Interactive comment on “*Groundwater storage dynamics in the world’s large aquifer systems from GRACE: uncertainty and role of extreme precipitation*” by Mohammad Shamsudduha and Richard G. Taylor

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Reviewer’s comments are italicised, and our responses are provided in normal fonts.

General comments:

The authors present a manuscript on GRACE-based terrestrial and groundwater storage changes in 37 major aquifer systems across the globe. I must say, the authors have done a commendable job to compare huge amount of data in all of those major global aquifers.

My major comments are provided below:

1. *The surface water storage was used from GLDAS estimates of surface runoff. How do the authors comment on surface water storage variations in natural structures such as, rivers, lakes and artificial structures like dams? I believe, the influence of surface water storage in natural and artificial structures can provide erroneous disaggregation of TWS. The smaller fraction of surface water storage is clearly visible in the figures on comparing the soil moisture and groundwater storages.*

R2 #1. We thank Reviewer 2 (R2, Dr. Bhanja) for his positive comments and providing valuable suggestions to improve the manuscript. As with R1, we agree with R2 that the representation of surface water storage (ΔSWS) by NASA’s GLDAS (Global Land Data Assimilation System) models (i.e. CLM, Noah, VIC, Mosaic) is uncertain and limited. As with a recent study (Getirana et al., 2017), we note that the vast majority of studies estimating GRACE-derived ΔGWS disregard ΔSWS, assuming its contribution to ΔTWS variability is small (e.g. Long et al., 2016) in contrast to other studies (e.g. Shamsudduha et al., 2012) that show that contribution to ΔTWS from observed ΔSWS is substantial (22%). However, more precise estimates of the impacts of ΔSWS on ΔTWS globally and its spatial variability are unknown due to lack of global-scale observations of surface water storage including anthropogenic structures such as dams and reservoirs. Similar to the approaches taken in recent studies (e.g. Bhanja et al., 2016; Thomas et al., 2017), we apply surface runoff as a reasonable proxy for ΔSWS derived from GLDAS LSMs. We recognise differences exist in surface runoff estimates simulated by GLDAS LSMs as noted previously in inter-comparison studies (e.g. Scanlon et al., 2018; Scanlon et al., 2019; Zaitchik et al., 2010). We contend, however, that dismissing ΔSWS entirely in the estimation of ΔGWS from GRACE does not serve to reduce uncertainty.

2. *Lines 304-316: I am not totally agreeing with the arguments provided by the authors. They have not provided sufficient factual evidences in support of these arguments. There can be multiple reasons behind that. Surface water storage in the reservoirs can also play crucial role here, which is not considered in this study.*

R2 #2. On lines 304 to 316 in the original manuscript, we argue that abrupt rises or falls in calculated ΔGWS can result from simple arithmetic operations of numeric values, given the uncertainty that exists in estimates of water storage from GLDAS LSMs expressed as anomalies. We agree with R2 that uncertainty in the estimation of ΔSWS may be one of the causes of these abrupt rises or falls. Because ΔGWS is calculated from GRACE-derived ΔTWS by subtracting storage anomalies from other terrestrial water components such as soil moisture storage (ΔSMS), surface water storage (ΔSWS) and snow water storage (ΔSNS), ‘mathematical artefacts’ in the calculation of groundwater storage change (ΔGWS) from GRACE and GLDAS datasets can occur where over/underestimation in individual components can collectively lead to abrupt falls/rises relative to GRACE ΔTWS as per equation 1 in the original manuscript.

3. *Please include a limitation section mentioning all the limitations in this study. For soil moisture storage, one of the major limitations is that the simulated values are up to 3.4 m at max, soil moisture at deeper layers are not used. This is particularly important in arid, semi-arid regions where vadose zone thickness is much deeper. "Uncertainty is generally higher for aquifers systems located in arid to hyper-arid environments (Table 2, see supplementary Fig. S79)." This observation can be linked with the non-representation of deeper soil moisture.*

R2 #3. We agree with R2 that substantial variability and uncertainty exists in simulated soil moisture storage by GLDAS land surface models. R2 is correct in noting that the number of layers and depth of soil horizons in the four LSMs differ with a maximum depth of 3.5 m in Mosaic. We agree that the depth to the deepest part of the unsaturated zone and soils in semi-arid and arid environments could be well below the maximum depth of soil layers considered in these models. For example, the thickness of unsaturated zone in the Southern High Plains in the US can range from 0 to 134 m with a median thickness of 37 m (Scanlon et al., 2009). We will nevertheless expand discussion of uncertainty in the representation of ΔSMS by GLDAS LSMs making specific reference to their consequences for soils in semi-arid and arid environments.

4. *Sections 3.5, 4.2 and elsewhere: In general, while describing extreme precipitation, researchers normally use precipitation per day time-scale. The authors seem not to use the daily precipitation data. Please change the discussion topic to mention precipitation only.*

R2 #4. We agree with R2 that precipitation intensity is most commonly discussed in relation to daily precipitation but this is not exclusive. Statistically, extreme precipitation can also refer to annual, seasonal, and monthly precipitation. In the manuscript, we define statistically extreme precipitation (i.e. 90th percentiles) on a monthly timestep over the period of 1901 to 2016 (116 years) consistent with the monthly timestep in the employed GRACE and GLDAS time-series datasets.

5. *Section 3.5: Observing non-significant, low correlation between precipitation and groundwater may indicate human interference. Central valley (16) is a clear exception here. This shows correlation analysis is not properly reflecting the observation.*

R2 #5. We agree with the R2 that the low correlation between precipitation and groundwater storage may indicate human interference (i.e. groundwater pumping) masking natural variability that may be caused by climate (i.e. precipitation variations). In the revised manuscript, we will expand discussion of potential factors overprinting natural variabilities in ΔGWS such as groundwater abstraction.

6. *Figure 3: Show the scale of variance.*

R2 #6. The variance in GRACE-derived TWS time-series records for all 37 large aquifer systems are presented in the Supplementary Table S1.

7. *"For example, centennial-scale piezometry in the Ganges-Brahmaputra aquifer system (no. 24) reveals that recent groundwater depletion in NW India traced by GRACE (Fig. 5 and supplementary Fig. S23) follows more than a century of groundwater accumulation through leakage of surface water via a canal network constructed primarily during the 19th century (MacDonald et al., 2016)." Centennial-scale data are not present in the manuscript. Please include them in SI. This is not only from the recharge of canal irrigation, groundwater resources in this area got benefited also from a significant rate of*

annual rainfall. The present decline is clearly linked to irrigation-linked withdrawal. Please mention these.

R2 #7. We thank R2 for their comments and suggestions regarding centennial-scale changes in groundwater storage in the Ganges-Brahmaputra Basin that contrast with short-term (2002-2016) declining trends in ΔGWS revealed by GRACE. We agree that recent declining trends result from intensive groundwater-fed irrigation in the region. The centennial-scale groundwater levels (1900 to 2010) are clearly shown in Figure 3b of the *Nature Geoscience* letter by MacDonald et al. (2016) and we will reproduce this figure, as proposed, in the revised Supplementary Information.

8. *Figure 8: Continuous rise in GWS observed in several basins including Amazon, where precipitation rates even show declining trends (Figure S18). Please discuss the probable reasons.*

R2 #8. We similarly note this interesting observation made by R2. Rising trends in GRACE-derived ΔGWS time series follows a similar trend in ΔTWS over the Amazon Basin that has been reported by Scanlon et al. (2018) at 41 to 44 km^3/year (period 2002 to 2014) and Rodell et al. (2018) at 51.9 ± 9.4 Gt/year (period 2002 to 2016). The magnitude of this rising trend in ΔTWS is explained by both the size of the region and the intensity of the Amazon water cycle (Chaudhari et al., 2019). Furthermore, Rodell et al. (2018) argue that large dam construction in southern Brazil and filling of reservoirs contributed to the rising trend in GRACE ΔTWS. We note that a slightly decreasing trend in soil moisture storage (ΔSMS) might be contributing to a positive change in ΔGWS over the Amazon Basin.

9. *Line 137: surface runoff or surface water storage (SNS).*

R2 #9. Thanks to R2 for pointing out this typo. We agree that it should read SWS, not SNS and will be corrected in the revised manuscript.

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