Authors' response to interactive comments by Anonymous Referee #2

Black text: Reviewer's comment

Blue text: Authors' response

This manuscript develops and evaluates methods to maintain appropriate spatial correlation when using a particle filter to estimate SWE for a model of southern Quebec. The application is clearly defined and the problems that can arise when using a particle filter with affordable size are described. As noted in the manuscript, it is well-known that particle filters can diverge and that the number of particles needed to avoid this divergence increases at least exponentially with the number of spatial degrees of freedom in the model. While the number of degrees of freedom in the SWE model being used is not explicitly investigated, indirect evidence is provided that 500 particles is insufficient for the application at hand.

The authors describe the problems that arise from the limited number of particles in terms of an inappropriate 'scrambling' of the resampled particles at adjacent grid points. Small differences in the impact of observations can lead to a resampled particle with quite different values at adjacent gridpoints that are believed to be strongly correlated for example. To address this, the authors propose to 'reorder' the association between the values and the particle index at each gridpoint. Their control procedure simply sorts the particles at each grid point so that particle 1 is associated with the smallest value of SWE for each model point. The new method proposed, referred to here as a Schaake Shuffle, uses a reference set of 'particles' for the model points, in this case generated by sampling periodically from a free run of the SWE model. This reference distribution might be referred to as a 'climatological sample' in some other earth system assimilation applications. This reference distribution provides information about the correlation structure of the free model. As a hypothetical example, it could include information that when SWE is higher in western Quebec it is usually lower in eastern Quebec. This type of information could be reflected in the particle filter assimilation after the use of the Schaake Shuffle reordering.

The authors would like the thank Reviewer 2 for their careful consideration of our work and mindful remarks and critics. We believe the integration of those comments will improve the overall quality of the metrics. We describe below how we intend to integrate those comments

A number of metrics are used to assess different aspects of a basic particle filter, the naïve sorting, the Shuffle, and the free run (open loop). No error estimates are provided for most of the results so it is difficult to assess the significance, and this is something that should at least be discussed if it cannot be formally addressed. For instance, it is difficult to assess if the 4 different curves in Figure 2 are meaningfully different. It appears that the basic particle filter is an outlier, while the other three are indistinguishable, but appearances can be deceiving. It is even more difficult to assess the significance of differences in Figure 3. In this case, maybe the open loop is an outlier, but I have no idea at all whether there are any meaningful differences in the other three plots. Any guidance the authors could provide would be helpful. At this point, I would be forced to conclude that there is no evidence that the 3 particle filter methods produce significantly different estimates of pointwise SWE.

There clearly are meaningful differences between the 3 filter methods in some of the subsequent figures. Not surprisingly, the variograms in figure 4 are very different.

However, more evidence about which is better could be provided in the discussion. I suspect that a solid argument could be made that the Shuffle results are probably better, but this requires knowing something about the correct answer and the authors should try to discuss how that could be known with some additional clarity. Figure 6, perhaps the most important in the manuscript, clearly shows a difference in the correlations between the base particle filter and the two correction methods. This is important since the thesis was that the correlations were damaged by the particle filter. However, no solid evidence is provided of what the answer should be for this application. I believe that the correlation scales are probably much larger than the base case, but I am not convinced that they are long as indicated by the sort and Shuffle. Again, if the authors could provide some information about what the right answer is believed to be it could strengthen the argument for using one of the new methods.

In summary, the manuscript is very clear in its description of the application, the challenges to the particle filter, and the description of the new methods. It is less clear in providing evidence about the efficacy of the new methods. It is my somewhat uninformed opinion that the Shuffle has some nice features, but stronger evidence of this would be a nice addition.

We understand that most of the comments from Reviewer 2 are articulated around the description and comments related to the different figures in the results section. In particular, it is true that in most figures, several alternatives are characterized by similar distributions of scores (curves) or spatial patterns (maps). Actually, the purpose of some of the figures was to show that the Schaake Shuffle affects (and improves) the spatial structure of individual particles, but not the overall behavior of the filter. The reordering affects specifically the spread of the particles than their central behavior. Consequently, it is absolutely normal (and expected) that some maps or curves are similar. To help the reader, we intend is to modify the descriptions of the figures mentioned by Reviewer 2 and take time to describe whether or not it was expected to notice differences between the different alternatives, and why it was expected. Emphasizing the individual conclusion we draw from each of figure will also help to support our overall conclusions about the usefulness of the Schaake Shuffle.

As an end note, I would suggest that state-of-the-art ensemble filters, or localized particle filters that make use of some of the advantages of ensemble filters, could be a competitive alternative for this application. Ensemble Kalman filters derive much of their power by being able to approximate the most important covarying directions in model phase space which is what the particle filter is unable to do. Localizing the ensemble filter can result in high-quality assimilated estimates of covariance with ensembles much smaller than 500 members. For instance, work by Zhang https://doi.org/10.1002/2015JD024248 and references cited therein report on ensemble Kalman filter data assimilation using multiple types of observations in a comprehensive land surface model. Work by Poterjoy documents the power of localized particle filters using a theoretically-supported approach that could extend Zhang’s results to deal better with the bounded nature of SWE, https://doi.org/10.1175/MWR-D-15-0163.1

Work by Anderson extends ensemble filters to bounded quantities like SWE while retaining the high-quality covariance estimates from localized ensemble filters https://doi.org/10.1175/MWR-D-19-0307.1

The authors might want to evaluate the efficacy of some of these methods for the Quebec SWE problem in their future work.

A more in-depth comparison of the difference between our particle filter and more standard ones has also been mentioned by Reviewer 1, so this point is discussed more in depth in our answer to Reviewer 1. We want to thank Reviewer 2 for their bibliographical suggestions that will help us improve this portion of the introduction. The final suggestion by Reviewer 2 will also be taken into account for future work and will be mentioned it in the final portion of the conclusion.