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Discussions

Interactive comment on "Improving estimates of water resources in a semi-arid region by assimilating GRACE data into the PCR-GLOBWB hydrological model" *by* N. Tangdamrongsub et al.

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We firstly would like to acknowledge the insightful comments and suggestions provided by M. Schumacher. Followings are the responses (R) based on the comments:

1) Treating observations as random variable l. 368 and matrix D in Eq. (7): Burgers et al. (1998) showed that it is necessary to consider the observations as random variable, i.e. that not only an ensemble of predicted model states but also an ensemble of observations has to be considered when calculating the update of each model ensemble member. Perturbations for the observations can be drawn from the error covariance matrix R. Otherwise, the error statistics of the updated model ensemble are underestimated (i.e. not correctly treated). In a correct implementation, matrix D does not

contain N identical columns as described in l. 368. This should be ïňĄxed or at least discussed by the authors.

R1: We implemented the EnKF as outlined by Evensen (2003). In our formulation, D contains the perturbed observations, i.e. each column is a replicate of the observation but perturbed with ∼N(0,R). This was not articulated well in the previous version of the manuscript. The text will be corrected to make this clearer as follows: "the GRACE observation vector is stored in the matrix D_{mxN}, in which each column is a replicate of the observation but perturbed with random noise ∼N(0,R). The analysis equation can be expressed as (Evensen, 2003): "

In addition, it is not possible to draw random errors from the full error covariance matrix of GRACE TWS changes on a 0.5x0.5 degree grid, since the matrix has a rank deïňĄciency. This is a critical issue and should be addressed by the authors as well.

R2: In our study, the error variance-covariance matrix associated with the post-processed GRACE data was used. We did not use the original error matrix since it did not represent the filtered GRACE signal used in our study. In our covariance computation (described in Sect. 5.2.2), the localization function with correlation length similar to the Gaussian smoothing used was applied. Although the main objective of the covariance localization is to reduce the spurious correlation at long distance caused by the limited realization number, the localization also affects the correlation at short distance, and a strong correlation at a short distance becomes slightly weaker. As a result, the error variance-covariance matrix derived based on our method has a full rank. Applying localization also improved the condition number of the covariance matrix, e.g., from ∼10ˆ{14} to ∼10ˆ{2} found in our study. Similar to Eicker et al. (2014), the matrix rank and condition number were determined using Matlab functions rank and cond, respectively. We thank reviewer for the advice. The clarification regarding rank deficiency will be included in the revised manuscript.

l. 507-508: The standard deviations of the EnKF results are however underestimated, since the observation vector was not treated as a random variable in Eq. (7). Therefore, the error statistics of the updated model states are not correct. This should be ïňĄxed or at least discussed.

R3: Please see R1

l. 588-589: This might change after correctly estimating the updated model ensemble spread by generating perturbations for the observations (revising Eq. (7)).

R4: Please see R1

2) Characteristics of error covariance matrices Eq. (8): Since both error covariance matrices (from the model and the observations) have a rank-defect due to (1) the fact that usually the number of model states is much larger than the number of model ensemble members and (2) GRACE cannot actually resolve TWS changes on a 0.5x0.5 degree grid, the inverse in Eq. (8) does not exist. This should be pointed out and a reference to sections 5.2.1 and 5.2.2 might be provided that describe how the authors deal with this issue.

R5: Please see R2

l. 251: GRACE observations are highly correlated on such a ïňĄne spatial resolution (similar to the above comment). Did the authors investigate this? Was this the reason to use a maximum correlation length for the observation error covariance matrix?

R6: Reviewer is correct. In our covariance computation (described in Sect. 5.2.2), the localization function with correlation length similar to the Gaussian smoothing used was applied. The localization helps to improve the matrix stability and we investigated this by checking the rank and condition number of the matrix as explained in R2.

l. 414-415: If I understand it correctly, the error correlation length is set to 250 km and TWS changes outside of this radius are assumed to not be correlated to the center grid cell. Is this reasonable? It would be helpful to investigate the correlations of points with longer distances to verify this choice. Does the "local" error covariance matrix have a

full rank?

R7: As the observation error variance-covariance matrix is derived based on the application of 250 km filter radius, the correlation error at distance beyond 250 km (correlation length) does not have a crucial impact on the result. In the submitted manuscript, we demonstrate the error characteristic in Fig. 8b. From the figure, the correlation reduces significantly beyond the correlation length. Additionally, the error variance-covariance matrix derived based on our method has a full rank.

Fig. 7: In the main text (l. 414-415), it is explained that a correlation length of 250 km is used (approx. four to ïňĄve 0.5x0.5 degree (âĹij50kmx50km at the equator) grid cells in each direction from the center grid cell). In Fig. 7, it is shown that only the neighboring grid cells are considered. Please clarify.

R8: Reviewer is correct. We realized that the figure caption was not explained clearly. To clarify this, we add an additional description in the figure caption as follows: “The graphic demonstrates the case of 1 pixel (0.5 degree) correlation distance. The boundary stretches farther for larger correlation distance.”

l. 419: Since the neighboring 0.5x0.5 degree grid cells are highly correlated, it is not reasonable - based on the GRACE error characteristics - to apply the EnKF without spatial error correlations on such a ïňĄne scale. A statement would be helpful to the reader.

R9: We thank reviewer for the recommendation, the statement will be added to the conclusion section of the revised manuscript as follows: “This is likely due to the fact that the neighboring 0.5ox0.5o grid cells are highly correlated, and it is reasonable to apply the EnKF with spatial error correlations on such a ïňĄne scale.”

l. 726-727: But: The authors do not use the full error covariance matrix as directly calculated from the observations. Instead a maximum correlation length of 250 km is assumed, and thus a part of the information within the full error covariance matrix is neglected. Therefore, the statement might be misleading.

R10: We thank for reviewer comment. To clarify this, we will modify the statement in the revised manuscript as follows: "…this is a reasonable price to pay as deriving the error variance-covariance matrix from the full (and only full) error covariance matrix reflects a better representation of the real GRACE uncertainty."

Major comments on citation of previous works: 3) Zaitchik et al. (2008) l. 90-91: That seems to be incorrect. Zaitchik et al. (2008) used an ensemble Kalman smoother (EnKS) approach to partition the monthly update increment (based on comparing monthly means of modeled and observed TWS changes) equally to each day of the month. GRACE TWS changes are only assimilated once per month and not every 10 days.

R11: We thank for reviewer comment. The statement will be corrected in the revised manuscript as follows: "…using a monthly observation value and distributing the update as daily increments (Zaitchik et al., 2008; Forman et al., 2012)."

4) Forman et al. (2012) l. 95: This work adapts the method as proposed in Zaitchik et al. (2008) to a snow-dominated basin.

R12: Please see R11.

l. 98: Please also consider the disadvantage of computational costs: The method has some computational drawback since the model has to be evaluated twice over the same month.

R13: We thank for reviewer suggestion. The additional sentence will be added in the revised manuscript as follows: "Another disadvantage is the additional computational cost of running the model twice for the same month."

5) Forman et al. (2013) l. 106: In Forman et al. (2013), the authors did not use correlated errors for the data assimilation. They investigated for which spatial resolution errors of GRACE TWS changes might be considered as uncorrelated. According to

these investigations, they assumed white noise for (sub-)basin averaged TWS changes from GRACE.

R14: We agree with reviewer. Forman et al. (2013) will be removed in this context to avoid the confusion.

6) Girotto et al. (2016) l. 89-95: In this work, the authors performed an analysis of introducing the update increments completely at the beginning of a month, the end of a month or equally distributed over all days of a month. This is worth to be mentioned along with the other citations.

R15: We thank for reviewer suggestion. Girotto et al. (2016) will be cited in the revised manuscript.

7) Schumacher et al. (2016) l. 39-40 and l. 106-108: A ïňĄrst analysis of assessing the effect of considering or neglecting spatial error correlations of GRACE TWS changes was performed in Schumacher et al. (2016) in form of a synthetic experiment, for which one of the authors of this HESSD manuscript was the editor and should therefore be very familiar with the work. It seems that the paper is methodologically the closest related to the analysis presented here and, therefore, should be cited and discussed. Findings should be compared to the ïňĄndings in the published paper.

R16: At the time this study was conducted, Schumacher et al. (2016) was not published, therefore we conducted the analysis independently based on our method (proposed in this HESSD paper). However, we thank reviewer for the recommendation, and Schumacher et al. (2016) will be cited in the revised manuscript.

l. 577: This was also seen and discussed in Schumacher et al. (2016). The authors should compare their results with the ïňĄndings in this paper, since the objective of both papers is to understand the effect of considering spatial error correlations of GRACE TWS changes on hydrological data assimilation results.

R17: We thank for reviewer suggestion. The additional statement will be included in the revised manuscript as follows: “The finding is somewhat in line with results from the numerical study by Schumacher et al. (2016) that considering correlated observation errors does not necessarily lead to a better agreement with GRACE observation.”

l. 715-718: The authors should add something like "in agreement with the recommendation in Schumacher et al. (2016)."

R18: We thank for reviewer suggestion. The given statement will be considered in the revised manuscript.

l. 719-724: The ïňĄndings in the HESSD manuscript allow for a clearer conclusion on improvements when error correlations of GRACE TWS changes are taken into account. What might be the reason for this? Differences in the study set up? Localization of model / observation error covariance matrices?

R19: The improvement is mainly due to a better representation of GRACE information in the EnKF. Ignoring error correlations in the DA led to an over-fit of the results to the observations, which led to less accurate state estimates. These statements will be presented in the revised manuscript.

l. 729: A reference to Schumacher et al. (2016) would strengthen this statement, since the HESSD manuscript is not the only study that concludes a beneïňĄt / more realistic GRACE data assimilation approach if implementing GRACE error correlations.

R20: We thank for reviewer for the suggestion, Schumacher et al. (2016) will be cited in the relevant context.

l. 752-753: Schumacher et al. (2016) should be added to the list of references.

R21: Schumacher et al. (2016) will be added to the list of references.

l. 755: Alternative methods have been investigated in Schumacher et al. (2016), namely a square root analysis scheme (SQRA) and the singular evolutive interpolated Kalman ïňĄlter (SEIK). Especially the application of the SEIK ïňĄlter showed promising

results. A citation would support the authors expectation that alternative methods, e.g. the particle ïňĄlter, would improve the data assimilation performance.

R22: We thank the review for the suggestion. We will consider this in the revision.

Minor comments: l. 583: "truth", i.e. to the independent measurements of individual water compartments. These measurements are also subject to uncertainties and not "true" values.

R23: To avoid the confusion, the statement will be changed to: “Validating against the in situ groundwater and streamflow data will quantitatively reveal the performance of each approach”

l. 756: "true" -> better "full" (true is difïňĄcult since often unknown / poorly known)

R24: “true” will be changed to “realistic”.

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