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Interactive comment on "3D-VAR multilayer assimilation of X-band SAR data into a detailed snowpack model" *by* X. V. Phan et al.

Anonymous Referee #1

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A new scheme for assimilating X-band Synthetic Aperture Radar (SAR) remote sensing data into a multilayer snowpack model is presented. A proposed Electromagnetic Backscattering Model (EBM) simulates the backscattering of the snowpack, using as input snowpack density and grain size properties from the multilayer one-dimensional Crocus snow model. Crocus is forced with SAFRAN atmospheric reanalysis data from the French alps. At each 11-day SAR timestep, the Crocus model is updated using a 3D-Var data assimilation approach, in which the distance between simulated backscatter and observed backscatter, as well as the distance between a priori and a posteriori estimates are minimized. The method is tested in a case study for the Argentière Glacier in the French alps, revealing a general good agreement between simulated backscatter (without assimilation) and changes in snowpack structure following assimilation. The success of the scheme is to be evaluated against in situ data in future

studies.

General Comments:

This article presents a new data assimilation scheme that makes use of newly available radar data that can potentially be used to improve snowpack evolution models. Although the scheme is not validated using in situ measurements, this is presented as a subject for future work. The article is well written and well-organized and should be published, pending minor changes. General comments are provided below:

(1) The presentation of results needs to be expanded and clarified somewhat. Within the results and conclusions sections, the authors should discuss what specific information was gleaned from the case study, how it relates to current literature, if applicable, and how this information can be used for future work. See specific comments for further suggestions.

(2) The authors mention that SAR data can be used to measure snow pack liquid water content. However, the model discussed only applies to dry snow. This should be made clear throughout the paper. For instance, the introduction section should emphasize that this is a model for dry snow and that the case study is carried out only for dry snow conditions. Data should be presented in the results section to show that it is unlikely that there were substantial changes in snowpack liquid water content for the study location and duration of the study period. The conclusions should include some discussion of liquid water and should note that the assimilation scheme cannot be implemented when changes in liquid water content are likely.

(3) It would improve the paper to expand the last paragraph of the introduction section and mention why this study is unique and novel. For instance, the authors could mention that the new availability of high-resolution radar data provides detailed snowpack information that can be used for assimilation, etc.

(4) The results section, Section 5, can be split into two parts. The first part discusses

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estimation of error of the quantities being assimilated. It begins on Line 9 on page 4896 and ends on Line 12 of page 4897. I would suggest making this a new section, section 4.4, which discusses error estimation. The remaining portion of Section 5 can remain as section 5.

Specific Comments:

1. P. 4882 Lines 14-16: This is a rather general statement. Can it be made more specific?

2. P. 4883 Lines 21-22: Suggest changing "i.e. the SAR backscattering coefficients" to "i.e. the number of SAR backscattering coefficients".

3. P. 4884 Lines 13-14: Please give a very brief description of the 3D-VAR method here.

4. P. 4884 Lines 13-18: I suggest expanding this paragraph to emphasize the novelty of this approach, and the role of liquid water, as discussed in the general comments. Also, it would be useful to provide a brief summary of the following sections here so the reader knows what is coming next. (e.g. in section 2 we present an EMW backscattering model, to be used in converting snowpack properties into backscatter, etc.)

5. P. 4885 Line 17: Define "RT equation".

6. P. 4885 Lines 8-10: Provide symbols in parentheses next to the name of each, e.g. "air-snow interface (Mas)".

7. Figure 1, caption: The caption should mention the transmission terms that are shown in the center of the snowpack.

8. P. 4886 Line 20: What does "n" represent?

9. P. 4887 Line 4: Suggest replacing "absorption" with "attenuation".

10. P. 4887 Lines 14-15: Perhaps replace with "the average size of snow particles

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becomes larger than the wavelength. . .” or “the characteristic length scale of the snow-pack structure becomes larger than the wavelength. . .”.

11. P. 4887 Line 22: Please define “j”.

12. P. 4888 Line 7: Specify that “k” is the layer number and k-1 is the layer above it.

13. P. 4889 Line 14: Define “I” in the basic radiative transfer equation.

14. Figure 2: This figure is from Vionnet et al., 2012. Do the authors have permission to use it? It should be specified in the caption that this figure is adapted from Vionnet et al., 2012 and that the authors have permission to use it here. Otherwise it should be removed.

15. P. 4891 Line 8: What is meant by “homogenous within a given mountain range”? Perhaps this should say “homogenous for a given mountain range and elevation”. Specify which mountain range applies here, i.e. the French Alps.

16. P. 4891 Line 20: Perhaps this should say “integrate observations and modeling. . .”?

17. Figure 3, caption: The caption refers to $\sigma 0$ while the figure shows σobs. Perhaps σobs should be replaced by $\sigma 0$, since $\sigma 0$ is used in the text.

18. P. 4893 Line 2: Perhaps it would be useful to mention, at the end of this section, what criteria are used to determine when the iteration process stops.

19. P. 4893 Line 16: The phrase “allowing to add an a priori information” is unclear. It is not clear what the authors trying to convey. Please revise this sentence.

20. P. 4894 Line 8: Is this a TerraSAR-X image? Replace “the image” with “a TerraSAR-X image” or indicate its source, if it is not from TerraSAR-X.

21. P. 4894 Line 16: Can the authors provide a brief description or reference regarding the Frost filter?

22. P. 4894 Lines 17-26: The purpose of presenting Figure 5 is not clear to me. Are the

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authors trying to show that TerraSAR-X data exhibits detectable changes that are likely due to changes in snow properties? If so this should be stated within this paragraph before introducing Figure 5. Also, the authors should discuss the possibility of changes in liquid water content during this period and whether they think liquid water could affect the observed changes. If the authors can provide a range of temperatures from SAFRAN, or a figure showing a timeseries of temperatures at different elevations, this would be helpful.

23. P. 4894 Line 18: What is the "area" being referred to? Are these all the pixels within the red box labeled 2700 m in Figure 4, or pixels along the red line within a range of 2700 m? Please provide the specific details here.

24. P. 4895 Line 1: Is Crocus run for all TerraSAR-X pixels? Specify this in this section and indicate that the elevation determines what SAFRAN data are used to force Crocus. If this is the case, what dataset is used to provide elevation?

25. P. 4895 Line 7: Specify the time period for Figure 6. There seems to be a smaller number of points per altitude compared to the previous figure. What is the reason for this? Also, insert "(d)" after "snow depth". 26. Figure 6, caption: Mention the time period covered by the data shown.

27. P. 4895 Line 8: Is it "relative" or "effective" permittivity?

28. P. 4895 Lines 12-15: As in the previous section, the purpose of this comparison is somewhat unclear. I think the authors are trying to say that there is an observed relationship between Crocus grain properties at reflectivity, and that it makes sense to use grain properties to calculate reflectivity. This should be made clearer here.

29. P. 4895 Lines 21-22: It might be helpful to remind the reader here of the symbols used for the roughness parameters of the two interfaces.

30. P. 4896 Lines 4-6: This does not seem to be true from the data presented in Figure 7. It would be more accurate to say that the two backscattering mechanisms

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are of comparable magnitude, with the volume scattering mechanism exhibiting more backscatter on average for values of SWE between 800 and 1000 mm.

31. P. 4896 Line 15: As shown in Figure 9, the snow depth can be indirectly changed even though it is not directly adjusted through assimilation. Revise to indicate that the algorithm does not directly change snow depth.

32. P. 4896 Line 21: For clarity, revise to "where σi and σj represent the standard deviation of the error on xi and xj, which. . ."

33. P. 4897 Line 13: Change "data is available" to "data are only available".

34. P. 4897 Lines 20-21: Figure 4 only shows 3 altitudes. Can all 7 be included?

35. P. 4897 Line 22: Data for three days, not two are shown in Figure 8. Please specify the dates here.

36. P. 4897 Line 26 – P. 4898 Line 1: Suggest simplifying the sentence to "EBM simulations for the Crocus open loop, i.e. independent of TerraSAR-X observations.

37. Figure 8: The blue triangles are often not visible. Can the figure be adjusted so that they are visible?

38. P. 4898 Line 12: Suggest changing "between EBM simulations" to "between EBM simulations for the open loop".

39. P. 4898 Lines 12-14: The authors suggest that the EBM is responsible for the gap between simulated and TerraSAR-X reflectivities. However, once assimilation occurs, the profile is quite close to the observed profile. Is it not also possible that Crocus may inaccurately simulate the snowpack for this region, and the assimilation process improves its representation of the snowpack? If the EBM is indeed inaccurate in this area, does this mean that the analyzed Crocus snowpack is potentially less realistic, and therefore there are limitations to the method used? The authors should add further discussion here.

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40. Figure 9: I would suggest revising the y-axis to read “Elevation within snowpack (cm)” “Depth” implies distance below the surface.

41. P. 4898 Lines 20-21: Generally, the open loop shows higher densities at deeper depths. I would suggest indicating that the speed of the densification process slows rather than simply saying that it changes.

42. P. 4898 Line 26: Define “slightly different”. What is, roughly, the average difference in temperature? These differences appear to be partially a result of the differences in snowpack thickness. Perhaps the authors should mention this.

43. P. 4898 Line 28: It would be helpful to include a concluding paragraph here discussing the implications of the results. For instance, the results show that substantial changes in showpack structure can occur as a result of the proposed assimilation process. If these changes are realistic than it may indeed be useful for improving predicted snowpack structure.

44. P. 4899 Line 9: “interesting results” is too general. Provide some specific details about the results.

Technical Corrections:

1. P. 4882 Line 2: Change “structure” to “structural”.

2. P.4882 Lines 11-14:. Suggested change: Change “. . .snowpack structure properties,. . .” to “. . .snowpack structure properties, allowing it to continue simulation of snowpack evolution, with adjustments based on remote sensing taken into account.”

3. P. 4882 Line 19: Change “greater” to “a great”

4. P. 4882 Line 20: Change “avalanches” to “avalanche”.

5. P.4883 Lines 2-3: Change “and therefore adjust these values according to modelling and observations error statistics.” To “and adjust these values according to error statistics of the model and observations.”

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6. P. 4885 Line 8: Change “Stokes vector scattered” to “Stokes vector for radiation scattered.”

7. P. 4886 Line 5: Change “Fig. 1” to “Figure 1”.

8. P. 4887 Line 4: Change “4 types: related. . .” to “4 types: (1) transmission between two layers, (2) absorption by the snow particles”, etc.

9. P. 4888 Line 16: “terms:” to “term:”

10. P. 4891 Lines 11 and 12: Replace “. . .” within parentheses with “, etc.)”.

11. P. 4891 Line 18: Change “data into” to “data with”

12. P. 4891 Line 21: Replace “searching a solution” with “searching for a solution”.

13. P. 4891 Line 23: Replace “scheme” with “schematic”.

14. Figure 3, caption: Change “scheme” to “schematic”. Change “input of the process” to “inputs of the process”. Remove comma after “σ0”.

15. P. 4892 Line 17: Change “with” to “where”.

16. P. 4893 Line 5: Change “a specific” to “specific”.

17. P. 4893 Line 17: Replace “used as guess” with “used as guess variables”.

18. P. 4893 Line 19: Replace “guess” with “the guess”

19. P. 4894 Line 3: Replace “on the region” with “in the region”.

20. P. 4894 Line 5: Change “Table shows” to “Table 1 provides”.

21. Figure 4: For clarity, it would help if portions of the image were labeled (a), (b), (c), (d). The caption should include a reference to each element. For example, “(a) General location of the TerrraSAR-X image in the French alps, (b) Closeup view of a portion of the area seen in (a), (c) The TerraSAR-X image within the area enclosed by the region outlined in (a) and (b),. . .etc.”

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22. Figure 4, caption: Change “the crop” to “a cropped”

23. P. 4894 Line 10: Change “altitude by” to “altitude in”

24. P. 4894 Line 12: Change “the whole season 2008-2009” to “the entire 2008-2009 season”.

25. P. 4895 Line 3: Change “consists” to “consist”, remove the “and” before “their density”.

26. P. 4895 Line 4: Insert “the” before “volume”.

27. P. 4895 Line 7: Change “Fig. 6” to “Figure 6”. Change “snow depth by the” to “snow depth and”.

28. P. 4895 Line 11: Remove “is” before “largely depends”.

29. P. 4895 Line 14: Replace “sensivity” with “sensitivity”.

30. P. 4895 Line 17: Replace “sensitivy” with “sensitivity”.

31. P. 4895 Lines 18-21: Change “correspond” to “corresponded”

32. P. 4895 Line 22: Change “ground” to “ground-snow interface”.

33. P. 4895 Line 23: Change “taken into consideration” to “used”.

34. P. 4896 Line 4: Change “Fig. 7” to “Figure 7”. Change “As it” to “As”.

35. Figure 7, caption: Change “differents snowpack structure” to “different snowpack structures”.

36. P. 4896 Line 6: Replace “it shows” with “this shows”.

37. P. 4896 Line 15: Replace “therefore” with “and therefore”.

38. P. 4896 Line 16: Change “At first” to “At the first”.

39. P. 4897 Line 1: Change “and are” to “and is”

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40. P. 4897 Line 5: Change “can be splitted into 3 cases 5:” to “can be split into 3 cases:”

41. P. 4897 Line 12: Change “fitted” to “fit”. Remove the word “only” following “variables”.

42. Figure 8: Replace “potision” with “position” on the x-axes.

43. P. 4897 Line 23: Insert “a” before “very”.

44. P. 4897 Line 24: “Standard deviation” rather than “standard variation”?

45. P. 4898 Line 6: Change “produce” to “produces”.

46. P. 4898 Line 9: Change “Fig. 8” to “Figure 8”.

47. P. 4898 Line 16: Change “done” to “effected”.

48. P. 4898 Line 22: Suggest making the sentence beginning on line 22 the start of a new paragraph.

49. P. 4898 Line 23: Add “in Figure 9” after “also shown.”

50. P. 4898 Line 28: Change “close loop simulation” to “closed loop simulations.”

51. P. 4899 Line 2: Change “using data analysis” to “using a data analysis”.

52. P. 4899 Line 3: Change “snowpack detailed simulation” to “ a detailed snowpack simulation”.

53. P. 4899 Line 7: Change “we have the possibility” to “we are able”.

54. P. 4899 Line 10: Change “snow cover area monitoring on massif scale” to “large-scale snow cover area monitoring”

55. P. 4899 Line 12: Change “will be concentrated” to “will concentrate”.

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