alpine areas, finding strong correlations between backscatter and modeled liquid water content, as well as good agreement with wet snow avalanche occurrences (excluding the first wet snow avalanche surge). The results suggest Sentinel-1 has potential for monitoring wet snow avalanche preconditioning, particularly with increased temporal resolution (starting from additional satellite tracks). The paper is in general well written and the use of detailed avalanche catalogue to find a correlation with the Sentinel-1 backscattering is very interesting, even the study area is relatively small. There are some methodological choices that requires further explanation and discussion before the paper can be published in TC.

Dear Reviewer 2,

We sincerely appreciate your time and effort in reviewing our manuscript and providing such detailed and constructive feedback. Your comments raised important methodological and theoretical considerations that will significantly enhance the clarity and rigor of our study. Below, we respond to each point and outline the corresponding revisions we will make (colour-coding: blue review comment, black answer statement).

Major Comments

1. **Assessment of Radiometric Terrain Flattening and Use of Multi-Track Composites**

I expected the authors to demonstrate the added value of radiometric terrain flattening before generating the LRW mosaic, utilizing all four available Sentinel-1 tracks over the study area. Given the rapid temporal changes in snowpack LWC, as acknowledged by the authors, averaging morning and late afternoon acquisitions (as done in the LRW approach, which is essentially a weighted average) may not be optimal. For example, if a morning acquisition has a higher weight, and the LWC is low due to a cold night (resulting in higher backscatter), this could skew the result. This is particularly problematic early in the season, when the afternoon acquisitions can be affected by rapid temperature and radiation drops, showing an already potentially low LWC (and therefore backscattering) from its (midday) peak (which may be the cause of the wet snow activities in April?). To rigorously assess Sentinel-1 ability to detect the initial wet snow avalanche surge, these temporal variations should be analyzed before constructing the LRW mosaic. This analysis would provide a stronger basis for your conclusions. Therefore, the rationale behind using a mosaic with varying timestamps to address layover and shadows at a specific time requires further clarification.

We acknowledge the reviewer's concern regarding the potential biases introduced by averaging Sentinel-1 acquisitions with varying timestamps, particularly given the rapid diurnal changes in snowpack liquid water content (LWC). While, in theory, this is a critical point, our empirical experience suggests that its practical impact is less pronounced. Nevertheless, to strengthen our conclusions, in the revised version we will include an additional analysis using all four available Sentinel-1 tracks to assess the temporal evolution of γ^0 at the WFJ station before mosaicking into an LRW. This will provide insight into the effectiveness of the terrain correction and allow us to quantify potential biases introduced by merging acquisitions from different times of day.

2. **Analysis of Angular Dependencies Between Tracks**

Furthermore, analyzing the four individual tracks prior to mosaicking would provide valuable insight into the effectiveness of the terrain flattening. Residual angular dependencies, especially on aspect angle (the angle between azimuth direction of Sentinel-1 and geographic north), can introduce biases between backscatter acquired from different tracks. Has this been addressed? I recommend showing the temporal evolution of γ^0 for all four tracks over the WFJ station to demonstrate the effectiveness of the terrain correction (in theory no bias should be visible between the tracks). Be aware that ascending and descending acquistions have generally a specular aspect angle.

We appreciate the suggestion to analyze angular dependencies and their potential influence on backscatter variation before mosaicking. To address this, we will include a visualization of the temporal evolution of γ^0 for all four tracks at the WFJ station. This will allow us to assess whether the terrain correction effectively minimizes residual angular dependencies, particularly concerning aspect angle effects. However, we expect that this test will not provide key insights on the matter, as the stations are inherently located in relatively flat terrain, where the influence of radiometric terrain correction is likely negligible.

3. **Strengthening the Literature Review**

The literature review could be strengthened by including additional background studies in both radar remote sensing of wet snow e.g. Murfitt et al., (2024) and wet snow avalanches e.g., Mitterer, and Schweizer (2013). In particular, citing key foundational works and recent publications would provide important context and allow for a more robust comparison with your results (see detail comments). This would also better support why in this study the Copernicus wet snow products were excluded a-priori.

We acknowledge that the manuscript would benefit from a more structured and focused literature review. As suggested, we will refine the discussion by:

- Removing references to dry snow backscatter changes and concentrating on wet snow literature.
- Including foundational works by Mätzler, Ulaby, and colleagues that describe backscattering mechanisms in wet snow.
- Citing more recent studies, including Murfitt et al. (2024), Picard et al. (2022), and Hendrick et al. (2024) and further recently published works.
- Investigating the connection between "first wetting" (Hendrick et al., 2024) and melting phases in SAR multitemporal data (Marin et al., 2020), as this could provide valuable theoretical insights.

- **Clarifying the Study Scope and Adjusting the Title**

While the application of a detailed avalanche catalog and Sentinel-1 backscattering time series is a novel aspect of this study, the title is misleading. The paper appears to be an exploratory investigation into the correlation between wet snow avalanches and LRW composites. Since a more robust justification for using LRW composites as the primary metric for snow wetness evolution is needed, I suggest to better sharpen the current title.

We understand that the current title may not fully reflect the study's primary focus. To better align with the manuscript's objectives, we propose adjusting the title to:

"Extracting Wet Snow Avalanche Precondition Information from Sentinel-1 Multi-Track Composites"

This revised title more accurately conveys that our study is exploratory and focuses on Sentinel-1's potential for monitoring avalanche preconditioning rather than providing a validated operational product.

5. **Ensuring Compliance with Open Science Standards**

Consistent with TC publications policy, I suggest the authors to make the LRW time series and all data publicly accessible. The statement "data available upon request" does not meet current standards for open science and reproducibility. Depositing the data in a recognized public repository (e.g., ENVIDAT or Zenodo, or Dryad) would greatly enhance the value and impact of this work by enabling independent verification and reuse of the data.

We fully support open data policies and recognize the importance of making our datasets publicly available. As noted in our response to Reviewer 1, we will:

- Deposit our code in GitHub.
- Archive all data in EnviDat, ensuring compliance with *The Cryosphere*'s data policy.

Detailed Comments & Minor Revisions

L17: more recent works have been published on how use Sentinel-1 for SWE/runoff modeling e.g., Cluzet et al. (2024) or Premier et al. (2023).

Line 17 We will update the literature references to include more recent studies, such as Cluzet et al. (2024) and Premier et al. (2023), on using Sentinel-1 for SWE/runoff modeling.

L23 to 34: This section would benefit from a more focused literature review. The current "ping-pong" between dry and wet snow literature makes it difficult to follow the narrative. Since the paper focus is on wet snow, I recommend removing the discussion of dry snow backscatter changes and concentrating on a comprehensive review of wet snow literature. Key works by Matzler, Ulaby and colleagues that describe the main backscattering mechanisms in wet snow should be included, as well as recent advancements e.g., Picard et al. (2022) or Murfitt et al. (2024). I also suggest exploring the potential link between the "first wetting" described by Hendrick et al. (2024) and the melting phases presented in Marin et al. (2020) for SAR multitemporal data. Investigating this connection could offer valuable theoretical insights.

Line 23-34 The literature review will be revised to:

- Remove discussions of dry snow backscatter changes.
- Structure the review to focus on wet snow SAR applications.
- Cite additional key references as suggested.

- L41: Two angles affect backscatter: local incidence angle and aspect angle. It is crucial to consider both, as they have distinct effects. To ensure the terrain flattening effectively corrects for these influences, please clarify whether the aspect angle was incorporated into the process. Showing the gamma naught (γ^0) values for all four tracks would be very helpful in identifying any residual biases between them.

Line 41 We will clarify the distinction between local incidence angle and aspect angle in terrain flattening. To visually assess residual biases, we will include an additional figure showing the mean temporal γ^0 values for all four Sentinel-1 tracks at the station WFJ.

L43-45: While I understand the intent of averaging to minimize noise, I believe it is important to consider that the identified "outliers" could represent real-world afternoon wet snow conditions not captured in the morning data. This raises concerns about potentially losing valuable temporal information. I also disagree with the assertion that multi-temporal averaging improves temporal resolution; by combining data from different times, it effectively lowers the resolution. Perhaps exploring alternative noise reduction techniques that preserve temporal fidelity would be beneficial.

Line 43-45 We agree that multi-temporal averaging does not improve temporal resolution but rather increases the effective revisit frequency by utilizing all four available tracks.

The added value of higher revisit frequency is only given if we use more than one ascending or descending track, we will clarify this point and emphasize that our approach enhances data availability rather than true temporal resolution.

L50: The use of a 5x5 meter resolution raises concerns, as the original Sentinel-1 data has a ~5x15 meter resolution. This upsampling introduces artificial detail and does not represent true information gain. A 20x20 meter resolution would be more consistent with the original data. Could you please justify the decision to use 5x5 meters and explain how this upsampling was handled?

Line 50 The decision to use a 5×5 m resolution will be explicitly justified. We will clarify that:

- The original Sentinel-1 resolution is ~5×15 m, meaning the upsampling does as stated by the author does not add information but simply aligns with a higher-resolution DEM thereby becoming closer to point measurements – which is our reference.
- We performed local validation using both a 3×3 window and single-pixel validation at station locations to ensure that upsampling did not introduce artifacts.

Line 69: please use the symbol γ^0 or gamma nought instead of gamma0

Line 69 We will ensure that γ^0 (gamma naught) is consistently used instead of “gamma0” throughout the manuscript and enhance to differentiate between γ^0_T (Radiometric terrain (RTC) corrected backscatter) and γ^0_{LRW} (Weighted sum of contributing RTC backscatter value)

Line 70: To ensure the validity of the results, please provide a more detailed description of how the gamma software processes γ^0. Has the output of the gamma software been compared and validated against the data elaborated by David Small? The original Small et al. (2022) paper highlights potential inaccuracies in SNAP (an ESA software) due to different implementations (see the end of Section II-B). This raises concerns about potential similar discrepancies. A direct comparison or a comment on this would be beneficial for the community.

Line 70 We appreciate the suggestion to provide further details on how γ^0 processing in Gamma software was conducted. The implementation of the radiometric correction into follows Small et al., 2022. As stated in the acknowledgements, we also worked in close collaboration with David Small and our products have been initially validated against products generated by Small et al. (2022).

L126: it is not clear how you perform the average and why.

Line 126 We will provide a clearer explanation of how the averaging process was conducted in SNOWPACK. Specifically, we will state that:
The mean was calculated using the two SNOWPACK values closest to the ascending and descending acquisition times, ensuring consistency with Sentinel-1 observations.

Results section: A comparison of the proposed processing with established methods, such as those of Mitterer and Schweizer (2013), Bellaire et al. (2017), and Hendrick et al. (2024), would greatly enhance the manuscript by demonstrating the novelty and performance of the proposed approach.

Results Section: We acknowledge the suggestion to compare our approach with Mitterer and Schweizer (2013), Bellaire et al. (2017), and Hendrick et al. (2024).

However, this analysis aims to demonstrate the potential for integrating the system into models like SNOWPACK in the future, once the increasing availability of freely accessible SAR data provides sufficiently high temporal resolution. Currently, and as discussed in the manuscript the temporal resolution remains too low to integrate a remote sensing product spanning several days into a model with 3-hourly predictions. Given that our study is exploratory, we do not directly integrate our approach into existing operational workflows. So instead, we will emphasize that our method provides a potential future complement to model-based LWC estimates (such as SNOWPACK), which are spatially restricted (e.g., Swiss nationwide applications) or less resolved than the models available in such high temporal resolution.

Figure 5: The gray dots are difficult to see and could benefit from increased contrast or a different color.

Figure 5 We will improve readability by adjusting the colour of the dots to enhance visibility.

Additional references:

Sascha Bellaire, Alec van Herwijnen, Christoph Mitterer, Jürg Schweizer, On forecasting wet-snow avalanche activity using simulated snow cover data, Cold Regions Science and Technology, Volume 144, 2017, https://doi.org/10.1016/j.coldregions.2017.09.013.

Cluzet, B., Magnusson, J., Quéno, L., Mazzotti, G., Mott, R., and Jonas, T.: Exploring how Sentinel-1 wet-snow maps can inform fully distributed physically based snowpack models, The Cryosphere, 18, 5753–5767, https://doi.org/10.5194/tc-18-5753-2024, 2024.

Marin, C., Bertoldi, G., Premier, V., Callegari, M., Brida, C., Hürkamp, K., Tschiersch, J., Zebisch, M., and Notarnicola, C.: Use of Sentinel-1 radar observations to evaluate snowmelt dynamics in alpine regions, The Cryosphere, 14, 935–956, https://doi.org/10.5194/tc-14-935-2020, 2020.

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

Murfitt, J., Duguay, C., Picard, G., and Lemmetyinen, J.: Forward modelling of synthetic-aperture radar (SAR) backscatter during lake ice melt conditions using the Snow Microwave Radiative Transfer (SMRT) model, The Cryosphere, 18, 869–888, https://doi.org/10.5194/tc-18-869-2024, 2024.

Picard, G., Leduc-Leballeur, M., Banwell, A. F., Brucker, L., and Macelloni, G.: The sensitivity of satellite microwave observations to liquid water in the Antarctic snowpack, The Cryosphere, 16, 5061–5083, https://doi.org/10.5194/tc-16-5061-2022, 2022.

Premier, V., Marin, C., Bertoldi, G., Barella, R., Notarnicola, C., and Bruzzone, L.: Exploring the use of multi-source high-resolution satellite data for snow water equivalent reconstruction over mountainous catchments, The Cryosphere, 17, 2387–2407, https://doi.org/10.5194/tc-17-2387-2023, 2023.

Citation: https://doi.org/10.5194/egusphere-2024-1510-RC2

References We will make sure to implement the suggested literature where appropriate and generally strengthen our literature review as mentioned earlier