Author response to R2

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

1) The reviewer suggested that we change the title of the paper as the previous title was not well aligned with the paper contents.

We agree with the reviewer that a more appropriate title is necessary and have updated this accordingly:

"Impact of remotely sensed soil moisture and precipitation on soil moisture prediction for a data assimilation system with the JULES land surface model"

We feel that this more accurately brings out the novel aspects of the paper, i.e. and exploration of the useful information two different EO data sources – one driving the model (precipitation) and the other being used as a target variable (soil moisture).

2) The reviewer asked us to either remove discussion of agricultural drought from the abstract or complement the Results, Discussion and Conclusion with how the work here would be useful for better decision making in crop cultivation.

We agree that agricultural drought is not discussed enough throughout the paper to warrant its inclusion in the abstract. We have removed the relevant text.

3) The reviewer asked that we include the reduction in root-mean squared differences for both the North and South within the abstract P1L5-6.

We have included the statistics for the two regions instead of the whole of Ghana. We have also updated the performance statistic used at the request of other reviewers to unbiased root-mean squared error. P1L5:

"The use of an improved remotely-sensed rainfall dataset contributes to 6% of this reduction in error in northern Ghana and 10% in southern Ghana."

3) The reviewer asked us to remove mention of forecasting from the abstract P1L10

We have removed this from the abstract

4) The reviewer asked us to comment on the novelty of this research, compared to *Bolton et al. 2010* P2L13-14.

Bolten et al. 2010 conduct state estimation using a sequential data assimilation technique (Ensemble Kalman Filter), meaning that whenever an observation is available the model state (in this case soil moisture) will be updated, but if no data is available the model estimate to soil moisture will not be updated. In this paper we are conducting parameter estimation using a variational technique. Once we have ingested data over some time window the model parameters governing soil moisture will be updated and so will future and past estimates to soil moisture. We have clarified this in the text. P2L16:

"It has been shown by Bolten et al. (2010) that assimilation of remotely sensed surface soil moisture can significantly improve the prediction of root-zone soil moisture and drought modelling, where a sequential DA technique is used for soil moisture state estimation."

5) The reviewer asked us to remove the term "observations" from P3L4-5.

We have removed this.

6) The author asked us to highlight that we update only two parameters of soil texture, with the third being updated implicitly P4L31.

We have amended the text to show this. P7L1:

"we updated the percentage of sand and silt in the soil at each minimisation step (with clay being updated implicitly)"

7) The reviewer asked us to unify our usage of terminology "grid cell" and grid box" P6L9 and P6L17 with Figure caption 2.

We have updated the text accordingly.
8) The reviewer commented that the amplitude of soil moisture is decreasing for the model (2010-2014) and wondered if the precipitation data showed the same pattern P6L13-14.
We agree there is a noticeable trend in the amplitude of soil moisture and this is also seen in the precipitation data for both TAMSAT products. We have added a comment on this in the paper. P8L10:
"In Figure 4 we can also see the amplitude of this seasonal cycle slightly decreasing, this is a pattern also seen in both TAMSAT products which exhibit a drying over the period 2010-2014 for this grid cell"
9) The reviewer suggested it would be good to show a skill of JULES over daily averages of ESA CCI data for 2009 for Figure 2 and 3.
We have included root-mean squared differences between JULES and CCI data in the text.
In relation to Figure 2, P8L8:
"The model skill for predicting this seasonal cycle is markedly improved after data assimilation, with a root-mean squared difference (RMSD) of 0.035 after data assimilation compared to a RMSD of 0.094 before for 2009"
In relation to Figure 3, P8L15:
"(RMSD of 0.059 after data assimilation compared to RMSD of 0.102 before for 2009)"
10) P6L20-21: "Although we do improve the fit to the observations after data assimilation in Figure 3..." – Reviewer asked us to add a quantitative metric.
We have included RMSD reduction as a quantitative metric, please see previous comment (no. 9).
11) The reviewer asked us to add a plot of the difference in precipitation between TAMSAT versions P6L30-31.
We have added the suggested figure (See new Figure 1) and also included a figure of cumulative rainfall over the period of the experiments (2009 – 2014) to show TAMSAT v2.0 is the drier product (see new Figure 2).
We have added text to section 2.2 discussing these figures, P4L15:
"In Figure 1 we show yearly cumulative rainfall averaged over 2009 - 2014 for TAMSAT v2.0 and v3.0, we can see the different spatial distributions of rain with v3.0 being wetter in the south and v2.0 wetter in the east. To show the difference in the amount of rainfall for the two products we also show cumulative rainfall for the period 2009 - 2014 averaged spatially over Ghana in Figure 2, this shows TAMSAT v2.0 to be the drier of the two products overall, as expected."
12) The reviewer asked us to update Figure 5 to have monthly or weekly RMSEs (rather than yearly) P6L32
We have updated this figure accordingly to display monthly rather than yearly averages and now display two new Figures (see Figure 7 and 8 in attached manuscript of proposed changes), as the reviewer has suggested this helps to understand dynamic patterns better.
P8L30:
"Figure 7 and 8 show experiment monthly root-mean-square differences (RMSD) for north and south Ghana respectively. For Figure 7 this shows that the most accurate model run overall is experiment 4 (TAMSAT v3.0 with DA). We see in the majority of years that towards the start of the season as soils are wetting up it is experiment 3 and 4 (TAMSAT v3.0 no DA and with DA respectively) that have the lowest RMSD, suggesting that it is precipitation, as opposed to the assimilation of soil moisture, that is most important for improving soil moisture estimates during this period. This relationship changes towards the end of the

rainy season with experiment 2 and 4 being the most accurate (TAMSAT v2.0 with DA and TAMSAT v3.0 with DA respectively) suggesting that assimilation of soil moisture estimates is most important in this period…"

13) The reviewer asked if there was another database of soil properties for comparison with HWSD and JULES-DA results P7L12-15.

We have used in-situ observations from The African Soil Profile Database compiled by ISRIC to compare with our results. We find an improvement in soil texture in the north of Ghana compared to the in-situ measurements. This is not the case for the south, where we slightly degrade our estimate of soil texture. Relevant text has been added to 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)."

14) The reviewer asked us to calculate summary statistics for the north and south of Ghana rather than the country as a whole P8L5-12

We have updated the summary statistics in Table 2 accordingly. At the request of other reviewers, we have also changed the statistics used in this table from RMSE and bias to unbiased RMSD and correlation.

15) P12L5- 8: The reviewer asked us to describe in details why "updating of soil parameters" (= updating all of the parametrization of water cycle processes in JULES) sometimes works worse than precipitation forcing updating.

We have added more explanation here. P15L9:

"This can be seen in Figure 7 where TAMSAT v3.0 without DA outperforms TAMSAT v2.0 with DA at certain times in the season. This is because at these times the data assimilation system is not able to overcome the errors in the precipitation forcing data to improve the estimates further. If there is too little rainfall, there is a point where the DA system cannot make the soil any wetter because we are not changing the model soil moisture state - only the soil texture."

16) The reviewer commented that it is not possible to improve predictions with no access to forcing data P12L12-14.

We have removed this text.

17) The reviewer commented that discussion of the data assimilation system was too technical for the discussion P12L15-22.

We have moved this text to the methods section 2.4

18) The reviewer commented that the conclusions were too technical and miss the HESS aims and scope P13L9-19.

We have updated conclusions to try and address this point

Typos:

P12L11: "after after".

Amended.