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Discussions

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Interactive
comment

Interactive comment on "Evaluating the value of a network of cosmic-ray probes for improving land surface modelling" *by* Roland Baatz et al.

Anonymous Referee #3

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The presented manuscript applies time-series data from 9 cosmic-ray neutron stations to the land-surface model CLM in the Rur catchment. The authors assimilate the data using an ensemble Kalman filter technique to update states and parameters of their model. The added value of training data in years 2011 to 2012 is assessed (1) by testing the model performance in year 2013, (2) by testing the model adaption capabilities to an invalid soil map, and (3) by jackknifing single stations from the training period. The application of the cosmic-ray neutron method in large-scale models is one of the challenges in state-of-the-art hydrology and thus the present study is worth to be published in the scope of HESS after major revision.

1 Evaluating the overall quality

Large parts of the manuscript are written in the style of a protocol, by listing lots of other publications who used similar approaches, by mentioning tools that were used, and by reporting every step of the performed analysis. However, I believe that scientific articles should be entitled to challenge their own strategy by discussing alternative methods, by justifying their selection of tools and decisions, and by explaining the corresponding implications. I would thus recommend to rewrite and extend major parts of the introduction and method section. Therein, some literature reviews are unnecessary and probably unrelated to the study and can be omitted or need further explanation (see line-by-line comments). Here, I would suggest to follow the guideline that cited papers should be discussed, and not just mentioned. Other parts concerning the data integration and the SWC model need to be described in more detail. I would further recommend to reduce the detail of the results section, which is hard to follow without proper discussion, and thus to merge it with the discussion section.

The results of the study were well structured and decribed, but are not entirely novel, and not sufficient to provide answers to all research questions raised by the authors. For example, to assess the value of a CRNS network of certain density to the performance of a land-surface model, various fractions of the 9 stations should be tested as requested by Referee #1.

Furthermore, the study uses some questionable assumptions, like a constant error of soil moisture data (although neutron measurement uncertainty highly varies with wetness condition), or the assimilation of SWC data assuming homogeneous vertical profiles and no changes of seasonal biomass (see line-by-line comments for details). Another questionable approach is to allow static site-specific parameters to be variable in time, e.g., hydraulic conductivity or soil porosity. This is highly counter-intuitive and should be discussed with respect to uncertain data and/or model conceptualization.

I agree to most of the general comments made by Referee #1 and will thus compensate

the previous reviews by detailed line-by-line comments below.

2 Line-by-line comments, scientific questions/issues, and technical corrections

- Title ("Evaluating the value of a network of cosmic-ray probes for improving land surface modelling"): I'd suggest to remove "the value of" to simplify the title. Furthermore, state observations usually do not improve a *model*, they rather improve *model results*, e.g. predictions.

Page 2

- L1: "Land surface models can model": bad phrasing, replace "can model" e.g. by "describe".

- L3: "CRP", please use the newly accepted abbreviation CRNS (cosmic-ray neutron sensing/sensor) with regards to the recent 5th COSMOS workshop.

- L14: improve readability, split in two sentences.

- L18: please add a statement about the impact of your findings for the scientific community.

- L21-22: this sentence needs a reference.

- L24: " and is " → "while it is"

- L27-28: the given number of references here appears to overwhelm the statement and its low relevance to your paper. Please use only the 1 or 2 most important citations.

- L30-31: Please discuss the alternatives in more detail to strengthen your decision to use CRNS technology. Were space-borne remote-sensing products assimilated to LSMs before? Why wasn't it successful? What about the use of airborne products with higher resolution and depth? You could also mention point-scale or large-scale soil moisture monitoring networks which have been used for evaluation of land surface models.

- L31: "not reliable for areas with dense vegetation": a paper by the same first author recently found that CRNS is also influenced by dense vegetation. Is it more reliable?

- L33: the selection of citations for this statement appears to be random/unrelated. If you want to provide references for the "intermediate scale", Zreda 2008 and Köhli 2015 might be appropriate.

- L34: "desired application scale of land surface models": please make the reader happy by finally providing concrete information. What is the scale? Are you talking about centimeters or lightyears? Please do not use citations inflationary and do not keep them untouched. How do the three citations help you to support your argumentation?

Page 3

- L1: omit "fast" as it repeats with the next sentence.

- L3: add "fast" to make clear that the sensor measures the non-moderated neutrons.

- L4: "15 ha", your SWC range seems to be 10 to 40%, which leads to an approximate CRNS footprint of 7 to 14 ha following Köhli 2015, excluding vegetation

and altitude influence. You could write "maximum area of 15 ha" to circumvent mentioning this variability.

- L6: omit "Desilets and Zreda, 2013" as it does only marginally address heterogeneous averaging. Franz 2013a is already a great reference to this topic, Köhli 2015 also touched this.

- L8: Bogena et al. 2013 did not perform simulations to the penetration depth. Instead, Franz et al. 2012 (`doi:10.1029/2012WR01187`) and Köhli et al. 2015 provided simulations that both support these values.

- L11: add a reference for COSMOS-UK, Evans et al. 2016, `10.1002/hyp.10929`

- L13-15: please rephrase to make clear what data assimilation is and is not.

- L15: It is not clear why you choose EnKF. Please at least mention other techniques and provide reasons for your choice. The sentence further should be moved to the end of the paragraph after you have introduced the history of DA.

- L16-34: This historical overview appears to be unnecessary in the context of your study. Neither do you explain what things like " four-dimensional variational DA" are, nor is the relation to your work described. Furthermore, citations are used inflationary again. Please reduce this paragraph to the key publications which support your study. Also think about moving certain studies about ensemble size, multiple time steps, and other filtering approaches to the methodology section, where you need justification for your approach.

- L30-32: Just to emphasize the previous comment, these lines particularly carry no information for non-experts due to the lack of explanation.

Page 4

- L1-19: As stated before, the whole literature review appears to be random and irrelevant to your work. Or at least the relations are not explained. For example, work from Montzka 2011;2013 and Han 2014b appear to be of some relevance for you, prior to others.

- L23-24: "Its capability to propagate surface soil moisture information into the deeper soil column was analyzed by Rosolem et al. (2014)", what does this sentence mean?

- L26: "The COSMIC operator", third repetition as a sentence starter.

- L27-29: combine those sentences: "neutron observations have been used to update states (...) and hydraulic parameters (...)"

- L29: "showed" → "demonstrated"

- L29-30: be more correct in phrasing. Rephrase that Villarreyes 2014 used a different model, but also estimated hydr. parameters by inversion. Han 2016 did so too, using support from neutron data, but neutron assimilation alone does not "update" a hydraulic parameter.

- L31: "This work further explores", omit "further". Until now it is not clear what *this work* does, you only told stories about work of others. Please summarize which of the presented approaches you are picking up and what scientific novelty you add.

Page 5

- L3-4: "the soil moisture characterization at the larger catchment scale", what exactly is meant by these terms, and how do you measure improvement?

C6

- L4: "how dense the CRP network should be", do you answer this question?

- L7-8: "soil maps and atmospheric forcings show spatial correlations over larger distances", this is an interesting point, please provide reference. Isn't the large-scale heterogeneity of soil maps only an artefact of soil data scarcity?

- L9: "10 stations", do you assimilate all 10, or just 9?

- L15: "feasibility of the updated large scale soil hydraulic parameters", how can a parameter be feasible? Please clarify your novel research question.

- L18-19: The sentences can be omitted as being obvious.

Page 6

- L6: correct wording, a "process" can not be "solved"

- L10: "Oleson et al. (2013) provide further details on CLM4.5", redundant information with regard to L5-6.

- L10-12: provide reasons why you artificially limit the scope and complexity of your study. What process would a "biogeochemical module" have added and why are they not important here compared to a prescribed LAI?

- L14: please finally (after lots of references in the introduction) provide concrete information about the grid size in your study (the reader is still lost between centimeters and lightyears)

- L23: use standard format for functions, $k[z] \rightarrow k(z)$

- L24: format $z \rightarrow z$

- L24: what is the difference between "soil moisture" and SWC? Why are you using the expression θ here, while SWC is used elsewhere (e.g., eqs. 24 and 25)?

- L25: use the more convenient expression $k_{\text{sat}}(z)$,

- L26 (eq. 1):

  - format $k[z] \rightarrow k(z)$,
  - rewrite $k_{sat,z} \rightarrow k_{\text{sat}}(z)$ as this is a functional relationship. In contrast, indexing a state variable θ_i is ok.
  - omit occurrences of 0.5 since $\frac{0.5}{0.5} \approx 1$,
  - case conditions (e.g., $1 < i < N \ldots$) are usually preceded by a comma in each line
  - the curly bracket on the right is not common in multi-case equations.

Page 7

- eq. 3 and 5: reformat $sand \rightarrow$ sand, same for clay.

- L6: "whereas", split sentence here.

- eqs. 9 and 10: this is a single equation, requiring only a single equation number, and a multi-case alignment using a curly bracket

- L12: reformat $mm \rightarrow$ mm,

- whole page: please motivate the reader why these details are important for your research question. Also provide information where all these empirical (fixed) parameters (or regression coefficients) are coming from. Is the underlying theory so well understood that no uncertainties or further dependencies are required?

C8

Page 8

- L4: "COSMIC parameterizes interactions". The *interactions are parameterized* by the underlying physical cross-section data. COSMIC rather *parameterizes the neutron transport*.

- L7-8: Repetition from the introduction.

- L10: "high energy neutrons are reduced" → "the number of high energy neutrons is reduced"

- L11: "with less energy in each soil layer", misleading/unphysical. Fast neutrons typically evaporate with constant energy.

- L12: rewrite "soil interaction", as fast neutrons predominantly interact with the water.

- L16-22 and eq. 14: this part can be omitted, since it is already well described in papers from Shuttleworth and Baatz, and does not add to the message of this paper. If you decide not to omit it, replace θ in eq. 14 to avoid confusion with soil moisture.

- L22: explain to the reader how the 300 soil layers in COSMIC communicate with the 10 soil layers from CLM.

- L26: what is a "COSMIC soil surface"?

- L25ff: it looks like you are not assimilating neutrons, but reiterating SWC from neutron data. The whole paragraph creates a great confusion about what the difference is between SWC, CLM SWC, weighted CLM SWC, and CRP SWC. In contrast to other less relevant paragraphs in this section, this part is highly unclear and simultaneously highly important to understand the most important

part of your model. Please rephrase the whole paragraph and clarify to the reader what exactly you do, and why (i.e., why not assimilating N directly?)

Page 9

- L5-10: Your paper is not a protocol. Again, it is described *what* you are using and *who else* used it, but the reader is left with the question *why* you (and others) made this decision. Shortly explain advantages of your strategy and why it serves your research question better than others.

- L11: what is f in $\vec{x}^f$?

- L19: confusing typesetting. Is it $\vec{H}$ as a function of the COSMIC model, or is $\vec{H}$ identical with the COSMIC operator?

- eq. 19: do not use T as a symbol for transposition, there is a reserved symbol for this: $\vec{Y}^\top$.

Page 10

- L18: redundant sentence.

- L20: why these values? is it comparable with the catchment-mean texture? If your question is, what impact a rough and uncertain soil map in data scarce region would have, wouldn't it be more reasonable to *smooth out* the existing soil map to a very rough degree, rather than using a completely arbitrary soil map?

Page 11

- L3-5: omit physical units (they are irrelevant in this context).

C10

- L8-11: How do you justify the perturbation of physical soil parameters like porosity and texture? Does the uncertainty of the soil map justify the huge variation ranges applied in this work? Are models allowed to adapt their physical basement to hydrological data (which also show uncertainty)?

- L15: omit "="

- How was the CRP SWC uncertainty determined? Assuming a constant CRNS error is not physical and might have substantial influence on the results (to be tested). For example, the error of neutron observations N is $\sqrt{N}$, while N can almost double from very wet to very dry conditions, which leads to a variation of the neutron uncertainty by 30%. This can propagate through the non-linear relation to soil moisture in such a way that your observed SWC is significantly more uncertain in wet periods compared to dry periods. Consequently, the DA approach should give more weight to dry periods during assimilation.

Page 12

- L16: Why do you use RMSE, although many alternative measures are accepted as state-of-the-art measures for time series evaluation, e.g., KGE or NSE, in order to assess bias, deviation, and correlation simultaneously?

- eqs. 23 and 24: reformat $SWC \rightarrow$ SWC, same with $RMSE$ and $bias$, as those are single multi-letter variables, not products of multiple single-letter variables. Following this style guide, rewrite $\text{E}_{RMS} \rightarrow E_{\text{RMS}}$. You can even omit "RMS" since E is the only error used in this work. This would improve readability of the results section.

Page 16

- L17-26: It is argued that changes in SWC states have impact to simulated ET flux. However, only for state-parameter updates (L19). Why is ET not affected by (SWC) state updates only?

- L32: "to E_{RMS}-values", omit "-"

Page 17

- L9: if precipitation data from COSMO_DE was used, why was this information omitted in the method section (only mentioning DWD)?

- L26: replace "fast" with "quickly".

Page 18

- L10-23: This question already needs an answer in the method section, I'd suggest to move the whole paragraph.

- L10-23: I cannot follow the argumentation. Baatz et al. 2014 suggested a correction function for neutron counts based on vegetation estimates. In your model, you already have LAI data every month, implementation of the correction functions in the model would probably be straight forward. Furthermore, to convert neutron data to SWC, some vegetation correction would be necessary, too. Third, assimilating CRP SWC assumes homogeneous vertical SWC profiles (before iteration), this assumption would be unnecessary if neutrons would be assimilated directly. I am afraid that this topic is more complex and needs further discussions and tests. It would be most convincing if you could show that neutron assimilation indeed gives different results than CRP SWC assimilation.

- L27: "neutron flux intensity", do you mean flux or intensity or both?

- L27: "Although ... only available at few locations", write more positively. Neutron data was available at up to 9 locations, which was intended to be the amazing novelty compared to other catchments!

Figures

1. South → south, same with North.

2. Please add grid lines

3. Please add grid lines

4. Please add grid lines

5. It is hard to distinguish two black lines with different meaning. Further indication of the expected "true" sand content (given by the soil map or soil samples) would be helpful to evaluate these plots.

6. This figure is not understandable without the text. Please shortly provide information about the B parameter in the caption to understand the message of this figure.

7. replace k(sat) → k_{sat}. It would be interesting to also show the evolution of the soil porosity parameter together with an indication of its measured value. Why does hydraulic conductivity (and probably also porosity) vary over time at individual sites? Those are expected to be constant physical parameters of the sites. In my opinion this is a serious flaw of the DA approach used here.

8. The purpose of this figure is not clear, as no observation data is provided to evaluate the model performance with respect to simulated latent heat.

Tables

1. what is C3? Replace "non arctic" with "non-arctic", probably add a citation to the caption for plant functional types.

2. •

3. improve readability by increasing font weight (boldness) for particularly good cases below an RMSE threshold, which is a common strategy in many journals.

4. same as 3. Rephrase the last sentence.

5. same as 4.