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Hydrology and Earth System Sciences
Discussions

Interactive comment on "Data assimilation of GRACE terrestrial water storage estimates into a regional hydrological model of the Rhine River basin" *by* N. Tangdamrongsub et al.

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We firstly would like to acknowledge the insightful comments and suggestions provided by Dr. Sylvain Ferrant. Followings are the responses based on the comments:

Comment1: There is a gap between the results analysis and the conclusions: Page 11857, line 3: "Though it is encouraging that GRACE assimilation improved the estimated streamflow, these results demonstrate that it clearly cannot replace high quality forcing data or good model calibration" P11859, line 3: in conclusion "GRACE assimilation is clearly beneficial ...From my point of view, there is no clear evidence of

improvement between ENOL and ENKF. The small to really small differences between both cases shown in Figure 11 should be used to demonstrate that there is not much improvement in this specific study

Response: We agree with the reviewer's comment that the differences between EnOL and EnKF in estimated streamflow are small. This is clear from Figures 9, 10 and 11, and is discussed at length in Section 5.3. The statement in the conclusions that GRACE assimilation is clearly beneficial refers to the results in general (e.g. the TWS) and not just the streamflow. To address the reviewer's concern, and to emphasize that GRACE assimilation results in an improvement in streamflow, we will revise Page 11859 lines 3-6 to read:

In conclusion, GRACE assimilation is beneficial, and the largest improvements are generally observed in the NCG (i.e. "data-sparse") cases. In addition to providing a modest improvement to the estimated streamflow, it may result in a noticeable improvement in TWS estimates, yielding an extra insight into the behaviour of the hydrological model, its forcing data and parameters.

Comment2: The abstract does not reflect the results presented in this study. The analysis showed a noticeable improvement in groundwater estimates when GRACE data were assimilated, with an overall improvement of up to 71% in correlation coefficient (from 0.31 to 0.53) and 35% in RMS error (from 8.4 to 5.4 cm) compared to the reference (ensemble open-loop) case.

Response: These statistics are presented in Table 4 and 5, and discussed in Page 11855, lines 15-17 "In general though, assimilation of GRACE observations leads into an increase in correlation coefficient (up to 71 %, at station 11 in the CG case) and a decrease in RMSE (up to 35 %, at station 1 in the NCG case)." The statistics in the abstract therefore reflect those discussed in Section 5.2. To clarify this, we insert the improvement (%) for each case study in Table 4 and 5 and include the discussion in Page 11855 line 17 to read:

"a decrease in RMSE (up to 35 %, at station 1 in the NCG case). In average, correlation and RMSE improvements in groundwater estimates for all cases evaluated were 13 % and 14 %, respectively."

and Page 11839, line 14 is modified as:

The analysis showed a noticeable improvement in groundwater estimates when GRACE data were assimilated, with a best-case improvement of 71% in correlation coefficient (from 0.31 to 0.53) and 35% in RMS error (from 8.4 to 5.4 cm) compared to the reference (ensemble open-loop) case.The average correlation and RMSE improvements in groundwater estimates for all cases evaluated were13 % and 14%, respectively.

Comment3: Groundwater results are presented in abstract but Figure 7 does not give a clear idea of the stream flow improvements with GRACE assimilation. On the contrary, ENKF simulation of the TWS is really close to the GRACE derived TWS. This indicates that the assimilation process reach good results but the model is not able to take advantage of this to simulate better the water cycle. "Only a slight overall improvement was observed in streamflow estimates when GRACE data were assimilated. Even not any improvement. I doubt this could be explained only by the forcing data errors.

Response: We agree that improvement in TWS does not translate directly to improved streamflow. This is discussed in Page 11855 line 26 and Page 11856 lines 1-2 "Because GRACE observations describe monthly variations over a larger area, they can do little to capture these individual streamflow events."

Peaks in the streamflow are largely determined by the fast response to precipitation from the upper stores. The global versus local forcing data cases are used to argue that errors in precipitation translate to streamflow. This is discussed in Page 11855, lines 25-28 "Use of the global data frequently underestimates the streamflow. This is clear on 5 June 2004, 24 August 2005, 6 October 2006, and 10 August 2007 in Fig. 9b and d. Comparing Fig. 9a to b, it is clear that the larger peaks in streamflow are poorly

estimated when the global data are used."

Comment4: One major water flux that is not taken into account is the water withdrawal for human and agriculture consumption. A recent study has used GRACEderived TWS to validate the calibration of an agro-hydrological model by taking irrigated water withdrawal into account (Ferrant et al., 2014, in Nature ScientificReport;http://www.nature.com/srep/2014/140115/srep03697/full/srep03697.html). This part of the water consumption has a huge impact on the TWS anomaly derived from GRACE, and is not taken into account in this study. This should be discussed as the Rhine river basin is highly inhabited and include high industrial and agricultural activities

Response: Based on Wada et al. (2014) (and personal communication), only 10% of the total water withdrawal over the Rhine is from groundwater. Irrigation accounts less than 1km3/year, and industry is the largest user. The net removal is small as the water is re-introduced to the system after being used for industry. This is markedly different to the extraction of groundwater for irrigated agriculture observed in India. Therefore, we neglected the water withdrawal for human and agriculture consumption from the state vector. We will include this discussion in Page 11843 line 26:

"storage (LZ). Only 10% of the total water withdrawal over the Rhine is from groundwater. Irrigation accounts less than 1km3/year, and industry is the largest user (Wada et al. (2014)). Furthermore, the net removal is small as the water is re-introduced to the system after being used for industry. This is markedly different to the extraction of groundwater for irrigated agriculture observed in India (Ferrant et al. (2014)). Therefore, this impact on TWS is not considered in this study. Groundwater storage (GW) is defined as the sum of just UZ and LZ..."

Comment5: Page 11850, line 2. The calibrated model is calibrated on spatial soil moisture whereas averaged soil moisture is used for the non calibrated model. Please detail. This is not obvious for the reader. What kind of soil moisture data is used? Is it remote sensing soil moisture products? In that case, it is difficult to get an idea of the soil water storage from a surface soil moisture estimate.

Response: Soil moisture data is never used for model calibration.

The model parameters, including those of the soil moisture routine, are calibrated using streamflow data only. This is described on page 11844, lines 6-9: "The OpenStreamswflow model was calibrated for the Rhine river basin using observations from in situ streamflow gauges (MuÌĹlders et al., 1999; Eberle et al., 2002, 2005; Photiadou et al., 2011)").

To account for uncertainty in model parameters, the parameters of the soil routine are perturbed. Page 11850, line 2 describes assumptions made regarding model parameters uncertainty in the ensemble simulation.

Comment6:Section 5.2 Here the improvements of the TWS assimilation on groundwater are not obvious and are discussed in details. It seems that calibrated soil moisture does not lead to appropriate groundwater during the assimilation process. Groundwater data should be discussed regarding the accuracy or representativeness of piezometric data. Local fluctuations of the water table cannot often be considered as representative of the basin average.

Response: The calibrated parameters do not lead to appropriate groundwater during the assimilation process as they are calibrated using streamflow, not groundwater itself. This is discussed in Page 11855, line 8-11 "Recall that the model is calibrated using streamflow, not groundwater data. So, while assimilation draws the modelled TWS towards the GRACE observations, the model parameters have a significant impact on whether or not this translates to an improvement in GW estimate", and in Page 11857, lines 19-27 and Page 11858, lines 1-6 "However, it is found that the improvement in TWS estimates did not always translate to an improved agreement between the estimated and observed groundwater storage variation at certain well locations. The differences may be due to the OpenStreamswflow parameters: if the upper limit on

soil moisture storage is too high (low), then the groundwater variations could be under (over)-estimated. This is particularly relevant in the type of model where the calibration is per sub-basin. This does not allow for local differences on the order of single or a few grid cells. Furthermore, the considered model was developed to simulate runoff, and is calibrated to produce the best estimate of streamflow. The groundwater terms, UZ and LZ, primarily serve as reservoirs for quick and base runoff generation. Assimilation of GRACE observations into a groundwater model can be expected to yield better results in terms of groundwater variations. The issue of scale is also significant. GRACE observes monthly variations on the order of hundreds of kilometres. Groundwater variations can be influenced by local features at finer scales. Validation against a denser network of well data or an independent groundwater model could be used to determine if an improvement occurs at the scale of the entire basin.".

Comment7:Page 11858 line 19, "GRACE could be combined with a hydrological model in a data-sparse region to yield additional insight into the variations in terrestrial water storage." I doubt this study demonstrates this. GRACE could be used as an extra observation to validate model, especially in a data-sparse region where any additional observations are welcome. Furthermore, TWS from GRACE is highly correlated to climate variables that are not always representative of a region in the case of global meteorological forcing data. The assimilation process will lead to redirect water fluxes between soil, groundwater and river to compensate the lack or the excess of water.

Response: One of the benefits of assimilation is the insight that can be gained by analysing the update increments, i.e. what adjustments are made to the state variables based on the discrepancy between model and observations. To clarify this, we will incorporate the reviewers comment and revise line 18 to read:

Given that the most significant improvements were observed in the NCG case, this suggests that GRACE observations are most valuable in data sparse regions. In these regions any additional observations, even those at coarse spatial and/or temporal resolution, are welcome. GRACE can provide essential independent observation for validation, and serves as a constraint for TWS within the assimilation process.

Additional references:

Wada, Y., Wisser, D., and Bierkens, M. F. P.: Global modeling of withdrawal, allocation and consumptive use of surface water and groundwater resources, Earth Syst. Dynam., 5, 15-40, doi:10.5194/esd-5-15-2014, 2014.

Ferrant, S., Caballero, Y., Perrin, J., Gascoin, S., Dewandel, B., Aulong, S., Dazin, F., Ahmed, S., and MaÅŢechal J.-P.: Projected impacts of climate change on farmers' extraction of groundwater from crystalline aquifers in South India, Nature Sci. Rep., 4, 3697, doi:10.1038/srep03697, 2014.

Interactive comment on Hydrol. Earth Syst. Sci. Discuss., 11, 11837, 2014.