Response to referee Nicolas Marchand

The work presented in this article aims to push further what was already described in P. Venäläinen 2021. The larger dataset used to analyze or validate the SWE retrieval value helps discussing the improvement of the method. The insertion of dynamic snow densities in the retrieval process of the SWE algorithm seems to be an interesting way to move forward, but it is not entirely clear through the paper how relevant the improvements are in terms or relative values (percentages). This might help seeing more clearly the contribution to the proposed improvement on the method. The limitations still existing on the globsnow swe retrievals are not discussed enough in the conclusion of this paper.

We thank the reviewer for their time and constructive comments on the manuscript. We take all the comments into account. Our replies are written in red and additions to the manuscript are noted in blue.

Implementing IDWR interpolated snow densities into the SWE retrieval algorithm reduces the RMSE and MAE by about 8 (9)% and 16 (18)%, respectively, for SWE under 500 (200) mm. We will add these relative values to the article. We will also add a discussion about the limitations of the GlobSnow SWE retrieval to the conclusion section, see below:

Implementing varying densities into the retrieval reduced overestimation of small SWE values and underestimation of large SWE values, though underestimation of large SWE values is still present. Assimilation of SD data used in the GlobSnow retrieval improves estimates of large SWE values, when compared to algorithms based only on radiometer data. However, the physics upon which the SWE retrieval is based limits the SWE estimates to below about 200 mm.

L45-47 - SWE retrieval limited by high uncertainties… put an example of those high uncertainties, seems rather relevant and would avoid to go find them in the literature, even if all necessary sources are there

We will add example to the text, see below:

However, the performance of SWE retrievals based on radiometer measurements alone is limited by high uncertainties and these retrievals do not meet user accuracy requirements with respect to retrieval skill and are poorly correlated in space and time with all other SWE products, see for example Derksen et al. (2005), Mudryk et al. (2015) and Mortimer et al. (2020).

L80… Snow density and SWE data... How were taken into account the variabilities of the different sources of the large dataset? Did you take into account the variability and incertitude on the measurments, or on the methods/models used to obtain them? You could include some basic information on those uncertainties in your table 1.

We did not explicitly consider the differing uncertainties, spatial scales or observation frequency prior to spatial and temporal interpolation. Testing different temporal aggregation methods, in addition to spatial interpolation techniques, was intended to identify the most appropriate approach to aggregate the available data. The snow density data were preprocessed (Section 4) before they were used for interpolation to reduce the effects of the outliers on the final snow density fields. For validation, we only use the manual snow course data because they cover a larger are and are thus more representative of the larger grid cell. However, for the derivation of density fields, both automated and manual data were necessary to obtain sufficient spatial coverage. Text added to ~L102-104 to this effect.

We did not assign measurement uncertainty to the in situ reference data during validation because measurement protocols vary widely even within a given agency and information about samplers used is not always available. We added information about the spatial scales to Lines 90-94. Generally, instrument error of snow tubes used in most manual snow surveys ranges from ~3% to 13% depending on the cutter and snow conditions (Dixon and Boon 2012, López-Moreno et al. 2020). This uncertainty does not include observer error or spatial variability (López-Moreno et al. 2020). Measurements from SNOTEL snow pillows were found to be within 5-15% of those from manual snow surveys (Serreze et al. 1999), while GMON sensors have a stated uncertainty of ± 15mm (15%) for swe < 300 mm (300-600mm) (Smith et al. 2017) but has been shown to be as low as ±5% in some cases (Royer et al. 2021). The 18% MAE improvement exceeds these general uncertainties from the literature.

L151 - Could go into more details about those snow free areas… radiometers… which frequencies… optical… what do you use… ? How accurate is it? Might be relevant to have more insight.

A time-series detection approach by Takala et al. (2009) is used for radiometer information and the JASMES 5km Snow Extent product is used to build cumulative snow masks. Text below will be added to the section.

A time-series thresholding approach by Takala et al. (2009) is used to detect the end of snowmelt and any remaining SWE estimates are cleared from those pixels. After this, SWE estimates are also cleared from regions where optical data indicate snow-free conditions. The JASMES 5 km Snow Extent data product 1978 – 2018 (Hori et al. 2017) is used to construct a cumulative snow mask in 25 km EASE-Grid projection. Cumulative masking retains the latest cloud-free observation for each EASE-Grid pixel and uses the daily product to update snow-free/snow-covered conditions, based on a 25% snow cover fraction threshold.

L217 - Don't you need to go more subscale than that for your variograms fittings? East and west Canada/USA separately, Europe and Asia separately? Can you justify this choice? Have "subcontinental" / "regional variograms" have been tested, and how would their results have compared to the IDWR method?

See answer below.

L265 - Supports previous point to also look into more detailed characterization (variograms to fit) regarding the areas… west versus east north America for example…

The Kriging interpolation is also used to interpolate the background SD field in the GlobSnow SWE retrieval and for this SD interpolation, the variogram is fitted separately for North America, Europe, and Asia. Given the successful implementation of this interpolation, a similar approach was used to interpolate snow densities. Variogram fitting was initially tested separately for Europe and Asia but as there is a limited amount of snow density data available in (eastern) Asia, especially in early and late winter, so fitting the variogram becomes very difficult or even impossible.

Testing “regional variograms” could be a potential avenue for future investigations, especially for North America.

L300 - Figure 4… increase police size of legend on the left and right of the plots… very difficult to read

We will update the figure with larger font size.

L330 - Paragaph… you put some facts out… might be appreciated for them to be backed with a few references.

We will add refences, Lemmetyinen et al. (2015) and Pulliainen (2006).

L337 - Difference in grain size… reference

The differences in grain sizes here refer to the differences in the effective grain sizes of the constant and dynamic density implementation (figure 5) and the differences in density mean differences between the constant snow density and derived IDWR densities. We will add reference to figure 5 to text.

L465 - Figure 10… increase legends left and right

We will update the figure with larger font size.

L495 - Dot missing

Noted, thank you.

L522 - It is not clear whether you put out this specific example a positive or negative consequence?

It is positive in that the annual IDWR densities are more accurate than annual Kriging densities in North America as more local variability is considered. However, this clear boundary in densities is probably not fully accurate. We have clarified the text to indicate the positive and negative aspects.

For example, although IDWR density estimates are more accurate than Kriging interpolated densities in North America, there is an artificial border in the IDWR density estimates between eastern and western North America that is not present in the Kriging interpolated densities.

L531 - How would you deal with the errors of reanalysis depending on the environment, latitude, lacking or overestimation of precipitations, … ?

These issues would need to be considered carefully if reanalysis products were to be used in the future but the study by Yang et al. (2021) shows promising results for using reanalysis data with the HUT snow model. Also, as the reanalysis snow density data would only be one of the inputs in the retrieval, effects of errors in the data are somewhat reduced.

L540 – 550 - You don't make it clear what it is you recommend to be used… one of the 3, or multiples at the same time… or different version depending on the geography?

The recommendation of which snow densities to use depends on application and spatial domain. For the SWE retrieval over the full Northern Hemisphere domain, IDWR densities produce the best results and we recommend this approach for the GlobSnow and ESA SnowCCI+ SWE products which are produyced for the full Northern Hemisphere domain. However, for some other applications or regional implementations decadal snow densities might be preferred as they are more accurate in some areas such as North America. We will add mention of this into the text.

The development of the SWE retrieval algorithm continues in the ESA SnowCCI+ project and, as implementing annual dynamic snow densities into the retrieval improves the retrieval skill, this modification will be used in the production of the next iteration of SnowCCI+ SWE. However, as decadal snow densities are more accurate in North America, they might be preferred for some applications.

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