Dear anonymous reviewer 1,

We are grateful for your helpful an detailed comments which allowed us to improve our manuscript.

The text in *italic* contains your original comments, the normal text represents our responses to your comments whereas the text in **bold font** shows the modifications made to the manuscript.

Responses to your general comments:

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.*

   The results and discussion sections (section 5) have been updated to improve clarity. The following changes have been made:

   - The text from "With preset air-snow interface ..." (p4896 line 9) to "...the average value of $\mathbf{R}$ = 0.03" (p4897 line 16) has been moved to the end of data assimilation section (section 3).
   - A figure has been added to show the implementation of the data assimilation process into Crocus and to define the "open loop", "guess" and "assimilated" snow profiles.

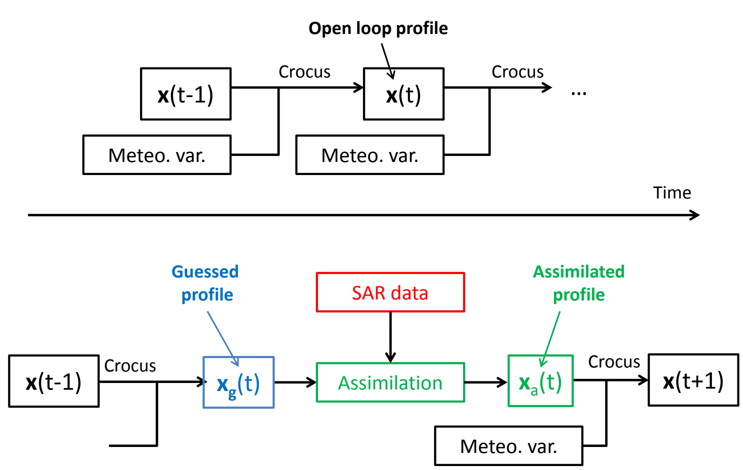

Figure 8. Implementation of SAR data assimilation in the Crocus temporal simulation of a snowpack.

A paragraph has been added to comment on this figure: **Figure 8 presents the implementation of the SAR data assimilation process into Crocus. The top part of the figure shows the Crocus simulation of snowpack without assimilation of SAR data. At instant t, Crocus simulates the snow stratigraphic profile from the previous state of snowpack (instant $t-1$) and the meteorological data hourly provided from SAFRAN. The time lag**

between instant t and instant $t-1$ is therefore one hour. We call this simulation "open-loop". The bottom part of the figure shows the implementation of data assimilation into the execution of Crocus. Each 11 days, a TerraSAR-X acquisition is used to modify the snowpack stratigraphic profile of Crocus through an assimilation process. The snow profile before assimilation is called "guess" and the analyzed snow profile after assimilation is called "assimilated". Consequently, at the date of the first TerraSAR-X acquisition (January 6th 2009), open loop and guess profiles are identical. Once this first SAR acquisition is assimilated into Crocus, guess and assimilated profiles differ. This modification permits to constrain a physical snowpack simulation using external information acquired at different dates.

- Figures 8 and 9 in the original manuscript have been updated with the latest results (using a newer version of Crocus, with all TerraSAR-X acquisitions included). They are now numbered 9 and 10 due to the addition of a figure above. We have also added a table comparing of the RMSE between σ_{snow} (EBM simulations) and σ_{TSX} (TerraSAR-X observations) to highlight improvements made by data assimilation.

Table 2. Comparisons of RMSE (dB) between simulated, $\sigma_{snow} = H(\mathbf{x})$, and measured, σ_{TSX}, reflectivities for different types of profiles

Date	$\mathbf{x}$ = open-loop	$\mathbf{x}$ = guess	$\mathbf{x}$ = assimilated
Jan 6th	3.6256	3.6256	3.2697
Jan 17th	3.1677	3.3645	3.1302
Jan 28th	3.4697	3.5326	3.3718
Feb 8th	3.4649	3.3619	1.8071
Feb 19th	3.3708	2.6463	1.2729
Mar 2nd	3.6877	1.7992	1.2276
Mar 13th	3.7383	1.2482	1.0652
Mar 24th	3.1840	0.6757	0.4370

The paragraph of p4898 from line 8 to line 14 has been updated with: **The agreement between TerraSAR-X reflectivity and the output of the EBM using Crocus simulated profiles can be observed in Figure 9, where EBM simulations of assimilated profiles converge gradually with time toward the TerraSAR-X backscattering coefficient. The graph correspond to March 2nd, 2009 shows that the convergence has been reached at all altitudes, as EBM simulations of guess and assimilated profiles are much closer to the TerraSAR-X measurements than the open loop profiles.**

Table 2 shows a comparison of RMSE between simulated and measured reflectivities for different types of profile: open loop, guess and assimilated. It can be observed that the σ_{snow} converge gradually toward the σ_{TSX} for the guess and assimilated profiles. At the last date of acquisition (March 24th), the RSME for guess and assimilated profiles are below 1 dB while the open loop profile still gives a RSME higher than 3 dB.

The discussion paragraph of p4898 from line 15 to line 28 has been updated with a new discussion

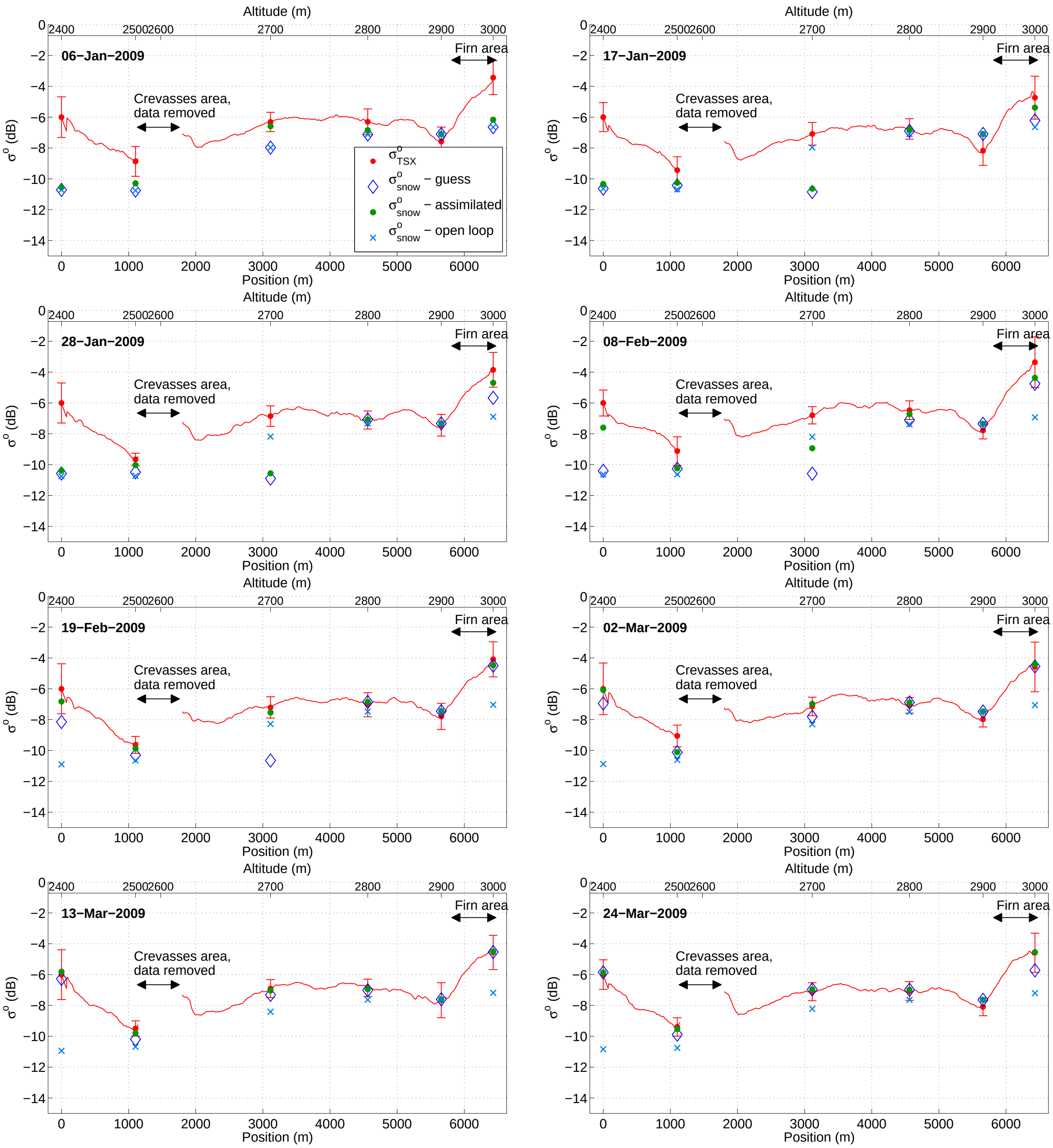

Figure 9. Results of simulation and analysis using TerraSAR-X acquisitions performed on March 2nd, March 13th and March 24th of 2009. σ_{TSX} (red) are mean values obtained from the SAR images over the Argentière glacier (corresponding to the red line of Figure 5). σ_{sim} (blue) represents the output of simulations using Crocus snowpack variables as inputs. Simulations obtained after data analysis are shown in green. Error bars show the standard deviation of the measured reflectivities.

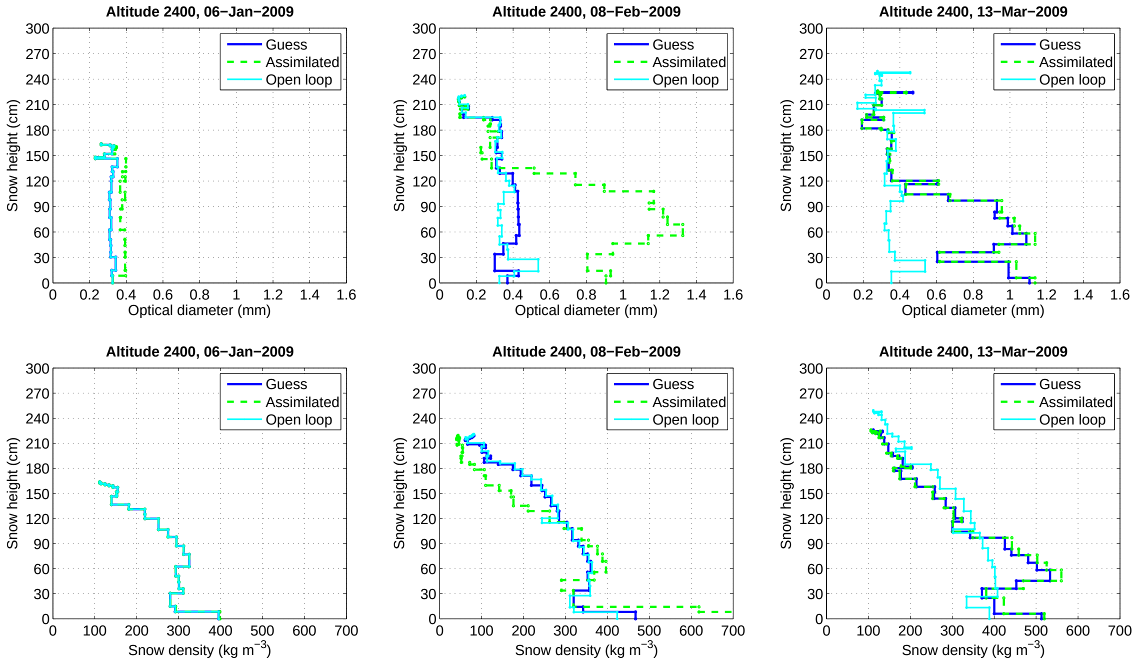

Figure 10. Results of 1D-VAR data assimilation on some Crocus profiles, which show changes made by the data assimilation algorithm on grain optical diameter (top) and snow density (bottom) on January 6th (left), February 8th (middle) and March 13th (right). Note that the assimilation only affects directly the grain optical diameter and snow density. These direct modifications are injected into Crocus, propagate in the subsequent simulations, and may then lead to open-loop and assimilated profiles with different snow heights.

of the results and a conclusion: **Figure 10 shows a detailed analysis of the modifications of the optical diameter and density of each layer due to data assimilation on January 6th, February 8th and March 13th, 2009 at the altitude of 2400 m. It can be observed that the assimilation algorithm tends to modify the grain optical diameter and density in the deep layers which have the strong influence on the backscatter intensity and whose slight modification reduce significantly the discrepancy between TerraSAR-X observations and Crocus simulations. The speed of densification process is therefore faster in the Crocus simulations with assimilation. The snow profile on February 8th records a large change in the optical diameter (from 0.4 mm to 0.8-1.3 mm in the layers from 0 to 100 cm of snow height), which results in a variation in the simulated backscattering coefficient for the assimilated profile, which can be observed in figure 9 at 2400 m. Note that this large increase in the diameter results in a large discrepancy between open loop and guess profiles on March 13th. It can also be noted that there is a difference of 20 cm in total snow depth between open loop and close loop simulation on March 13th, which shows that the modifications of optical diameter and snow density made by data assimilation also modify indirectly others physical properties of the Crocus simulated snowpack.**

These results show that we have combined three models (Crocus, EBM, adjoint model) and the TerraSAR-X data to constrain spatially and temporally the snowpack evolution. It is the first time that active X-band radar data are not used directly to perform an assessment of snowpack properties, but used to estimate physical parameters of each snow layer through a data assimilation algorithm. This algorithm needs to be further validated in the future using in-situ measurements and advanced 3-D imaging techniques (Ferro-Famil et al., 2012).

- The first paragraph of the conclusion section has been rewritten: **This study presents a new system using data assimilation and a multilayer snowpack backscattering model based on the radiative transfer theory to constrain the evolution of a snowpack simulated by the snow model Crocus. The proposed new backscattering model adapted to X-band and higher frequencies enables a fairly accurate calculation of EMW losses in each layer of the snowpack. Through the use of 1D-VAR data assimilation based on the linear tangent and adjoint operator of the EBM, we are able to modify in a physically consistent way the snowpack profiles calculated by the snowpack evolution model Crocus. This process has been applied to a time series of TerraSAR-X images and Crocus simulations during the winter of 2008-2009 over the Argentière glacier. Results show that SAR data can be taken into account to efficiently modify the evolution of snowpack simulated by Crocus. This process can be further developed and used in real application such as large-scale snow cover monitoring or snowpack evolution through a long period of time.**

[Ferro-Famil et al., 2012] Ferro-Famil, L., Leconte, C., Boutet, F., Phan, X., Gay, M., and Durand, Y.: PoSAR: A VHR tomographic GB-SAR system application to snow cover 3-D imaging at X and Ku bands, in: Radar 720 Conference (EuRAD), 2012 9th European, pp. 130133, 2012.

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.*

   Indeed, the study is limited to dry snow medium only. We have modified the abstract to specify that the electromagnetic backscattering model (DMRT) is developed only for dry snow (p4882, line 6-8): **These snowpack properties are used as inputs of an Electromagnetic Backscattering Model (EBM) based on Dense Media Radiative Transfer (DMRT) theory, which simulates the total backscattering coefficient of a dry snow medium**.

   The introduction on the study site of Argentiere glacier has been modified to underline the dry snow condition (p4894, line 6-9): **The area of interest covers the Argentière glacier (Altitude: 2771 m, 45.94628° N, 7.00456° E). The size of the domain is approximately 5 km × 6 km. Over the glacier, altitude varies from 2400 m to 3200 m, and the snowpack is essentially composed of dry snow.**

   The Crocus simulated snowpack for the studied period has been verified for dry snow condition (p4897, line 18-20). The conclusion section has been updated with the discussion on the limitations of this method: **This system however, has some limitations, like the inability to simulate and assimilate under wet snow conditions due to the hypothesis used in the EBM. Another important hypothesis made in this study concerns the spherical shape of snow grains. This assumption highly simplifies the modeling problem, but on the other hand prevents the simulations over cross-polarization channels (HV and VH). The discussion on how to resolve these limitations should be addressed in another study on the modeling of electromagnetic waves interactions with a snowpack.**

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.*

   The introduction section has been updated with more information on the novelty of this study. The schematic of the data assimilation process has been improved and put in the introduction section for more clarity.

   P4882, line 23: **The new generation of Synthetic Aperture Radar (SAR) satellite data provides images with metric resolution and short revisit time. The TerraSAR-X satellite, with 1.477 m x 2.44 m resolution and 11 days revisit time, provides dense information both spatially and temporally on snowpack evolution. In this study, we propose a new process which uses these multi-temporal images of TerraSAR-X to constrain the Crocus model through data assimilation.**

   P4884, line 1: **The advantages of the assimilation using SAR images are the quasi-independence**

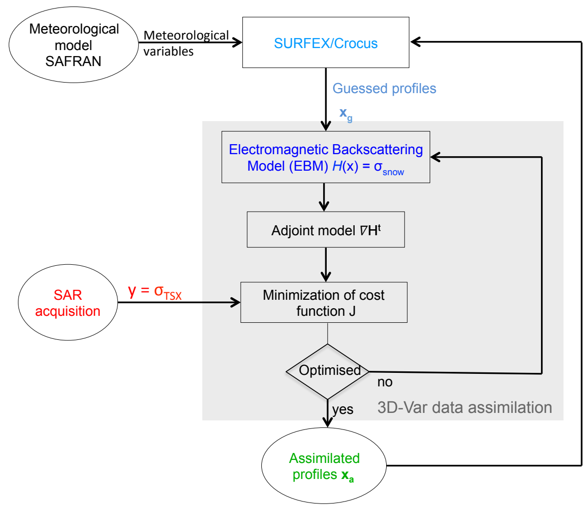

Figure 1. Global schematic of the data analysis used in this study. The inputs of the process are the SAR reflectivities, σ^0 (observation) and the snowpack stratigraphic profile calculated by Crocus (guess). The output is the analyzed snowpack profile $\mathbf{x}$ that minimizes the cost function.

with respect to atmospheric conditions, the high resolution of analysis and the sensitivity of SAR responses to the presence and structure of volumetric mediums. The use of data assimilation on SAR data and meteorological models to predict certain physical properties of snowpack has been developed in the literature (Nagler et al., 2008; Takala et al., 2011). This study attempts to implement a data assimilation system which is capable of constraining a detailed snow metamorphism model at a layer scale (modification of the physical properties of each layer) using X-band SAR data.

[Nagler et al., 2008] Nagler, T., Rott, H., Malcher, P., and Muller, F.: Assimilation of meteorological and remote sensing data for snowmelt runoff forecasting, Remote Sensing of Environment, 112, 1408 1420, Remote Sensing Data Assimilation Special Issue, 2008.

[Takala et al., 2011] Takala, M., Luojus, K., Pulliainen, J., Derksen, C., Lemmetyinen, J., Karna, J.-P., Koskinen, J., and Bojkov, B.: Estimating northern hemisphere snow water equivalent for climate research through assimilation of space-borne radiometer data and ground-based measurements, Remote Sensing of Environment, 115, 3517 3529, 2011.

P4884, line 13: **This study reports for the first time, on a new process based on the DMRT model and on the one-dimensional variational analysis (1D-VAR) to assimilate TerraSAR-X data into the snow model Crocus. A global schematic of this process is presented in figure 1.**

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

The error estimation subsection has been parted from the result section and moved to the 1D-VAR data assimilation section, as stated in the answer the the first general comment.

Responses for your specific comments:

1. P. 4882 Lines 14-16: The sentence has been modified: "Results of data assimilation using TerraSAR-X images on specific site Argentère glacier (Mont-Blanc massif, French Alps) show that we can take into account the SAR data in the evolution of snowpack simulation."

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

3. P. 4884 Lines 13-14: The introduction section has been rewritten

4. P. 4884 Lines 13-18: The introduction section has been rewritten

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

6. P. 4885 Lines 8-10: Symbols provided next to the name of each factor.

7. Figure 1, caption: Figure has been modified

8. P. 4886 Line 20: The expression of these terms can be found in Fung and Chen (2004). The citation in the paper has been modified.

9. P. 4887 Line 4: "absorption" replaced with "attenuation".

10. P. 4887 Lines 14-15: Sentence replaced to "the average size of snow particles becomes larger than the wavelength".

11. P. 4887 Line 22: "j" defined.

12. P. 4888 Line 7: Specified the layer number k and k-1

13. P. 4889 Line 14: "I" defined.

14. Figure 2: We have the right to use the figure, the authors of the figure has been cited.

15. P. 4891 Line 8: Sentence modified to "homogenous for a given mountain range and elevation" with the French Alps specified.

16. P. 4891 Line 20: Sentence modified to "integrate observations and modeling"

17. Figure 3, caption: Caption has been modified.

18. P. 4893 Line 2: The criteria to determine when the iteration process stops has been added

19. P. 4893 Line 16: The phrase has been modified.

20. P. 4894 Line 8: TerraSAR-X image specified in the text.

21. P. 4894 Line 16: Reference to the Frost filter added.

22. P. 4894 Lines 17-26: The figure has been modified to include 3 different altitudes, along with the snow precipitation chart for the same periods of comparison. The goal is to relate the changes in TerraSAR-X backscattering to the evolution of snowpack

23. P. 4894 Line 18: The specific details has been added for the areas of study.

24. P. 4895 Line 1: Crocus is fed by the meteorological data which has the resolution of 100 m of altitude. Therefore the assimilation is applied on the average backscattering of each 100 m of altitude on Argentière glacier.

25. P. 4895 Line 7: Each point on the figure 6 represents the average backscattering coefficient on a date of the time series of TerraSAR-X acquisition

27. P. 4895 Line 8: Word modified to "Effective permittivity".

28. P. 4895 Lines 12-15: The paragraph has been improved

29. P. 4895 Lines 21-22: The symbols of roughness parameters of the two interfaces have been added.

30. P. 4896 Lines 4-6: The discussion of the sensitivity of the EBM to snowpack parameters has been improved.

31. P. 4896 Line 15: The comments on figure 9 has been modified.

32. P. 4896 Line 21: Changed to "where "i and "j represent the standard deviation of the error on xi and xj, which. . ."

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

34. P. 4897 Lines 20-21: The trail of then glacier on figure 4 now indicates all 8 altitudes from 2400 m to 3000 m

35. P. 4897 Line 22: Figure 8 now contains the assimilation results of all 8 dates in the time series of TerraSAR-X

36. P. 4897 Line 26 " P. 4898 Line 1: Sentence modified

37. Figure 8: Figure 8 has been replaced with new results where the effect of data assimilation is clearer

38. P. 4898 Line 12: Further discussion has been added.

40. Figure 9: The y-axis has been modified to "Snow height (cm)"

41. P. 4898 Lines 20-21: The paragraph has been improved.

42. P. 4898 Line 26: The paragraph has been improved.

43. P. 4898 Line 28: The conclusion paragraph has been modified.

44. P. 4899 Line 9: The conclusion paragraph has been modified.

Responses to your Technical Corrections:

1. P. 4882 Line 2: Changed "structure" to "structural".

2. P.4882 Lines 11-14:. Changed ". . .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: Changed "greater" to "a great"

4. P. 4882 Line 20: Changed "avalanches" to "avalanche".

5. P.4883 Lines 2-3: Changed "and therefore adjust these values according to mod- elling and observations error statistics." to "and adjust these values according to error statistics of the model and observations."

"6. P. 4885 Line 8: Changed "Stokes vector scattered" to "Stokes vector for radiation scattered."

7. P. 4886 Line 5: Changed "Fig. 1" to "Figure 1".

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

9. P. 4888 Line 16: Changed "terms:" to "term:"

10. P. 4891 Lines 11 and 12: Replaced ". . ." within parentheses with ", etc.)".

11. P. 4891 Line 18: Changed "data into" to "data with"

12. P. 4891 Line 21: Replaced "searching a solution" with "searching for a solution".

13. P. 4891 Line 23: Replaced "scheme" with "schematic".

14. Figure 3, caption: Changed "scheme" to "schematic". Changed "input of the process" to "inputs of the process". Removed comma after ""0".

15. P. 4892 Line 17: Changed "with" to "where".

16. P. 4893 Line 5: Changed "a specific" to "specific".

17. P. 4893 Line 17: Replaced "used as guess" with "used as guess variables". 18. P. 4893 Line 19: Replace "guess" with "the guess"

19. P. 4894 Line 3: Replaced "on the region" with "in the region".

20. P. 4894 Line 5: Changed "Table shows" to "Table 1 provides".

21. Figure 4: Figure has been updated for more clarity

22. Figure 4, caption: Changed "the crop" to "a cropped"

23. P. 4894 Line 10: Changed "altitude by" to "altitude in"

24. P. 4894 Line 12: Changed "the whole season 2008-2009" to "the entire 2008-2009 season".

25. P. 4895 Line 3: Changed "consists" to "consist", remove the "and" before "their density".

26. P. 4895 Line 4: Inserted "the" before "volume".
27. P. 4895 Line 7: Changed "Fig. 6" to "Figure 6". Change "snow depth by the" to "snow depth and".
28. P. 4895 Line 11: Removed "is" before "largely depends".
29. P. 4895 Line 14: Replaced "sensivity" with "sensitivity".
30. P. 4895 Line 17: Replaced "sensitivy" with "sensitivity".
31. P. 4895 Lines 18-21: Changed "correspond" to "corresponded"
32. P. 4895 Line 22: Changed "ground" to "ground-snow interface".
33. P. 4895 Line 23: Changed "taken into consideration" to "used".
34. P. 4896 Line 4: Changed "Fig. 7" to "Figure 7". Change "As it" to "As".
35. Figure 7, caption: Changed "differents snowpack structure" to "different snowpack structures".
36. P. 4896 Line 6: Replaced "it shows" with "this shows".
37. P. 4896 Line 15: Replaced "therefore" with "and therefore".
38. P. 4896 Line 16: Changed "At first" to "At the first".
39. P. 4897 Line 1: Changed "and are" to "and is"
40. P. 4897 Line 5: Changed "can be splitted into 3 cases 5:" to "can be split into 3 cases:"
41. P. 4897 Line 12: Changed "fitted" to "fit". Removed the word "only" following "variables".
42. Figure 8: Replaced "potision" with "position" on the x-axes.
43. P. 4897 Line 23: Inserted "a" before "very".
44. P. 4897 Line 24: Modified to "Standard deviation"
45. P. 4898 Line 6: Changed "produce" to "produces".
46. P. 4898 Line 9: Changed "Fig. 8" to "Figure 8".
47. P. 4898 Line 16: Changed "done" to "effected".
48. P. 4898 Line 22: Paragraph has been rewritten.
49. P. 4898 Line 23: Paragraph has been rewritten.
50. P. 4898 Line 28: Paragraph has been rewritten.
51. P. 4899 Line 2: Paragraph has been rewritten.
52. P. 4899 Line 3: Paragraph has been rewritten.

53. P. 4899 Line 7: Paragraph has been rewritten.

54. P. 4899 Line 10: Changed "snow cover area monitoring on massif scale" to "large- scale snow cover area monitoring"

55. P. 4899 Line 12: Changed "will be concentrated" to "will concentrate".

Sincerely yours,
Xuan-Vu Phan
on behalf of all co-authors.