

## **On the assimilation of optical reflectances and snow depth observations into a detailed snowpack model**

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### **Summary:**

A study is carried out to determine the impact of assimilation of synthetic reflectance data (similar to that which can be obtained from MODIS satellite data) on the agreement between the snow model simulation and the synthetic true snow depth. Crocus is forced with inputs from the SAFRAN reanalysis for a single location in a mountainous area of France at Col de Lautaret. The input data is evaluated at a separate site (Col de Porte), where a long record of in situ meteorological data is available. Based on errors from the Col de Porte location, an ensemble of meteorological forcing data is generated from the SAFRAN data for the Col de Lautaret site, and used to create an ensemble of snowpack simulations. A particle filter method is used to constrain the evolution of the ensemble of model simulations during data assimilation. Assimilation of synthetic reflectance data reduces the uncertainty in the ensemble of simulations, as well as the range of possible dates for disappearance of the snowpack. Sensitivity experiments indicate that assimilation of reflectance data is most effective when the data are spread out in time, and when reflectance measurements occur following a period of no precipitation. Assimilation of synthetic snow depth measurements results in a larger reduction of uncertainty relative to the assimilation of reflectance data, but such measurements are not readily available on wide spatial scales. The authors show that assimilating reflectance data reduce uncertainty in snow simulations, especially when combined with available snow depth measurements. Future work involves assimilation of real MODIS data.

### **General Comments:**

The study is important and relevant in that it has showed the potential usefulness of assimilating reflectance data into a snow model. The design of experiments appears to be well thought out, and the results of the sensitivity experiments are particularly interesting. The presentation of procedures carried out is sometimes unclear. The study is scientifically sound, and most of the comments relate to making the presentation more clear. I feel the paper should be published after relatively minor changes discussed below:

1. The abstract be specific as to the procedures that were carried out. It should make clear from the outset that the authors are examining the usefulness of assimilating reflectance data, but are not using real reflectance data during assimilation. The Crocus model should be mentioned as the model used to calculate snow depth, and the source of meteorological inputs (SAFRAN), as well as the method used to generate an ensemble of input forcing should be mentioned.

2. It should be clear throughout the paper wherever “observations” are synthetic observations derived from model results. In these instances “truth” should be changed to “synthetic truth” and “observations” to “synthetic observations”, etc.
3. A paper describing the potential for assimilating MODIS data in a distributed way over the Greenland Ice Sheet has been recently published (Navari et al., 2015), but discusses assimilation of ice surface temperature data derived from MODIS (i.e. in a different part of the electromagnetic spectrum). Since that study also uses MODIS data (albeit in a different way with far infrared measurements from MODIS) it could be referred to in the introduction.

Navari, M. Margulis, S. A., Bateni, S. M., Tedesco, M., Alexander, P., and Fettweis, X.: Feasibility of improving a priori regional climate model estimates of Greenland ice sheet surface mass loss through assimilation of measured ice surface temperatures, *The Cryosphere*, 10, 103-120, doi: 10.5194/tc-10-103-2016, 2016.

4. The application of errors from Col de Porte at Col de Lautaret needs more discussion. The methods used to adjust errors from one site to the other site should be discussed in more detail, perhaps in the supplement.
5. The comparison between the ensemble of simulations at CdL and RMSE at multiple locations seems unfair in that the spatial distribution of snow depth errors is not necessarily the same as the distribution of errors associated with errors in input forcing. As the authors mentioned, errors at CdP and CdL are different partly because of differences between the sites (forested vs. open). It seems likely that errors in SND at CdL will be smaller than those at other locations because of the lack of forest cover. Therefore I don't see the purpose of the comparison described in Section 3.5, except perhaps to illustrate that errors may be larger when considering multiple locations, and therefore, perturbations may need to be adjusted spatially in future use of “real” data assimilation. It may make more sense to create an ensemble at CdP, and to see whether the ensemble method captures the RSME of SND at that particular location, given the known uncertainties in forcing data at CdP. This would somewhat validate the method being used to generate errors in SND and other variables.

### **Specific Comments:**

1. **P. 6830, Lines 7-8:** This sentence is unclear. I'm not sure what is meant by “essentially ascribed”. Inclusion of details discussed in the general comments section may allow this sentence to be modified or replaced.
2. **P. 6830, Line 11:** Perhaps this sentence can be modified to make it more clear that the reflectances are not real: “The assimilation of synthetic spectral reflectances, designed to match the spectral resolution of the

MODerate resolution Imaging Spectroradiometer...” Also note the correct name for MODIS.

3. **P. 6830, Lines 19-21:** Since real data have not been assimilated yet, perhaps this statement is slightly too strong. “Should become” could be changed to “has the potential to become” or something similar.
4. **P. 6833, Lines 8-10:** Perhaps here, the forcing data used at Col de Lautaret can be introduced, and the method of generating an ensemble of forcing can be briefly noted as well.
5. **P. 6833, Line 18:** Change “reflectance observations” to “synthetic reflectance observations”. Perhaps also change “one point” to “CdL”.
6. **P. 6833, Line 19:** Suggest changing “this previous experiment” to “the reference experiment”
7. **P. 6834, Lines 26-27:** Over what period is this threshold applied, a single model time step? Does the threshold change if the time step also changes?
8. **P. 6835, Line 1:** Change “identical layers” to “a set of identical layers” for clarity.
9. **P. 6835, Lines 5-7:** Change “layer that is too small relatively” to “layers that are too small relative”, and change “is aggregated with an adjacent one” to “are aggregated with adjacent ones”. Is the “optimal vertical profile” an optimal profile of layer thicknesses? How is this optimal profile determined? Please clarify briefly.
10. **P. 6835, Line 24:** Please spell out the acronym SAFRAN. Also a few more details about SAFRAN would be appreciated, for instance, what kinds of observations go into the product, and what is its spatial resolution?
11. **P. 6837, Line 9:** The phrase “simulate the errors” is a bit confusing... perhaps you mean that you need to first simulate the impact of errors on the simulation of the snowpack?
12. **P. 6837, Lines 14-16:** Perhaps provide further explanation as to why these errors are not considered. I would imagine these errors are difficult to evaluate as they may vary by location and may be difficult to separate from other sources of error. Can the authors briefly comment on how their inclusion might affect the results presented?
13. **P. 6838, Line 3:** I think it would be better to refer to RMSE rather than the “standard deviation of the difference”, for consistency with other portions of the paper.
14. **P. 6838, Line 5:** Does “significant” refer to statistical significance? Please clarify.
15. **P. 6838, Lines 6-8:** Differences can also occur because of measurement errors at CdP.
16. **P. 6838, Line 13:** Hourly interpolation of the daily analysis wasn’t discussed earlier. Please elaborate.
17. **P. 6838, Lines 15-17:** This sentence is unclear. What is the average RMSE or range of RMSE values at the stations? Which study highlights the spatial variability of SAFRAN? I presume it is the Durand et al. (2009) study, but this is not clear from the sentence. How much do the RMSEs change across stations? What are the implications of this spatial variability for this study;

- i.e. can the uncertainty estimates at CdP really be used as indicators of the uncertainty at CdL?
- 18. P. 6839, Line 2:** Mention how tau is chosen here rather than later on.
  - 19. P. 6839, Line 6:** Some formulas should be included describing how a given variable at a given timestep is perturbed (through either multiplication or addition).
  - 20. P. 6839, Lines 7-8:** What is meant by “the nature of the variable”? It becomes a bit clearer later on, e.g. precipitation should not be additively perturbed to avoid creating precipitation where there is none. Can the authors be more specific? The second criteria is also unclear and does not seem to be mentioned later. Please provide a more detailed description of how a method is chosen for a given variable.
  - 21. P. 6839, Lines 14-16:** I suggest discussing how tau is adjusted when tau is introduced in the previous paragraph. More details should be provided as to how tau is chosen, i.e. how is it determined that the “temporal variation” of perturbed variables is similar to that of the original variables?
  - 22. P. 6839, Lines 18-19:** Suggest saying that the maximum value of shortwave radiation is set to  $200 \text{ W m}^{-2}$  for clarity. Is this done because of the presence of clouds? Please make this clear.
  - 23. P. 6839, Lines 20-23:** This is out of place here, and should be mentioned earlier in the previous paragraph.
  - 24. P. 6839, Lines 27-29:** Suggest modifying this sentence for clarity: “In particular a forested area masks a portion of the shortwave radiation at the CdP site, and modifies the local wind field. The model does not account for this forested area, resulting in the large discrepancies between model and observations.”
  - 25. P. 6840, Lines 1-4:** The procedure for these adjustments should be provided, along with the results of the sensitivity tests if possible, in the supplementary material. Also, the standard deviation for wind speed appears to be different. Was this also adjusted?
  - 26. P. 6840, Lines 5-6:** Actually the standard deviations used to generate the ensemble are not provided in the left column, as they have been adjusted for the new location. I suggest adding another column showing the prescribed standard deviations for CdL. Also perhaps this is best mentioned after mentioning the use of an ensemble in the next paragraph.
  - 27. P. 6840, Lines 12-13:** It would be helpful to remind the reader here how these are taken into account in this case.
  - 28. P. 6840, Lines 13-14:** Explain why it is not crucial to account for inter-variable correlations for the purposes of this experiment.
  - 29. P. 6841, Lines 1-3:** Are the impurity concentrations consistent with any previous measurements of snow impurity content?
  - 30. P. 6841, Lines 8-13:** The details of the figure could be shortened somewhat since they are already mentioned in the figure caption.
  - 31. P. 6841, Lines 17-18:** Change “dispersion range ( $\Delta \text{SWE} \approx 300 \text{ kg m}^{-2}$ )” to “dispersion range of SWE ( $\Delta \text{SWE} \approx 300 \text{ kg m}^{-2}$ )”

- 32.P. 6841, Lines 18-19:** It would be better to refer to the snowpack here: “The snowpack in some ensemble members has just started to melt, while in other cases, the snowpack has already disappeared.”
- 33.P. 6842, Line 11:** It seems that the RMSE is calculated as a RMSE for modeled vs. in situ snow depths across multiple stations. Please clarify what the RMSE refers to here.
- 34.P. 6842, Line 14:** The letter  $n$  was used in the equation for Spd as an indicator of the ensemble number. Here, I believe it refers to neither time, nor ensemble member, but to a station identifier, and  $M$  is the total number of stations, at a given time. Please clarify and change the notation to avoid confusion.
- 35.P. 6842, Line 18:** It is not clear what the “reference” is at this point. Perhaps replace with “a synthetic true reference simulation”
- 36.P. 6842, Lines 19-21:** Since observations are not mentioned yet, perhaps this should be moved to the next paragraph.
- 37.P. 6843, Line 11:** The term “twin” has not been defined yet. It would be helpful to define it here rather than later on for those readers not familiar with the terminology.
- 38.P. 6843, Line 19:** Perhaps change “more physics details” to “further details”.
- 39.P. 6843, Line 22:** Again I think it would be better to mention this in section 3.6.
- 40.P. 6843, Line 23:** But the synthetic observations come from the same model into which data are being assimilated. The model is not independent. Please revise, and clarify that the synthetic observations come from a single Crocus ensemble member.
- 41.P. 6844, Line 1:** I suggest changing “control simulation” to “synthetic truth simulation” for clarity, here and in other places where it is mentioned.
- 42.P. 6844, Line 2:** Perhaps change “virtual observations” to “synthetic observations” for clarity.
- 43.P. 6844, Lines 2-4:** It may be helpful to mention the virtual or synthetic observations extracted from the simulations. In particular it would be helpful to mention (for understanding the following section) that synthetic reflectance observations are obtained from Crocus, through the use of the TARTES model.
- 44.P. 6844, Line 7:** Change “truth” to “synthetic truth” for clarity.
- 45.P. 6844, Lines 6-8:** Suggested change to the sentence: “Data assimilation performances are evaluated by comparing RMSE for ensembles with and without assimilation, and by comparing the synthetic true simulation to the 33<sup>rd</sup>, 50<sup>th</sup>, and 67<sup>th</sup> quantiles from the ensembles with assimilation.”
- 46.P. 6844, Lines 16-18:** Mention that these are derived using TARTES in Crocus.
- 47.P. 6845, Lines 5-6:** I suggest moving this sentence to the end of the paragraph.
- 48.P. 6846, Lines 24-25:** The sentence is unclear. Suggested change: “Inversely, a new perturbed forcing is assigned to a duplicated particle for propagation to the next analysis.”

- 49.P. 6847, Line 7:** How are these “clear sky days” chosen? Are these based on the real measurements at CdL, or are they from real MODIS data? Please clarify.
- 50.P. 6847, Lines 8-9:** Are real MODIS data used in this case? If so, please provide details about MODIS data in an earlier section. If not, I think this sentence can be removed, because this study does not make use of real MODIS data.
- 51.P. 6847, Line 13:** Clarify that the envelopes are the envelopes from SD and SWE ensembles for the baseline experiment (e.g. “SD and SWE ensembles for the baseline experiment...”)
- 52.P. 6847, Lines 17-18:** Suggest changing sentence to: “This is observed in Fig. 3, where the baseline experiment envelopes (blue shading) are narrower than those of the ensemble without assimilation (grey shading).”
- 53.P. 6847, Lines 21-23:** Mention the terms “forecast” and “analysis” to be consistent with Figure 4.
- 54.P. 6848, Line 1:** What is meant by “the continuous flow of observations”? I think the authors mean to indicate that the observations are well distributed in time. Please clarify.
- 55.P. 6848, Lines 4-5:** Change “extended and unobserved periods without precipitation” to “extended periods without precipitation and without available observations”
- 56.P. 6848, Line 11:** Which figure should we refer to for the example on 28 January?
- 57.P. 6848, Line 19:** Change “the whole ensemble to a unique set” to “all ensemble members to the same set”
- 58.P. 6848, Line 20:** Change “discrimination between members impossible only from the reflectances” to “discrimination between members using reflectances alone impossible”
- 59.P. 6848, Line 21:** Change “the analysis” to “the subsequent analysis”
- 60.P. 6848, Line 22:** Again, which figure should be examined here?
- 61.P. 6848, Line 28:** Change “at the end” to “towards the end”.
- 62.P. 6848, Lines 2-4:** This statement is not really supported by the previous analysis, although it is shown that this is important later. Either note that this will be shown later, or remove this sentence.
- 63.P. 6849, Line 8:** Suggest changing “impact of the limited number of available data” to “impact of limiting the number of available observations” for clarity.
- 64.P. 6849, Lines 9-10:** Change “first one” to “baseline experiment” for clarity. Change “...carried out but assimilating an observation” to “...carried out, but assimilation is performed...”.
- 65.P. 6849, Line 15:** As the envelope for the experiment is wider than the reference experiment, I think it is an overstatement to say that the fit is “perfect”.
- 66.P. 6849, Line 23:** Change “that the limited number” to “that assimilating a limited number” for clarity.
- 67.P. 6850, Line 7-10:** Is it possible to give each of these simulations a meaningful name? This would be very helpful when references are made to

- each simulation in the paper. Otherwise the reader forgets the details of the simulation. If the authors think it would be more confusing to name each simulation, the details should be briefly mentioned when describing the results, e.g. “In case (i), where assimilation occurs only at the beginning of the season, results show...”
- 68.P. 6850, Line 13:** Change “ensemble spread retrieves” to “ensemble spread at the end of the season returns”
- 69.P. 6851, Lines 20-21:** This sentence seems a bit out of place. Perhaps it can be moved to the end of the paragraph and expanded on a bit.
- 70.P. 6852, Line 5:** The snowpack is probably also more sensitive to absorbed solar radiation.
- 71.P. 6852, Lines 13-14:** Although this seems likely, I’m not sure what evidence from the experiments that were done supports this statement.
- 72.P. 6852, Line 25:** Suggest changing “punctual usage in time” to “low temporal frequency”
- 73.P. 6852, Line 3:** It would be nice to also have an additional supplemental figure showing the impact of including both snow depth and reflectance for the 2010/11 season.
- 74.P. 6853, Line 15:** Could the use of a high spatial resolution make assimilation more useful?
- 75.P. 6854, Line 7:** Change “improves” to “reduces”
- 76.P. 6854, Line 15:** Change “provides results almost as good” to “reduces RMSE almost as much as”
- 77. Table 1:** Suggest changing “Standard Deviations” to “RMSE” for consistency with other parts of the paper.
- 78. Table 1, caption:** Mention the range of years for the 18 years of observations from CdP.
- 79. Table 2:** I think having names for simulations would be more useful than including figure numbers here, or both names and figure numbers could be included. Simulations could be given meaningful names, or referred to as “case (i)”, etc. as discussed in the text.
- 80. Table 2, caption:** What does “Seasonal” refer to? The 2010/2011 season, or the period when snow cover exists for all seasons?
- 81. Figure 1, caption:** Change “band 1 of MODIS” to “center of band 1 of MODIS” for clarity. Define SD and SWE.
- 82. Figure 3, caption:** Change “patterns” to “shading”, when describing the envelope colors. Clarify whether the quantiles are for the baseline experiment or ensemble without assimilation.
- 83. Figure 5:** The figure is initially difficult to understand. “Model control” should be replaced by “Synthetic true snow depth”. Change the left and right titles to “SD and SD RMSE (m)” and “SWE and SWE RMSE (kg m<sup>-2</sup>)” for clarity.
- 84. Figure 5, caption:** Define “seasonal means”.

#### Technical Corrections:

1. Change “envelop” and “envelops” to “envelope” and “envelopes” throughout.

2. **P. 6832, Line 3:** Change “active microwave” to “active microwave measurements”
3. **P. 6832, Line 13:** Change “on board TERRA...” to “onboard the TERRA...”
4. **P. 6832, Line 28:** Change “snow simulations” to “snow simulation”
5. **P. 6833, Line 2:** Change “Moreover, 2...” to “Two...”
6. **P. 6833, Line 3:** Change “serie” to “series”
7. **P. 6833, Line 4:** Change “Indeed, the Col de Porte...” to “The Col de Porte...”
8. **P. 6833, Line 6:** Change “statistic” to “statistics”
9. **P. 6834, Line 8:** Change “of the avalanche” to “of avalanche”
10. **P. 6835, Line 5:** Change “its maximum” to “a maximum”
11. **P. 6837, Line 15:** Change “other physical laws parametrization” to “other parameterizations of physical laws”
12. **P. 6837, Line 20:** I believe “present section” should be changed to “following section”.
13. **P. 6839, Line 2:** The exponent in the expression for  $\varphi$  should be raised.
14. **P. 6839, Line 10:** Change “longwave radiations” to “longwave radiation”.
15. **P. 6839, Line 13:** Change “a week period” to “a one week period”.
16. **P. 6840, Lines 2 and 3:** Change “longwave radiations” to “longwave radiation”.
17. **P. 6840, Line 11:** Change “inter-variables” to “inter-variable”
18. **P. 6840, Line 14:** Change “Real data assimilation...” to “A real data assimilation...”
19. **P. 6840, Line 19:** Change “is not” to “are not”
20. **P. 6840, Line 20:** Change “their dry” to “the dry”
21. **P. 6841, Line 17:** Change “24 days spread” to “a 24 day spread”
22. **P. 6842, Line 4:** Change “ensemble of simulation” to “ensemble”
23. **P. 6842, Line 21:** The word “consequently” can be removed.
24. **P. 6842, Line 22:** Remove “In that purpose,”
25. **P. 6843, Line 2:** Change “than the CdL” to “as the CdL”
26. **P. 6843, Line 7:** Change “perturbations calibration” to “calibration of perturbations”
27. **P. 6843, Line 9:** Change “measurements sites” to “measurement sites”
28. **P. 6843, Line 10:** Change “model error” to “model errors”
29. **P. 6843, Line 13:** Add comma after “not crucial for our study”
30. **P. 6843, Line 16:** Change “prior” to “prior to”
31. **P. 6843, Line 18:** Change “observations datasets” to “observational datasets”
32. **P. 6844, Line 1:** Change “obtained” to “obtained by”
33. **P. 6844, Line 12:** Change “RMSE” to “RMSEs”
34. **P. 6844, Line 20:** Change “they are mainly varying” to “they mainly vary”
35. **P. 6845, Line 4:** Change “measurements provides” to “measurements provide”
36. **P. 6845, Line 6:** Change “later” to “latter”
37. **P. 6845, Line 13:** Change “to 0.003 m” to “to be 0.003 m”
38. **P. 6846, Line 1:** Change “simplest” to “simpler”.
39. **P. 6846, Line 12:** Suggest changing “particular flavor of the particle filter” to “particular type of particle filter”



- 40.P. 6846, Line 19: Change “distances to” to “distances from”
- 41.P. 6846, Line 27: Change “or” to “and”.
- 42.P. 6847, Line 13: Change “All along the season” to “Throughout the season”
- 43.P. 6847, Line 25: Change “RSME SD” to “RMSE for SD”
- 44.P. 6848, Line 8: Change “poorly” to “not very”
- 45.P. 6848, Line 17: Change “On top of this” to “Moreover”
- 46.P. 6848, Line 22: Remove “the” before dates.
- 47.P. 6848, Line 27: Change “coarsely” to “roughly”
- 48.P. 6848, Line 2: Change “meets limitations” to “exhibits limitations”
- 49.P. 6849, Line 6: Change “clouds coverage” to “cloud coverage”
- 50.P. 6849, Lines 12-13: Change “patterns” to “shading”
- 51.P. 6849, Line 18: Change “uncertainties” to “uncertainty”
- 52.P. 6849, Line 24: Change “are not” to “is not”
- 53.P. 6850, Line 9: Change “precipitations” to “precipitation”
- 54.P. 6850, Line 10: Change “snowfalls” to “snowfall events”
- 55.P. 6850, Line 13: Change “the snow melt” to “the snow melt period”
- 56.P. 6850, Line 24: Change “stays to 23 days” to “stays at 23 days”
- 57.P. 6851, Line 20: Change “all along” to “throughout”
- 58.P. 6852, Line 12: Change “Excepted” to “Except”
- 59.P. 6852, Line 16: Change “a ‘surface’ information only” to “ ‘surface’ information only”
- 60.P. 6852, Line 20: Change “spatialized” to “spatially distributed”
- 61.P. 6853, Line 13: Change “encourage to combine” to “indicate the usefulness of combining”
- 62.P. 6853, Line 22: Change “estimate uncertainties” to “uncertainty estimates”
- 63.P. 6854, Line 26: Change “kind of data assimilation” to “kinds of data assimilation”
- 64.P. 6855, Line 12: I believe all equations in this section should be given a number.
- 65.P. 6855, Line 13: I believe these equations come primarily from Gordon et al. (1993) and this reference should be referred to here.
- 66.P. 6856, Line 4: I believe  $X_{k-1}$  just to the right of the integration sign should be  $X_{k-1}$
- 67.P. 6856, Line 5: Change “Bayes’ rule” to “Bayes’ rule”
- 68.P. 6857, Line 8: Please provide a reference for “Kitagawa”.