Author response to R3

We thank the reviewer for their comments which have helped to strengthen our manuscript. Please find the responses below:

1) The reviewer suggested that we change the notation from RMSE and BIAS to RMSD and mean relative error as the prior notation makes the assumption that the ESA CCI estimates are close to the truth. The reviewer also commented that we should make an effort to include some independent observations.

We agree that the notation suggested by the reviewer is more appropriate and we have updated the manuscript accordingly. Another reviewer has also raised the concern over the quality of the observations with which we are comparing, especially as they are CDF matched to another land surface model. We have taken their advice and also included temporal correlation and the unbiased RMSD (ubRMSD) as metrics to show that the model still improves after removing any competing bias. We have added text commenting on the issues for the ESA CCI combined soil moisture product. We have also included independent in-situ observations of soil texture from the African Soil Profiles Database to judge our models soil maps and added text discussing the performance of CCI soil moisture over West Africa in section 2.3, P4L27:

"Dorigo et al. (2015) also show that the ESA CCI product performs well over Western Africa when judged against in-situ soil moisture observations from the AMMA network (Cappelaere et al., 2009) with stations in Benin, Mali and Niger. When judged against the AMMA network CCI soil moisture was shown to have a high correlation (~ 0.7) and one of the lowest unbiased root-mean squared differences (~ 0.04) of the 28 worldwide networks used in the study. This bodes well for our comparison over Ghana, which has a similar climate regime in the north to the sites in the AMMA network."

2) The reviewer suggested we included different performance scores as from the two included it appeared that the DA mainly acted to reduce the BIAS (mean relative error).

We agree that an additional performance score would be beneficial. As another comment from the author of a short comment on the paper has also suggested. We have included their suggestion of temporal correlation and ubRMSD to show that the DA technique also reduces random errors within the model, rather than just acting to rescale the model predictions. P11L8:

"Satellite soil moisture products can be subject to larger errors and biases associated with data processing. This is particularly true for the CCI level 3 combined active and passive product used in this paper, as in order to merge information from 11 different sensors data is CDF matched to the GLDAS-Noah v1 model (Rodell et al., 2004). Therefore, any bias within the GLDAS-Noah model will be included in the level 3 soil moisture product used here. To make sure we are not just correcting the bias of the JULES model to that of GLDAS-Noah we include summary statistics of unbiased root-mean squared difference (ubRMSD) and temporal correlation in table 2. In every case we find that after data assimilation we improve both ubRMSD and correlation and in the majority of cases find the best results for experiment 4 (TAMSAT v3.0 with DA). For the north of Ghana, we reduce the ubRMSD by 18% from experiment 3 (0.0622 $m^3 m^{-3}$) to experiment 4 (0.0508 $m^3 m^{-3}$). From experiment 2 to 4 we can see that, after data assimilation, using TAMSAT v3.0 rainfall over v2.0 has contributed to a 6% reduction in ubRMSD when calculating statistics over the whole period. In the south of Ghana we reduce the ubRMSD by 21% from experiment 3

(0.0590 m3 m−3) to experiment 4 (0.0467 m3 m−3), here improved rainfall data has contributed to 10% of this reduction."

3) The reviewer commented that the assumption made that CCI soil moisture observations are representative of the JULES top 10cm soil layer is unrealistic. They suggested we reformulate this assumption or use an exponential filter to address this.
We agree that the assumption made originally is perhaps not realistic. We have therefore updated the JULES model to run with a 5cm soil top layer and have re-run our experiments. We have updated the text in section 2.1 to reflect this and have also included the references mentioned by the reviewer commenting that this is another option. We find similar results as when running with a 10cm soil depth except a larger dry mean relative error in the north after data assimilation (see Figure 6). This is understandable as a shallower soil layer will dry more quickly. P3L16:
"In this paper we have updated JULES to run with a top layer of 5 cm to be more representative of the ESA CCI soil moisture observations. Another option to deal with the issue of representativity would be an exponential filter (Albergel et al., 2008) which has been used in sequential data assimilation studies previously (Massari et al., 2015; Alvarez-Garreton et al., 2016)."

4) The reviewer asks us to demonstrate the soil texture after DA more closely reflects reality than the HWSD.
We have included comparisons of our retrieved soil maps to in-situ observations of soil texture from the African soil profile database. We find that we can improve soil texture estimates in the north but are unable to do so in the south. We have added discussion about this in the text. P10L7:
"Comparing estimates of soil texture derived from CCI soil moisture to in-situ observations is inevitably problematic due to issues of representativity in the spatial domain. However, independent sources of verification are difficult to find over Ghana. We therefore compare our soil maps to in-situ observations from The African Soil Profile Database (Leenaars et al., 2014). This database is compiled by the International Soil Reference and Information Centre (ISRIC) with the quality of the data being rated from 1 (highest quality) to 4 (lowest quality), here we compare only to observations with a quality flag of 1 or 2. In table 1 we show the root-mean-squared error (RMSE) for our soil maps when compared to 21 in-situ observations of soil texture in the north of Ghana and 36 in-situ observations in the south (locations shown as red dots in Figure 9). For the north of Ghana where we have most confidence in our results we find a reduction in RMSE for both sand and clay (almost halving the RMSE in clay). However, the RMSE for silt is increased. In the south of Ghana we do not manage to recover a better estimate of soil texture after data assimilation, with an increase in RMSE for silt and clay but a decrease in RMSE for sand. The inability of the data assimilation to improve soil texture estimates at certain points is most likely due to issues of spatial representativity between the modelled soil map and the in-situ data. It is also possibly impacted by errors in our pedo-transfer functions, which may perform better if specifically calibrated for Ghanaian soils (Patil and Singh, 2016)."
5) Section 2.2 Define here which are the differences between TAMSAT 2.0 and 3.0
We have added text explaining the difference between the 2 products and added two figures showing how the products differ over Ghana. P4L10:

“TAMSAT v3.0 differs from TAMSAT v2.0 in that it uses an updated calibration against in-situ data that is more representative of local scales. […] For more information on the differences between the two TAMSAT products see Maidment et al. (2017).”
See new Figures 1 and 2 in attached manuscript of proposed changes.
6) Equation 1. Define N. Also xi should not be xo?
The reviewer is correct xi should be x0, N is the number of observations within the chosen time window. We have updated the text to clarify this.
7) Section 2.4. The reviewer asked us to describe how the matrices B and R are estimated.
We have described how B and R are specified in this section. P6L12:
“As we do not have a good estimate to the error in the prior estimates of model parameters we chose a conservative 5% standard deviation for the prior error covariance matrix B. This ensures we do not retrieve unrealistic estimates of soil texture after data assimilation. For the observational error covariance matrix R we have a diagonal matrix with variances estimated from the standard deviations included in the ESA CCI soil moisture product.”
8) P12L15 The reviewer asked us to remove the phrase “retrieve hydraulic parameters”.
Removed.