Response to Anonymous Referee #1

(1) In this manuscript, the authors investigate whether it is possible to infer the temporal variability of certain hydrological model parameters that are often assumed to be stationary. To that end, the method of ensemble Kalman (EnKF) filter is applied, which is known for its ability to account for time-varying state variables. The authors apply their approach first to a synthetic basin with varying degrees of uncertainty and then to two different real-world basins with different temporal variability of model parameters. Their results demonstrate the overall ability of EnKF for time-variant parameter identification.

The manuscript itself is very well written. The introduction gives an adequate overview on the relevant questions and properly motivates the study. The methods section provides the reader with the necessary information on the used model, the EnKF used for the inference and the criteria used for evaluating success. The results are presented in a way that it easy to follow and understand, and the discussion provides the necessary context for these results. The data given through figures and tables is clear, well presented and sufficient to support the conclusions drawn by the authors. Furthermore, the presented conclusions are very relevant for the Scientific Community interested in model calibration and are well suited for the scope of HESS. I have to say that I really liked the study and the way it is presented in the manuscript. I cannot see any major problems and I think the authors did a fine job throughout. In conclusion, I would strongly recommend publication.

Reply:

We thank the reviewer for the positive summary and helpful comments.

(2) Page 5, Line 62: The authors present two established methods to account for time-variant parameters: windowed assimilation (dividing the calibration set into smaller subsets) and parametric assimilation (assuming a parametric model for the time dependency) and contrast this with EnKF which is a non-parametric

assimilation procedure (no form of the time dependency is assumed). I wonder how their approach might fare against parametric techniques. Typically, parametric estimation techniques are superior when the true form of the dependency is known but their performance quickly decreases when this condition isn't meet. Maybe, the authors want to elaborate where they see the strengths and weaknesses of their method vis-a-vis these other approaches. This may be relevant for parameters like C (the evapotranspiration parameter), where plausible parametric models for the time dependency are possible. In fact, the authors use a parametric model for C (for simulation and not for estimation, of course) in their synthetic basin. In such a situation, a parametric estimation scheme may outperform EnKF.

Reply:

As the reviewer mentioned, the performance of the parametric estimation is significantly affected by the catchment conditions (e.g., climate and vegetation), and it is difficult to obtain the true form of the parameter function. We agree with the reviewer that a parametric estimation scheme may have a better performance if the true parameter function can be obtained. Even though the EnKF-based estimation cannot perfectly match the time-variant values of the parameters, it can successfully capture the temporal variations of the parameters based on the results from the synthetic experiment. The results from the two case studies show that the estimated time series of the parameters can be linked to the variations of the catchment characteristics, illustrating the good performance of the proposed method. One of the advantages for estimating the time-variant parameters using the EnKF is that it can conduct real time updating for the parameters based on the observations, providing time series of parameter values without assuming the parameter functions or sub-dividing the calibration set.

(3) Page 6, Line 82: The authors use the term data assimilation of which EnKF is a particular implementation. The term is introduced in the introduction together with its abbreviation and never used again. If you introduce a term, it better be

important later on. If not, I would propose to skip this term and start with EnKF right away.

Reply:

Thank you. The data assimilation methods applied in hydrology include EnKF and others such as Particle-DREAM. EnKF is a typical data assimilation method. We have revised the aim for clarification (Page 6, Line 84-85).

"The aim of this study is to assess the capability of the EnKF to identify the temporal variations of the model parameters for a monthly water balance model."

(4) Page 8, Line 17: The authors say that EnKF is based on the Monte-Carlo method. I am not sure about the wording. First, Monte Carlo is not really a method but a buzzword for virtually any method that employs a random number generator at some point. Second, the randomness is only one element of EnKF, with others being the approximation of the covariance by the sample covariance and the assumption of Gaussianity for the PDF's.

Reply:

Thank you. We agree with the comment. The Monte Carlo is not really a method, and the EnKF is not only based upon the Monte Carlo but also the Kalman filter formulation. The wording has been modified in the revised manuscript (Page 8, Line 119-121).

"As a sequential data assimilation technique, EnKF is based on the Monte Carlo and the Kalman filter formulation to produce an ensemble of state simulations for updating the state variables and their covariance matrix, conditioned on a series of observations (Evensen 1994; Burgers et al., 1998; Moradkhani et al., 2005; Shi et al., 2014)."

(5) Page 8, Line 19: The authors care to mention that EnKF is applicable to a variety of non-linear problems. I am not an expert on the issue but I alway thought that EnKF assumes a linear forward model. I know that extensions of the Kalman filter to non-linear models exist. Is that what the authors talk about?

If so, it's a little bit confusing.

Reply:

Thank you. The standard Kalman filter (KF), which is a data assimilation technique for linear systems, has been modified to the Extended Kalman filter (EKF) for nonlinear problems. EKF is used for linear approximation and has limits in estimation stability when the nonlinearity degree increases in the system. Ensemble Kalman filter (EnKF) uses statistical distributions to represent uncertainties of model and observation errors and to produce ensembles for updating state and parameter variables. EnKF has been used for a variety of nonlinear problems (Evensen, 2003; Weerts and El Serafy, 2006), especially for the estimation of model states and parameters (Moradkhani et al., 2005; Wang et al., 2009; Xie and Zhang, 2010; Xie and Zhang, 2013; Samuel et al., 2014). Therefore, we use EnKF to identify the temporal variations of model parameters in this study since the hydrologic model is nonlinear.

(6) The authors consistently speak of uncertainty intervals (e.g., Page 19, Line 14). What do they mean by that? Credible intervals, confidence intervals, prediction intervals or something else? In my opinion, only credible intervals represent uncertainty, so the authors should elaborate on what they mean.

Reply:

Thank you. The uncertainty intervals used in this study are prediction intervals, which are obtained from the updated ensembles of the model parameters (Vrugt et al., 2013). It has been clarified in the revised manuscript (Page 19, Line 311-313).

"The grey areas represent the 95% prediction uncertainty intervals, which reduce quickly and approach a stable spread."

(7) Page 13, Line 97: If the authors care to explain that NSE=1 is a perfect match, they should also explain that it starts at -∞. People, who do not know about the NSE, may be lead to think that it varies between 0<NSE<1, which is obviously not the case. On the other hand, people who do know about the NSE don't need

that information.

Reply:

Thank you. The explanations are added to clarify the meanings of *NSE* values (Page 12-13, Line 195-198).

"It ranges from $-\infty$ to 1. A *NSE* value of 1 means a perfect match of simulated runoff to the observations, while a value of 0 means the model simulations are the same as the mean value of the runoff observations; and negative *NSE* values indicate that the mean observed runoff is better than the model simulations."

(8) The authors diverge from the established IMRaD structure by splitting the Methods part into the 'Methodology' and 'Data and study area' section. This is nothing major, but it was a little bit disorienting when I first read the manuscript.

Reply:

Thank you. The "Data and study area" part includes a synthetic experiment and two case studies. Therefore, we split the Methods into two parts.

(9) The manuscript appears to have been typeset with a word processor like Microsoft Word and it shows. There are several major widows and orphans throughout the manuscript (e.g., Page 4, 7, 8, 11, and 24). I guess the publishing office takes care of it in the final version, but it was a drag while reading. In particular, section headings shouldn't be left dangling on a single page (see, e.g., Page 13 and 15).

Reply:

Thanks. The widows and orphans have been adjusted in the revised manuscript.

(10) Similarly, the line numbering was confusing. Either use continuous line numbering or start a new every page.

Reply:

Thanks. We are not sure if the reviewer got the right pdf version of the manuscript,

but the line numbering in the file “hess-2016-370.pdf” is continuous (Line 1 to 629) from Page 1 to 42 after double checked.

(11) Punctuation is missing throughout all equations that aren’t inline. Punctuation rules should apply to both inline and non-inline equations (see, e.g., Higham, Nicholas J. (1998), Handbook of Writing for the Mathematical Sciences, SIAM, ISBN 0-89871-420-6).

Reply:

Thanks. The writing of symbols and equations is checked and revised. Punctuation is added for all the equations (Page 9, Line 131; Page 7-13).

(12) Instead of acknowledging the contribution of the reviewers (who haven’t done anything at this point), the authors may want to include the data providers (e.g., the China Meteorological Data Sharing Service System).

Reply:

Thanks. The acknowledgement to data provider has been added (Page 25, Line 415-416).

“The authors thank the China Meteorological Data Sharing Service System for providing a part of the data used in this study.”