# Reply to Referee #1

February 1, 2025

We thank the reviewer for his insightful and useful comments. We will address them to improve the manuscript. Below, you will find the reviewers comments in red and our reply in black.

## 1 Referee #1: Major Comments

- **Zonal and Regional Analysis**:
The paper highlights WIVERN's superior sampling capabilities, but the interpretation of regional results (e.g., Antarctic basins) could benefit from more detailed discussion. For example, if the temporal resolution WIVERN offers is crucial for mass balance studies in these regions.

  Typically, annual and greater scales are useful to understand the ice sheet response to multi year climate modes (e.g. El Niño), ice flow changes due to long term melting or thickening, the impact of ice sheet melting on the sea level rise and the interannual variability of the ice sheet mass balance.
On the other hand, daily to seasonal time scales are useful to understand the seasonal variability, the grounding line migrations and short-term oceanic or atmospheric forcing.

  We will expand the discussion on regional results, including a short explanation on how the temporal resolution is useful for mass balance studies.

- **Clarity of Figures and Tables:**
While figures support the findings, some lack detailed captions or sufficient detail to differentiate WIVERN and CloudSat results effectively. Explaining key trends (e.g., differences in RMSE across snowfall classes) in the text accompanying each figure would improve clarity.

  We will include more details in the explanation of the results and figures.

- **Future Prospects and Limitations:**
While the article touches on potential future research directions, it does not fully address the limitations of the current analysis (e.g., assumptions about the unbiased nature of the reflectivity-snowfall relationship). Adding this discussion would provide balance.

  We agree with the comment and will better discuss the limitations of the current analysis, such as the assumption of the Z-S relationship being unbiased, the assumption of not having a greater path integrated attenuation due to the slant view geometry, and the fact of having a stronger ground clutter over land which might reduce the number of shallow events observed by WIVERN.

- **Improved Approach for Error Statistics**
The methodology for computing error statistics (e.g., RMSE, Absolute Bias) appears to be based on instantaneous measurements, i.e., snowfall rates derived from ERA5 at specific times corresponding to satellite overpasses, with modifications to account for uncertainties in the Z-S relationship. If this interpretation is correct, the resulting error distribution will follow a Gaussian distribution with zero mean (assuming unbiased error) and a standard deviation equal to the uncertainty in the Z-S relationship. Consequently, the RMSE decreases as 1/sqrt(N) by definition due to increased sampling, but this approach does not directly assess how sampling impacts the derived climatology. To evaluate the sampling's effect on climatological estimates, a different approach should be considered:

  - Define the Observing Period: For example, consider a one-month observation period.

- Compute Monthly Accumulations: Use the ERA5 hourly dataset to calculate the "true" monthly snowfall accumulation (or mean snow rate) for each grid cell.
- Compare with Sparse Spaceborne Measurements: Derive monthly accumulations (or mean rates) from the spaceborne measurements using their more sparse sampling.
- Compute RMSE on Monthly Estimates: Calculate the RMSE by comparing the monthly ERA5 estimates with the monthly estimates derived from the spaceborne measurements.

This approach would more accurately quantify the impact of sampling on the derived climatology, as it evaluates errors at the monthly scale rather than relying solely on instantaneous measurements.

We agree with the referee, but we think we adopted the same approach he described as more accurate to evaluate the sampling's effect. Specifically, we followed this procedure:

- Define the observing period: e.g. one month observation period.
- Compute the monthly accumulations: use the ERA5 hourly dataset to calculate the "true" (or reference) monthly snowfall accumulation (or mean snow rate) for each grid cell.
- For each time instant of the ERA5 hourly dataset (i.e. for each hour), compute a mask that flag each point of the grid whether it is observed by CloudSat or not within that hour. The same has been done for WIVERN.
- Hourly masks are applied to the ERA5 hourly dataset to derive the hourly observations of CloudSat and WIVERN.
- Monthly accumulations derived from spaceborne measurements are obtained by summing multiple hourly spaceborne measurements.
- Calculate the RMSE on monthly estimates by comparing the monthly ERA5 estimates with the monthly estimates derived from the spaceborne measurements.

Based on our understanding of the approach suggested by the referee, we think the methodology he suggested is the same as we adopted, and we will explain it better in the manuscript. Please, let us know if this is not true, as we may have misunderstood the methodology you suggested.

- **Misleading Implications About Shallow Snowfall Detection**:
  The article primarily focuses on snowfall estimation over land, which is critical for ice sheet mass balance studies. However, the introduction gives a misleading impression that WIVERN will observe more shallow snowfall events than CloudSat. While this may hold true over open oceans due to reduced surface clutter at slanted incidence angles, it is not the case over land or sea ice. This distinction is crucial and should be clarified to avoid overestimating WIVERN's capabilities in these contexts. Addressing this limitation upfront would align reader expectations with the radar's realistic performance in various environments.

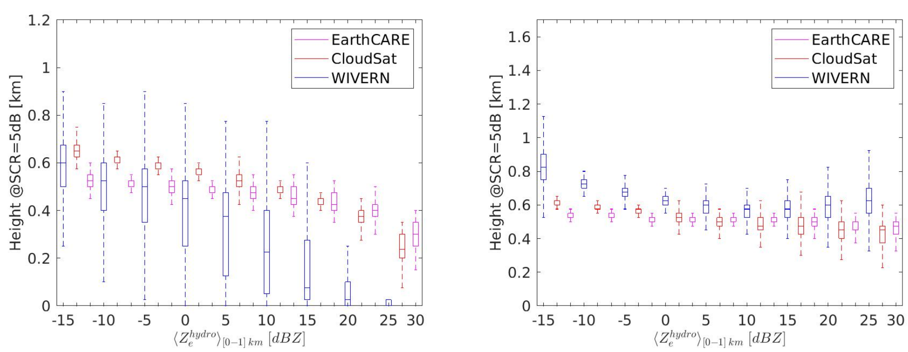


Figure 1: Height of the Signal To Clutter Ratio (SCR) equal to 5dB for different values of $Z_e$ of the hydrometeors at the surface. Whisker plot shows the median, the $\pm15^{\text{th}}$ and the $\pm15^{\text{th}}$ values.

Another study computed the height of the Signal To Clutter Ratio (SCR) = 5 dB for WIVERN, CloudSat and EarthCare, for different classes of hydrometeor reflectivity at the surface ($Z_{[0-1]km}^{hydro}$).

These are shown in figure 1. Boxplots represent the median, 15th and 85th percentile values. Over ocean (left panel), the impact of WIVERN clutter is weaker than the one of CloudSat and EarthCare, especially at larger $Z^{hydro}_{[0-1]km}$. Instead, over land (right panel), WIVERN clutter is slightly stronger, than the other two. We will make this limitation clearer to the readers, and we will address it also earlier in the manuscript.

- **Complexity and Clarity in Figure 4**:
  Figure 4 presents complex data, and the description lacks sufficient detail to make it accessible to readers. Key concepts, such as the definition of accumulation classes, need clarification. For instance:

  - Do the accumulation classes (e.g., snowfall between 36 and 108 mm per year) correspond to snowfall accumulation over the specified period (10 days, one month, or one year) in the ERA5 dataset?
  - How is the ERA5 variability computed for these classes? Is it the standard deviation of snowfall rates for grid cells corresponding to the specified range or maybe it's a mean of the normalised standard deviations?

  Although the concept behind the figure is straightforward, the lack of a detailed explanation makes it harder to follow. Additionally, referencing the central limit theorem (https://en.wikipedia.org/wiki/Central_limit_theorem) could greatly simplify the discussion. The explanation could say that the PDF being sampled is the ERA5 hourly snowfall product for each pixel separately, and the difference in sampling (WIVERN with n1 samples vs. CloudSat with n2, where n2<n1) leads to RMSE convergence as std(snow rate)/sqrt(n) when n is large. This statistical insight could make the sampling error analysis more intuitive. As the domain size or sampling time window grows the value of n grows too and RMSE decreases. The RMSE will be additionally inflated by the S-Z relationship uncertainty but this will affect both instruments in the same way as n gets larger.

  The accumulation classes correspond to the snowfall accumulation over the specified period, in the corresponding ERA5 dataset sampled by WIVERN or CloudSat, and averaged over the given spatial scale domain.
  The variability is computed as the standard deviation of the snowfall rates in all the grid cells across 20 years of data having snowfall rates belonging to a given class, divided by the mean of the snowfall rates of the same grid cells.
  We agree the figure may lack of clarity and we will improve the description of the figure. We will also reference to the central limit theorem when explaining the obtained RMSE results, as the reviewer suggests.

- **Blind zone effect**
  To provide a complete assessment, the paper should include an analysis of how ground clutter affects snowfall statistics for both WIVERN and CloudSat. Currently, this aspect is not addressed, which leaves a significant gap in understanding the limitations of these radar systems. While deriving these statistics directly from ERA5 data would be ideal, it would require extensive effort to analyse the vertically resolved precipitation product. A practical alternative would be to use statistics from the DAR-DAR (Radar-Lidar) A-train product. By deriving a 2D PDF of surface precipitation rate versus cloud top height, the authors could simulate the probability of an event being captured by both radars. This could be done by randomly sampling from the derived PDF. Events with weather system tops falling below the clutter height should have their precipitation set to zero, similar to the treatment in the radar sensitivity discussion. This approach would provide an insightful comparison of WIVERN and CloudSat performance, accounting for ground clutter effects. Obviously, it would not account for processes below the ground clutter height but it will provide a more comprehensive picture of radar limitations in snowfall detection.

  We will use data shown in figure 1 and discussed in the fifth major comment in synergy with DAR-DAR product, as suggested by the reviewer, to evaluate the ground clutter effects on snowfall statistics. We will then include the analysis and results in the next revised version of the manuscript.

## 2 Referee #1: Minor Comments

- Due to the orbit repeat cycle of 25 days, the analysis of CloudSat data blow this time resolution period has limited value.

  We will work to remove the 10 day resolution period and include the seasonal time-scale.

- L106: pencil beam term is used for the delta distribution, use “nadir observations” instead.

  We will substitute the two expressions.

- L190: units of snowfall rate should be mm/h

  We will correct it.

- Figure 7. Some of the colours in the colour bar are repeated or too similar to be distinguishable (e.g. two shades of grey: G7.2 and G3.3 or red G1.2 and G4.1, please use hatching or another way to make them less alike)

  We will improve the colorbar to make the plot clearer.