Author's response

Dear Dr. Calvet,

Thank you for your comments. We have made our best efforts to modify the manuscript according to the suggestions made by the reviewers. The reviewer comments are included below in black, while the author responses are directly below in red. All the line numbers are according to the revised manuscript. The revised manuscript, supplement document, and track changes document have been uploaded. The track changes document does not support figures. The figures can be viewed in the revised manuscript. Thank you for providing us the opportunity to share our research findings.

Regards,
Ahmad et al.

Reviewer- 1

I have read the authors' replies to reviewers comments and the revised paper. Unfortunately, I believe the authors did not address the main problem I have raised in my review, i.e., "the main problem with the paper is that the better results are obtained when SMAP soil moisture data are assimilated without the correction of the BIAS."
The authors replied:
"The main point highlighted in this paper is that CDF-matching removes the irrigation signal from the retrievals, and therefore, we note that better results are obtained across croplands for simulations without any CDF-matching."
My points are:

1) If CDF-matching removes the irrigation signal, the CDF matching approach is wrong and it should be applied differently. I have made a suggestion, but other options can be explored as well.

Response: Thank you for your comments. We have endeavored to update the manuscript according to your suggestions. We found that better results are obtained without any pre-processing of the SMAP soil moisture retrievals (observations). In regions where irrigation is significant, it is recognized that the *a priori* model is biased and that the SMAP retrievals, in general, perform better in these areas. Pre-processing the SMAP soil moisture retrievals (via CDF-matching or some other model-based bias correction procedure) results in the loss of the irrigation signal implicit in these soil moisture retrievals. In turn, such a bias correction step is often detrimental to the soil moisture assimilation exercise.

On the subject of *explicit* representation of irrigation physics within a land surface model, an accurate parameterization of model physics is always preferred over dynamic state updates via data assimilation. If the land surface model was perfect, that would be ideal – and data assimilation would be completely unnecessary. However, an accurate and robust parameterization of anthropogenic irrigation at all locations in space and time does not currently exist. Hence, in the meantime, we present a framework that can help

improve modeled soil moisture estimates when no *explicit* representation of irrigation water quantity or irrigation timing is available. Please see response to comment #2 to reviewer #1 below for more discussion on this particular topic.

To further stress this point, we included results from an alternate CDF scaling method in the supplementary document and provided additional justification as to why a seasonal assimilation methodology would not work for many locations within the study domain. Furthermore, comparison of in-situ measurements across the Tibetan Plateau suggest better performance of assimilation results *without* any pre-processing even though biases are likely present in the land surface model or SMAP retrievals or both. Ideally, in-situ measurements could be used instead of the biased model climatology during the bias correction of the SMAP retrievals. However, the unavailability of publicly accessible soil moisture measurements across croplands (post-2015) limits the use of in-situ measurements for bias correction or validation of the modeled estimates.

We also realize that, although, the DA-NoCDF estimates have better accuracy as discussed in this study, it may not always be the case, i.e., DA-CDF estimates may yield better results for the assimilation of biased satellite retrievals in an unbiased model. Therefore, the implementation of this method may vary depending on the model used, observations assimilated, and the regional hydrologic processes. A series of discussions about the limitations described above, as well as important considerations for a follow-on study, are included at:

Lines 501 to 506 :
“It is important to note that while in the presented study, estimation accuracy is better for assimilation without CDF-matching, the results might be different for other cases. That is, the assimilation of retrievals without bias adjustment may not improve the estimation accuracy as compared to assimilation of CDF-matched satellite retrievals. In this particular study, the SMAP soil moisture retrievals effectively capture the irrigation signal, and as such, help improve the Noah-MP modeled soil moisture estimates via assimilation. However, there is the possibility that assimilation of a different soil moisture retrieval product may degrade the accuracy of the modeled estimates depending on the inherent biases in that given soil moisture retrieval.”

Lines 549 to 555:
“Considering the lack of in-situ observations available for use in this study, it is difficult to clearly ascertain the influence of assimilation without CDF-matching in areas that are not irrigated. Across the Tibetan Plateau, DA-NoCDF estimates exhibit the lowest RMSE. However, the evaluation of DA-NoCDF estimates across unirrigated areas in the southern part of the study domain is limited by the scarcity of ground data. A follow-on study should explore the influence of including (as well as excluding) CDF-matching in areas that are not irrigated. This experiment could help explore suitable approaches for incorporating the information obtained from satellite retrievals to correct the modeled estimates without introducing additional bias to the modelled estimates.”

Lines 555 to 559:

"In a broader perspective, there is a need to develop a bias correction technique for satellite retrievals that is independent of the accuracy or bias of the model climatology. Using *in-situ* measurements for pre-processing of the satellite retrievals would be one potential method. Current efforts in South Asia by various governmental and non-governmental organizations to measure in-situ soil moisture would benefit the development of suitable methods of bias correction of satellite observations."

2) The same for the model, if the model does not simulate irrigation in an extensively irrigated area, the model is not suitable. For instance, if the model did not simulate evaporation, we surely agree that the model cannot be used. Why not for irrigation?
Response: We agree with the reviewer that it is important that the model used be representative of regional conditions. It is important that the model should include the relevant (dominant) processes that drive the local hydrologic cycle and incorporate explicit treatment of irrigation into the model physics. However, it is quite difficult to accurately model irrigation across South Asia using an explicit framework considering the lack of publicly-reported irrigation rates. In this paper, we show that the soil moisture estimates can be improved through assimilation when using a land surface model that is biased at some locations in space and time. Zhou et al. (2021) are currently working on developing an irrigation modeling routine that would be able to better capture the influence of regional irrigation. This effort is expected to benefit future explorations of soil moisture across South Asia.

The following text has been added to lines 543 to 544:
"Simulating the complex regional irrigation scheme is a difficult task that is further complicated by the inaccessibility of relevant pumping data, manual operation of reservoirs, and unsystematic canal to field irrigation."

Zhou, Y., Zaitchik, B.F., Kumar, S.V. and Nie, W., 2021, December. Satellite-informed simulation of irrigation in South Asia: opportunities and uncertainties. In AGU Fall Meeting 2021, American Geophysical Union.

I apologise the authors for not being more supportive, but I believe that these two points need to be strongly stressed. We should improve our modelling and observation capability, we can't simply assimilate satellite data to correct unmodelled processes. Due to many causes of the bias between model and observations, results can be good or bad by chance.
Response: We agree with the reviewer that it is quite important to improve both the model as well as the observations. All models and observations have certain shortcomings. No dataset perfectly represents regional hydrologic processes, and as such, there will always be a need for corrective updates. However, assimilation provides a way to integrate the benefits of modeling and remote sensing in order to develop a product that has better accuracy than the stand-alone datasets.

The following text has been added to lines 506 to 508:

"It is important that the model physics be improved as well so that the regional hydrologic processes are accounted for, resulting in a more representative model which could then be used for bias correction of satellite retrievals."

Reviewer- 2

The authors addressed in detail all the reviewers and editor comments and suggestion. The link between the actual results and discussion/conclusions is now better balanced, reflecting the limitations from the lack of in-situ observations to evaluate the impact of the DA (over the irrigated regions), and the "potentially questionable" use of the satellite data without bias correction. Therefore my recommendation is to accept the manuscript for publication in HESS.

Response: Thank you for your comments. The manuscript has been updated according to the suggested changes.

I just leave a few minor technical suggestion to the authors below.

1. New title: The new title is more general, but better aligned with the content of the study. Although I'm not native English "via SMAP retrieval assimilation" sounds a bit strange. I would suggest to change it to "Soil moisture estimation in South Asia via assimilation of SMAP retrievals". But I leave this just as a suggestion for the authors. (lines in the document with track changes)

Response: The title has been changes to "Soil moisture estimation in South Asia via assimilation of SMAP retrievals"

2. Ln 235: "RMSE values were computed for model and SMAP" : "RMSE values were achieved for model and SMAP"

Response: The following text has been added to line 230:
"Based on the test results, it was noted that the smallest bias and RMSE values were achieved for model and SMAP soil moisture retrieval error standard deviations equal to 0.04 $m^3 m^{-3}$."

3. Ln 523: "would not work in this study": "would have limitations in this region"

Response: The following text has been added to line 513:
"Hence, implementation of CDF-matching only during certain months would have limitations in this region"

4. Ln 528; Sentence "It highlighted the limitations ... surface model" is not necessary, as this is already mentioned in the first sentence of the paragraph.

Response: The sentence "It highlighted the limitations ... surface model" has been removed from the text.

5. Ln 533: "new parameters are identified to" to "new parameters are required to"

Response: The sentence at line 521 has been modified to:

“However, an important point to consider is that with an increase in the hydrologic coupling between surface and deep soil layers, the complexity of the land surface model would also increase as new parameters are required to model the feedback loop between adjacent soil layers.”