Text formats:

Referee – bold, non-italic

Answer of the author – non-bold, non-italic

Cited text – non-bold, italic

Reviewer 1

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GENERAL COMMENTS

The manuscript is well written and clear. The topic is of interest for the HESS readership as cosmic-ray probes represent a relatively new technology for ground measuring soil moisture over large areas. Therefore, we need to assess the impact of this new technology for improving land surface modelling. The paper describes several assimilation experiments in which soil moisture data from cosmic-ray probes are used for improving soil moisture modelling through CLM land surface model. Results are (quite) well described and clearly structured. However, in my opinion, several aspects should be improved/changed before the publication. I reported below a list of the general comments to be addressed with also the specification of their relevance.

Thank you for your positive evaluation and for your time reviewing this manuscript. We carefully address your comments in the following indicating the planned revision of the manuscript.

1) MAJOR: Some of the results shown in the paper are well-known. I am aware that it is important to show real-world experiments, mainly by considering new technology, but the main results given in the paper were already reported in several previous studies: a) the assimilation of ground-based soil moisture data is able to improve soil moisture modelling, b) the joint state-parameter assimilation is better than the state assimilation only, and c) the assimilation is more effective when soil texture information are wrong (i.e., there's larger room for improvement). I believe that the paper results need to be published, but I would like to see some new findings that can be obtained by using the same material (data and modelling) presented in the paper.

As pointed out later in this response, the present study describes a way to propagate CRP measurements into horizontal space using the local ensemble transform Kalman Filter:

"Although information on neutron flux intensity was only available at few locations in the catchment, the local ensemble transform Kalman filter (LETKF) allows updating of soil water content (SWC) at unmonitored locations in the catchment considering model and observation uncertainties."

Another key finding was pointed out in the abstract, where we quantified the possible improvement of soil moisture prediction using a land surface model:

“*For the biased soil map, soil moisture characterization improved in both periods strongly from a ERMS of 0.11 cm3/cm3 to 0.03 cm3/cm3 (assimilation period) and from 0.12 cm3/cm3 to 0.05 cm3/cm3 (verification period) and the estimated soil hydraulic parameters were after assimilation closer to the ones of the regional soil map.* “

This is a major novelty. In the discussion section, the limited land surface model precision was estimated and related to the measurement error:

“*The soil map BK50 led to ERMS-values in open loop simulations below 0.05 cm3/cm3 which left little room for error reduction considering the measurement error of 0.03 cm3/cm3.*”

We would like to draw your attention to the conclusion section of this manuscript. The conclusion adds important findings of this work based on the results and discussion Sections. This work stresses the direction of research which should be taken for the use of CRP data in parameter estimation of land surface models:

“*For now, CRP neutron intensity observations were not assimilated directly. In future studies it would be desirable to use the COSMIC operator for assimilating neutron intensity observations directly. However, in this case the impact of biomass on the CRP measurement signal would have to be taken into account. Therefore, it is desirable to further develop the COSMIC operator to include the impact of biomass on neutron intensities.*”

For instance:

A) What are the results if only one (or two) cosmic-ray probes are assimilated? In the real world it is expected that the number of probes will be limited and, hence, the use of a limited number of probes is surely of great interest.

Thank you for the suggestion. We will present in the revised version of the manuscript additional simulation experiments with a smaller number (4) of cosmic ray probes. This allows verification at five other cosmic ray probes.

B) What is the impact in terms of fluxes? In section 4.6 a comparison of annual evapotranspiration maps without and with the assimilation is carried out, but simply showing that the resulting maps are different. However, it is obvious that changing soil moisture will change evapotranspiration. Is it possible to perform an independent validation by using data about the actual evapotranspiration in the basin? Or likely by using discharge observations? I believe that some new results should be included in the paper (even though I am aware that authors are usually reluctant to perform additional analyses). Moreover, the results in terms of soil moisture simulation should be synthetized (see Comment 5).

In the revised version of the manuscript we will present a comparison of simulated ET (before and after data assimilation) and measured ET by eddy covariance at a few locations. We will discuss in detail the implications of the comparison. However, a comparison for many EC-stations is not possible as the correction of the energy balance gaps of the EC-data and many data gaps in the EC-data are not trivial to be resolved.

2) MAJOR: The description of the data assimilation experiments should be improved. As usually, a number of subjective choices were made in the setup of the data assimilation experiments, and these choices may have a significant impact on the results. For instance, a fixed error for soil moisture estimates from cosmic-ray probes is considered (0.03 cm3/cm3). Similarly, the perturbation factors for input data (precipitation and shortwave radiation) and parameters (10 and 30%) are arbitrarily selected. A sensitivity analysis on these choices should be carried out. It might be that different choices produce very different results.

Thank you for these constructive suggestions. We agree that a number of assumptions needed to be made. The assumption on the measurement error for the soil water content was thoroughly evaluated and more details can be found in our earlier papers on this (e.g., Bogena et al., 2013; Baatz et al., 2014; Baatz et al., 2015). We feel that there is no need to repeat experiments with other values for the measurement error.

However, we agree that perturbation of meteorological forcings and soil hydraulic parameters are subject to larger uncertainty. However, the perturbation of soil hydraulic parameters is done in CLM by perturbing soil texture. The currently applied perturbations of up to 30% are already large and we feel that this covers adequately the uncertainty with respect to texture. We also already tested two different magnitudes of perturbation of precipitation, including a 50% and 100% error. We feel that the applied perturbations are realistic and the difference in the two applied perturbations was already large.

In addition, simulations were not strongly affected by the magnitude of the perturbations. The simulations are also CPU-intensive. We expect that an extension of the experiments for further magnitudes of perturbation would not supply significant additional insights.

3) MODERATE: Similarly as above, the selection of one single biased soil texture map is arbitrary. Why only one soil map? Why 80% of sand content and 10% of clay content is selected? What is the average sand and clay content percentage in the basin? Again, a sensitivity analysis is needed. Otherwise, it might be that a very large error in the soil map is used to highlight the positive impact of assimilating soil moisture data. What happens for a less biased map? This aspect should be clarified.

Thank you for this suggestion. In the revised version, we intend to include a simulation with a third soil map that may be close to the expected values of the BK50 soil map. Table 1 shows the sand content at the nine locations assimilated for the BK50 soil map. However, we would like to stress that the high resolution BK50 soil map represents not the *true* sand and clay content but is rather the expected sand and clay content with errors represented by the perturbation. Considering this, the BK50 soil map already is a “less biased map”. We will add information on catchment wide average sand and clay content, and what was the motivation to select the biased soil map as initial soil map in part of the simulation experiments:

"The BK50 soil map provides the initial high resolution soil texture for the catchment and is the most detailed soil map available for the defined region. Average sand and clay content of the catchment are 22.5% and 21.4%, respectively. As an alternative, simulations were also performed for a biased soil texture distribution with a fixed sand content of 80 % and clay content of 10 % (S80 soil map). This represents a large error with respect to the expected soil properties. However, perturbations of 10 and 30 % guarantee some variability in the initial soil properties. The S80 soil map simulations allow evaluating the joint state-parameter estimation approach because given the expected bias, we can evaluate whether and to what extend the soil properties are modified by the data assimilation to be closer to the available high resolution soil map."

4) MINOR: In CLM the subsurface lateral flow is not considered. It has an impact on soil moisture simulation and, mainly, on the capability to modify soil moisture simulations at unmonitored locations. Therefore, I expect that the assimilation of in situ soil moisture data will have a local effect. However, the jackknifing data assimilation experiments show that the assimilation produces significant changes also at unmonitored locations. Why does it happen? I believe it should be clarified in the paper.

Thank you for this detail. It is correct that CLM does not consider subsurface lateral flow. The updates of soil moisture in space depend on spatial correlations of soil moisture. In this study, spatial correlations of soil moisture are the consequence of spatial correlations of the atmospheric forcings, spatial correlations of soil hydraulic parameters and their interaction with the land surface model. Atmospheric reanalysis data and the soil map provided a good basis for the imposed spatial correlation structure. The imposed spatial correlation structures on the perturbations determine to a large extend the soil moisture updates in space.

5) MINOR: In sections 4.2 and 4.5, too many details are provided in the description of the results for each single site. I suggest focusing on the most important results to improve their readability. Also, discussion section is too generic, especially the first paragraph. In the specific comments, I added some corrections and suggestions that should be implemented. On this basis, I believe the paper deserves to be published only after a major revision.

Results section and discussion section will be shortened respectively sharpened, also taking into account the detailed comments of reviewer #3.

SPECIFIC COMMENTS (P: page, L: line or lines) Title: The paper, in the current version, demonstrates that the assimilation of soil moisture data from cosmic-ray probes is able to improve soil moisture modelling, not "land surface modelling" (e.g., evapotranspiration or discharge fluxes). Therefore, I suggest changing the title. Abstract: The abstract should include information on the location of the study area and on the employed data assimilation technique.

P4, L7: Formatting error for Kurtz et al. (2016). Please correct.

Thank you. This will be corrected.

P5, L19: It should be COSMIC in place of COMIC.

Thank you. This will be corrected as well.

P12, L11: Is sigma=0.5 considered for perturbing precipitation in all the assimilation experiments? Please clarify.

We changed:

"For jackknife simulations, the perturbation of soil texture was set to 30 % and precipitation perturbation was set to σ= 0.5 for all experiments."

P12, L25: It should be "four data assimilation scenarios" in place of "six assimilation scenarios".

Thank you. This will be changed.

P19, L18-19: This sentence is too broad, please modify.

Thank you. We agree and changed the sentence to:

"Hence, this study represents a way forward towards the integration of CRP information in the calibration or real-time updating of land surface models."