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Discussions

Interactive comment on "Data assimilation in integrated hydrological modelling in the presence of observation bias" *by* J. Rasmussen et al.

J. Rasmussen et al.

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Anonymous Referee #1

Thank you for your comments. We have here tried to answer these point-by-point.

-Comment: The introduction does not have enough depth. Significantly more work has been done on bias estimation through data assimilation in hydrology, and hardly any of this work has been discussed. At least a good effort is needed to improve this.

Changes: We have added more references to parameter estimation in data assimilation as well as bias estimation and have hereby placed our work in a broader perspective.

-Comment: A number of issues regarding the data assimilation algorithm are very unclear. On page 8137, the authors state that a linear operator H is used when assimilating data. But the authors assimilate discharge, and the relationship between discharge and ground water levels and soil moisture is nonlinear. We need more detail on how the data assimilation system is set up. Clearly define which variables are in the state vector, and which in the observation vector.

Reply: A linear operator is used as stream discharge is observed directly and so is groundwater head. The state vector contains both of these variables plus stream water level, all of which are model states. As such, there is no need for a nonlinear operator. However, we agree that the state vector is not clearly defined.

Changes: In section 2.4.1 (State variables), the following is inserted: "In this study, the state vector contains groundwater head, stream discharge and stream water level, all of which are updated at each updating time step."

-Comment: Also on page 8137, what is the "observation covariance"? Is this the observation error covariance?

Reply: Yes.

Changes: Changed.

-Comment: On page 8139, it is explained how the localization weight is calculated. But it is still not clear to me how exactly this is used. Please provide some more explanation.

Reply: We have expanded on the description, and refer the reader to Rasmussen et al. (2015).

Changes: Inserted into section 2.3.2 (Localization): "As each state vector member is analyzed in the ETKF, the ensemble of model observations (i.e. the ensemble of model states at the observation locations) is generated, and the sample correlation coefficient between each of the model observations and the state member is determined. The localization weights of the observations to the state member being analyzed are then calculated from the correlation coefficients as follows."

-Comment: Also on page 8139, make it more clear how H is extended. It is stated that H is extended accordingly, but that is not enough detail. Please also see my earlier comment on the linearity of H.

Reply: We agree that the description is not adequate.

Changes: The sentence is changed to "The mapping matrix H is extended according to equation 10", with equation 10 showing the relationship between the extended state vector and the vector of model observations.

-Comment: I have a serious problem with using covariance inflation. A number of papers have shown that when the ensemble is adequately generated, this is not necessary. More-over, this inflation will make the algorithm inconsistent with its theoretical derivation, and therefore will make it work suboptimal. This needs to be at least mentioned and discussed.

Reply: We agree that the use of covariance inflation is unfortunate. However, the issue has been widely researched and is commonly used in a multitude of data assimilation applications. As the reviewer remarked, covariance inflation is unnecessary if the ensemble is adequately generated, but this is not likely to be the case in this study, as the uncertainty of different aspects of the physical system is unknown.

Changes: The issue with using covariance inflation as described by the reviewer has been noted in the paper: "Using covariance inflation is, like using localization, inconsistent with the derivation of the filter and only necessary due to inadequate or incorrect noise description and ensemble generation. However, due to the complex nature of the model, generating an ensemble that perfectly represents the uncertainty of the model is difficult and particularly in the test using real data outside the scope of this paper." References to applications of covariance inflation have been added to the first

paragraph of the section.

-Comment: I also have a question with using damping (page 8140). This is (the way I understand it) not consistent with covariance inflation. First, this inflation is applied to make sure the updates are sufficiently large, but then the damping is applied to reduce the updates. This needs a much stronger justification. Again, this is inconsistent with the theoretical derivation of the filter, and will thus make the results suboptimal. And I really think that both these tricks (inflation and damping) could be avoided through a better ensemble generation.

Reply: Damping, like inflation and localization, does indeed make the filter suboptimal. However, with the complexity of the physical system, the model, and the state vector structure, we found that "tricks" such as these are necessary, and that mathematical optimality is not feasible with the current knowledgebase. This also seems to be the general opinion in the scientific community, as witnessed by the multitude of data application research in which inflation, localization and damping is used without much discussion. Damping does reduce the updates, but it does not cancel out the inflation; not partly nor completely. After the update of states and parameters, damping actually helps to maintain the spread of the ensemble, as the update is likely to reduce the spread of the ensemble to a near collapse.

Changes: None.

-Comment: Below equation 15, please again provide more details on the augmentation of H.

Changes: The equation showing the relationship between the unbiased model observation and the biased model state has been included.

-Comment: Equation 21: The updated bias is calculated as the old one minus the gain multiplied by the innovation. I have a question about this minus. In all papers on observation bias estimation there is a plus here. Assume that there is a large bias between observations and results. From equation 21 this bias will reduce. Plugging this reduced bias into equation 22 the unbiased states will increase while they shouldn't. Perhaps it is a typing error but please double check this. If it is correct, I would suggest to explain why the minus is there, as opposed to the other papers on observation bias estimation.

Reply: Correct; the minus is a simple typing error.

Changes: Corrected.

-Comment: Section 2.3.7.: why not update the states each time a discharge observation is available? This would or at least should lead to better results.

Reply: Updating the states every time observations are available is very time consuming and more importantly was found to induce numerical instability in the model after the update. Updating causes certain spin-up effects, in which the groundwater part of the model attempts to return to stable state, and updating the states before the equilibrium has occurred led to increasingly erroneous updates and eventual numerical instability. Furthermore, the slow dynamics of groundwater means that little or no change in groundwater head occurs in one day, and updating would be unnecessary. Any "Stand-alone" updating of stream discharge (without updating the groundwater head) would quickly be cancelled out by the groundwater-stream interaction .

-Comment: Section 2.4.1.: This is a mistake that is made in a large number of papers in hydrology on discharge assimilation. Discharge is NOT a state variable, it is a diagnostic variable. State variables have to be seen as initial conditions, to which you apply the model equations, and then you get the results that you update with the Kalman filter. Discharge is simply NOT a state variable, it is a model output. If you enter the discharge in the state vector, and you check the requirements of observability and controllability, they would not be fulfilled. If one wants to assimilate discharge into a hydrologic model, the discharge has to be entered in the observation vector, and the soil moisture and water table levels in the state vector. The observation system is in

this case NONLINEAR. There are a number of papers on this, that the authors really should read. Please note that this is the same principle as for example assimilating radar backscatter values or surface brightness temperatures into a hydrologic model.

Reply: It is correct that for typical lumped, conceptual rainfall-runoff models discharge is not a state variable. In this case the state typically consists of the water content in different conceptual reservoirs. However, since the model is predicting the discharge (i.e. the model includes the inverse observation operator), one can include discharge in the state vector and thereby obtain a linear observation operator (see e.g. Clark et al., 2008). With the MIKE SHE model the state description is different. The MIKE SHE model includes the MIKE 11 river model, which uses an alternating calculation scheme, where calculations of discharge and water levels are performed in every other calculation point, and both variables are required to be updated and used as initial conditions. Both stream discharge and stream water level are therefore included in the state vector and updated simultaneously with the groundwater head. The observation operator is in this case linear, as both discharge and groundwater head are observed directly.

-Comment: The last sentence before section 3.1.2. is a little bizarre: "Test have shown that the length of the assimilation window is of little importance and therefore no other assimilation window was tested." Doesn't this sound a bit contradictional?

Reply: Agree.

Changes: Changed to "Precursive tests have shown that the length of the assimilation window is of little importance and therefore no other assimilation window lengths were evaluated in this study ."

-Comment: Section 3.1.2.: I do not agree with the statement that updating every observation is too often, I actually think the opposite is true. This may be the result of issues in the setup of the filter, as I explained in my earlier comments.

Reply: See earlier reply.

-Comment: Last sentence before section 3.3.: If you plug an ensemble of forcings and parameters into a nonlinear model, and even if these ensembles are unbiased, it is very likely that the resulting ensemble of model results will be biased, because of the nonlinearity. Please add this explanation.

Changes: Added: “Note that due to the nonlinearity of the model, the noise, while unbiased, is likely to cause some bias in the ensemble of model results.”

-Comment: Just a detail: section 3.4.: why are data this old being used?

Changes: Added to section 2.2.1 (The Karup catchment): The catchment was the subject of an extensive monitoring campaign between 1970 and 1990, and the large amount of observations available makes the catchment an excellent subject for the study of hydrological data assimilation.

-Comment: Section 3.4.2.: are the RMSEs biased or unbiased?

Reply: The RMSEs are biased, but are still (with reservations) an expression of the ability of the model to recreate the dynamics of the process as observed in the observations.

Changes: None.

-Comment: Page 8155: It is true that both methods were tested in Drecourt et al, but they looked at model biases, not observation biases. This should be clarified.

Changes: Clarification inserted: “[is similar to the one derived and presented in Drecourt et al (2006)] but modified to estimate observation bias rather than model bias”

-Comment: End of page 8156 and top of page 8157: you could actually calibrate this gamma parameter. Why not try this?

Reply: Calibrating the gamma-parameter is a good idea, but we feel that it falls outside the scope of the current study. It is however something that we will consider in follow-up studies. Changes: None.

Interactive comment on Hydrol. Earth Syst. Sci. Discuss., 12, 8131, 2015.