Manuscript egusphere-2024-3169 version 2

Radar Equivalent Snowpack: reducing the number of snow layers while retaining its microwave properties and bulk snow mass

Note to editor:
We thank all the reviewers for helpful, constructive and thorough comments that helped improve the manuscript. All comments were considered and are addressed in the document below.

Reviewer's comments (R1, …)
Answers to reviewer.
Modification to text. They are visible in green in the track change version.

Reviewer: 1

General comments
• The core idea in the paper, the application of the K-clustering method to reduce the complexity of the snowpack while retaining the backscattering properties and snow mass, is nice and straightforward. However, compared to this, the paper feels a bit cluttered. I think the manuscript would benefit from more clarity.
• For example, are all the 6 reference methods needed? I recognize that together they show how much things can go wrong if one considers the simplest possible case (single layer snowpack), but on the other hand, is this essential to the main point of the manuscript? Is this additional information more important than the distraction that it adds to the results?
• In some instances, the notation is a bit confusing (see specific comments for examples).
• I hope that the authors would check the manuscript again and look for places to improve the clarity beyond the specific comments listed below.

We tried to improve the clarity of the paper by integrating all specific comments and some other improvements directly into the manuscript. We improved the consistency of the terminology in the method and removed some reference methods in Figure 3. Section on computation efficiency was moved to the appendix and a small section on SWE retrievals implication was added.

Specific comments
1. Lines 3-4: "…, with more complex layering yielding richer information but at increased computational cost." It should mention also the increased number of unknowns, since the context is retrieval process.
Thanks, we added "number of unknowns" at the end of the sentence.

2. Line 5: "…, while preserving the microwave scattering …" Perhaps "preserving" is too strong term here, since the scattering does change in the process.
It was changed to "nearly preserving".

3. Line 7: "Then, a weighted average…" This sentence seems disconnected from the previous sentence.
The text was modified to bring to the two sentence together.

4. Lines 13-14: "SWE retrievals can be applied to simplified snowpacks, while maintaining similar scattering behavior without compromising the modeled snowpack properties": The use of the method for retrievals was not demonstrated in the paper.

Indeed we are not showing the use of the method in a retrieval, we are simply mentioning that this method can be used in SWE retrieval applications. This sentence was changed to: “In SWE retrieval applications, this method can be used to simplify snowpacks and reduce the number of variables to optimize, while maintaining similar scattering behavior without compromising the modeled snowpack properties.”

5. Lines 39-40: “… or the identification of weak layers in the context of …” is this part relevant?
This part was removed.

6. Line 44: “SWE (depth and density)” -> “SWE (function of depth and density)”
“Function of” was added

7. Lines 69-71: Sentence starting with “If a method that …” sounds bit weird, please check.
The sentence was modified as follows:
This would allow the accuracy of SWE retrieval not to be compromised and the computation time to be reduced.

8. Lines 119-142 contain quite specific description of the RT modeling. Is this necessary for this paper?
We think it is necessary since it shows how the extinction coefficient is calculated which is central to the methods described in paper.

9. Line 153-154: Ikotun et al. is referred twice.
The second citation was removed, and to avoid repetition, we changed the beginning of the sentence to:
This algorithm identifies groups …

10. Line 163: Unnecessary parenthesis, (\kappa_e) -> \kappa_e, please fix elsewhere also.
Parenthesis were removed.

11. Line 166: “(referred to equal thickness)” -> to as
“as” was added

12. Lines 165-170: h_norm is not defined here? Also, the paragraph discussion h_norm seems to cut between two parts of the text that both discuss K-means clustering. Please consider clarifying and restructuring.
We added this to define h_norm.
… based on the normalized height h_norm which is the height of a layer divided by the thickness of the whole snowpack.

We also rearrange the whole paragraph. This part was moved earlier in the paragraph.
The grouping of layers was done in two ways. The first method was used as a baseline comparison. This method (referred to as equal) aggregated layers based on the normalized height h_norm which is the height of a layer divided by the thickness of the whole snowpack. For instance, two equal thickness snowpack, the top half of the snowpack, i.e all the layers with h_norm greater than 1/2 of the snowpack thickness would be aggregated into a first layer and the bottom half would contain all the layers with h_norm that are less than or equal to ½ of the snowpack thickness. This method is a basic way to obtain an equivalent snowpack with layers of equal thickness. Also, a 1-layer simplified snowpack was considered by grouping all the layers into 1 group to evaluate the worst-case scenario in reducing the number of layers.

13. Also, this paragraph could be otherwise improved. E.g. the sentence “The 1-layer was created by

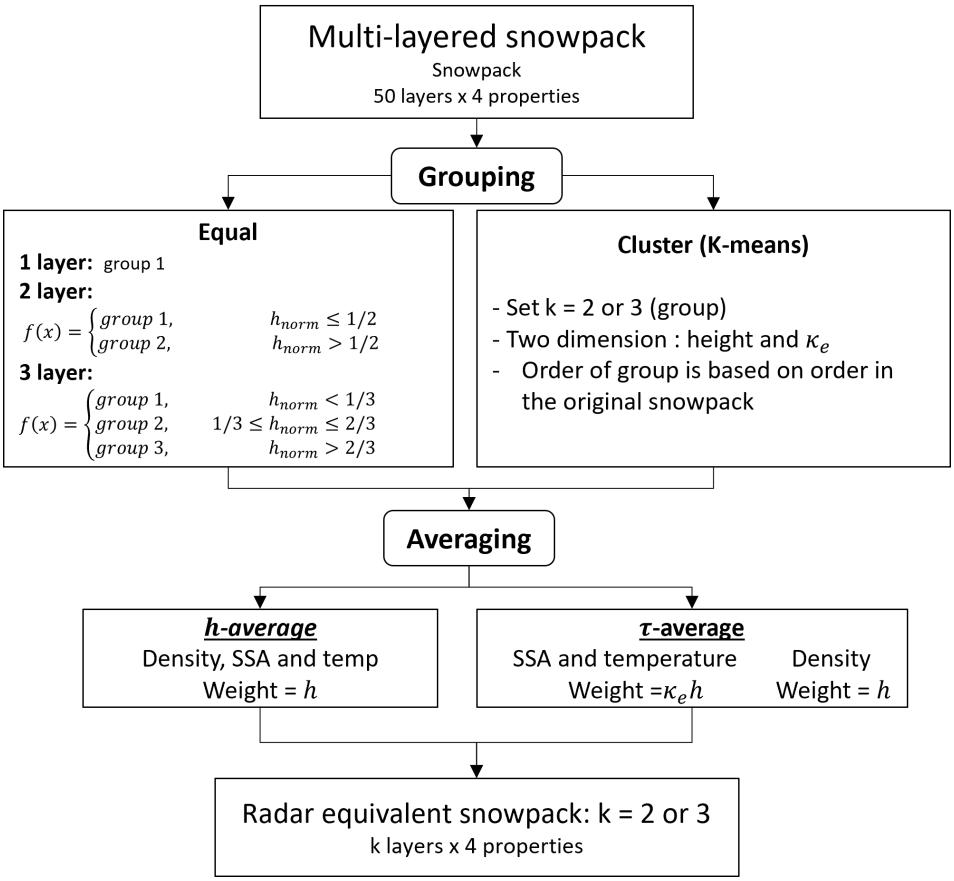
grouping all layers into 1 group" is a bit weird.
The sentence was modified.
Also, a 1-layer simplified snowpack was considered by grouping all the layers into 1 group to evaluate the worst-case scenario in reducing the number of layers.
14. Lines 171-173: Use of h_group is a bit confusing. Is "group" used here as an index, i.e. group = 1,2,3? On the other hand, is the symbol used anywhere in the text after (is it necessary)?
The symbol was removed.

15. Line 174: "(referred to as h_i)" -> "(… h_i-average/averaging)"
The whole paragraph was revised. Link to previous comment.
Once the grouping of layers was done, the snowpack layer properties (density, temperature, and SSA) were averaged. We investigated two different ways of averaging: (1) a weighted average based on h as a baseline (referred to as the h-average), and (2) a new weighted average based on the optical thickness τ=ke×h (Zhu et al., 2021) for SSA and temperature (referred to as the τ-average). The h-average is used for density in both average methods, as it ensures the conservation of SWE. The average density of a snowpack with multiple layers of thickness hi can be defined by:

16. Line 179: "… whole snowpack h_n …": Confusing to use n as a subindex, how does it differ from h_i?. E.g. h_snow could be better.
We change the index to h_snow.

17. Schematics in Figure 1 could be improved to clarify the process. At the moment it is difficult to interpret. I think what should be highlighted is the fact that the process in this paper has two levels, the grouping method and the averaging method, both of which have multiple options, and the different combinations of these two produce the "methods" that are being compared. In addition, some technical points: 0.33 and 0.66 or 1/3 and 2/3? The word "group" appears both as italic and non-italic text. Also, please make the equations less vague, e.g. h_group = \sum h_i, what is summer over?
We added this sentence before Figure 1.
The method is divided into two operations applied on layers: grouping and averaging.

We made the suggested modifications to Figure 1.



18. Line 184: re-defines RMSE, why? It's not used in that section again.
No but it is used later in the paper multiple times.

19. Line 195: The last sentence in the paragraph (starting with "The difference in backscatter was estimated…") is unclear.
The sentence was modified as follows:
The difference in backscatter was estimated between the reference simulation and the transparent simulation to estimate how much the internal interfaces are contributing to the total backscatter.

20. Line 206: "… layers classified as 2 at …". Please make it more clear, e.g.: "classified/assigned as/in/under group/category 2.
We added group #2
The two layers classified as group #2 …

21. Line 210: "… with averaging using the h_i method" This is referred later as h_i-average method? Please use consistent terms for clarity.
We modified the term to be always h-average and \tau-average

22. Line 211: "(1 to 3)" -> "(from 1 to 3)"
We made the modification

23. Line 213: Please clarify sentence "Using a cluster is not always better …". E.g. "… Using a K-means clustering method is not …"
The sentence was modified as follow:
Using the K-means clustering method is not always better than equal grouping

24. Line 214: “\tau-method”. This is later referred to as \tau-average? Please use consistent terms for clarity.
Yes, see comment 21

25. Line 216-217: “Figure 4 shows biases … as a function of snow properties”. Seems a bit awkward sentence, add “methods” after mentioning the two methods?
We modified the sentence as follow:
Figure 4 shows biases for the 3-equal and 3-cluster with h-average method as a function of snow properties

26. Figure 3. is a bit cluttered with the number of time series. Is it necessary to show the differences in its own plots? How would the results look in a scatterplot?
We modified Figure 3 by only showing the different grouping and averaging methods for 3 layers.

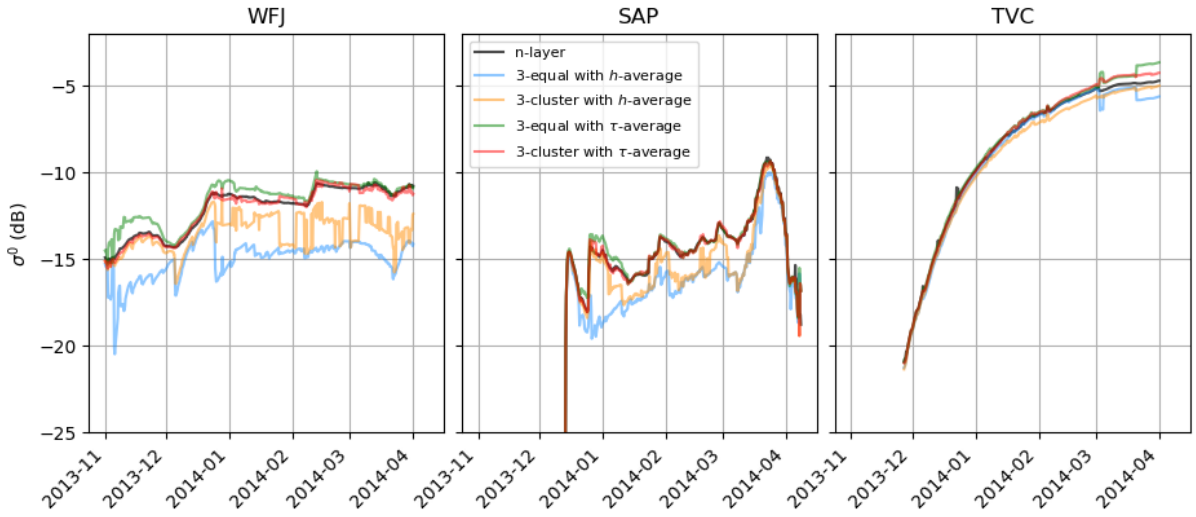


Figure 3. Backscatter time series for reference simulations and different 3-layer grouping and averaging methods. The simulations for the 2013-2014 season at WFJ, SAP and TVC are shown

27. Line 231-233 “The 3-equal with \tau-average achieved similar performance to the …” This seems like an important result. Why is it not mentioned in the conclusions? Is it not so that due to its simplicity, the 3-equal grouping is more reliable compared to K means?
The 3 equal grouping is not more reliable than the K-means. Only that the averaging is a more important factor than the grouping in preserving the backscatter. We also added this in the conclusion.
We found that the averaging method was more important than the grouping method in preserving the backscatter.

28. Could Table 2 be replaced with a graph representing the information, and the Table moved to appendix? This could help to convey the message more clearly.
We decided that the Table was the best option to show the result for all sites, multiple seasons and methods.

29. Section 3.2. is interesting but on the other hand the manuscript is quite long. Is this section necessary for the main point of the manuscript? If it is, then some technical comments: “> 10 GHz, up to 30 GHz” please use words instead of symbols, e.g. “from 10 GHz, up to 30 GHz”. Same comment for “> 40 GHz”. Sentence “…3-equal with h-average because…” add “method” after h-average.
We think this section is important enough to be in the paper. We removed the symbol in this section.

30. Table 3: Change column name “layering” -> “number of layers” and remove repetition of “layer” from the data rows. Similarly, column name “\sigma_0 computation time” could include the unit (s) and avoid repeating it on the data rows. In my opinion the grouping times and associated \sigma_0 computation times (the last 4 numbers in the table) could be given in the caption of the table to reduce its size and make it clearer.
We added all your proposed change. This sentence was added in the caption. We also moved this section to the appendix.
The backscatter computation time for 3 layers is 0.15 s and 0.12 s for 2 layers. The grouping method takes 0.005 s.

31. Line 274: Similar to previous comment, sentences “… while preserving their microwave scattering behavior …” expression “preserving” is perhaps too strong. Please consider another expression, e.g. “aiming to preserve”.
We feel like “preserving the scattering behavior” reflects that. We are not saying we are conserving scattering or preserving the scattering. However, we added “nearly impact the scattering behavior” in the previous paragraph.

32. The last paragraph in conclusions is a good addition. However, I found the paragraph too vague. The application of the method to SWE retrievals is one of the main motivations of the study and it is mentioned on many occasions in the manuscript. Therefore, I think it requires more attention and concrete detail. Also, I think this part should be moved to discussions and summarized in conclusions in shorter format.

We added this paragraph on SWE retrievals implication in a new section (3.3) of discussion.

In SWE retrieval applications, the number of variables that need to be optimized plays a crucial role in determining the accuracy and efficiency of the retrieval process. One of the most significant advantages of adopting a radar equivalent snowpack representation is its ability to reduce the number of optimized variables without substantial loss of information. Now, an important choice still has to be done on whether 2 or 3 layers is best. We saw that backscatters from a 2-layer snowpack are slightly degraded compared to using a 3-layer snowpack (Table 2). Despite this small degradation with simplifying into 2 layers, retrieval applications could still benefit in terms of computational efficiency and reduced solution space, which can be advantageous for operational or large-scale applications. However, simplifying into 3 layers would offer a better representation of snowpacks across all climates.

In a Bayesian retrieval, calculating the mismatch term involves running a radiative transfer model and then optimizing the resulting posterior parameters. Using the radar equivalent snowpack would imply that the optimization is performed for a snowpack represented by a reduced number of layers, rather than its full complexity. Concurrently, the prior distributions for snow properties, which are sourced from SVS2, are also reduced to this number of layers. This consistent approach ensures that both the forward modeling for the mismatch term and the prior information is based on a comparable, simplified structural representation of the snowpack.