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

Marc Bierkens (Referee #1)

bierkens@geo.uu.nl
Received and published: 2 January 2020

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

General comments

The authors use the results of three different GRACE-based TWS methods and 4 Land surface models to generate an ensemble of groundwater storage anomalies. These are subsequently analyzed by a non-parametric statistical method to separate seasonal signals from non-linear trends and residuals.

The main message of the paper is that trends in GWS anomalies (ΔGWS), if existing, are non-linear in the vast majority of main aquifer systems and that rainfall anomalies play an important role in explaining these non-linear trends.

I enjoyed reading the paper. I find that it is a well-written with an important message that deserves publication. However, I have a few comments.

Moderate comments:

1. *I find the lack of reference to estimates based on global hydrological models (GHMS) remarkable. The first spatially distributed global assessment of depletion rates where based on such models and, albeit indirect, should be used in the discussion. They are the basis for the "narratives on global groundwater depletion" that are mentioned in the discussion and the abstract (See https://iopscience.iop.org/article/10.1088/1748-9326/ab1a5f/meta for an overview of these studies). This is the more remarkable, given that the authors do use Land Surface Models (LSMs) to estimate ΔGWS from GRACE ΔTWS.*

Response to reviewer 1 (R1) #1. Firstly, we thank the reviewer (Professor Bierkens) for his positive comments regarding the manuscript and for providing very constructive suggestions to improve the manuscript. Regarding the lack of reference to global hydrological models (GHMs) in "narratives on global groundwater depletion", we agree that this is a critical omission from the original manuscript, which focused on uncertainty in the estimation of GRACE-derived ΔGWS that is typically reliant on estimates of components of terrestrial storage from LSMs (e.g. Long et al., 2016) including commonly used models from NASA's Global Land Data Assimilation System (GLDAS). The revised manuscript will engage fully and directly with evidence from GHMs in describing narratives of "global groundwater depletion" including the recommended study by Bierkens and Wada (2019) and references therein (e.g. Wada et al., 2010; de Graaf et al., 2017).

2. *Regarding the estimation of ΔGWS from GRACE ΔTWS (Equation 1): I am quite doubtful that the surface water storage from integrating LSM runoff on a monthly basis is sufficiently accurate. Even a small basin as the Rhine has a discharge peak routing time of a week, while that of the Amazon amounts to 3 months. Apart from the lack of river routing, GLDAS LSMs do not include the storage and delayed discharge from reservoirs, lakes and inundated floodplains (GHMs do a better job in that respect; see https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2018GL081836). This fact may lead to underestimation of ΔSWS and subsequently an overestimation of ΔGWS and its noisiness. Granted, comparison with piezometric data in the Limpopo and the*

Ganges-Brahmaputra is favourable, but this can be scaled easily by changing specific yield.

R1 #2. We agree with the reviewer's concerns regarding the use of GLDAS LSMs to account for surface water storage (ΔSWS) in the estimation of ΔGWS from GRACE, highlighted recently by Scanlon et al. (2019). The original manuscript first notes that most GRACE studies do not account for ΔSWS in the computation of ΔGWS with the assumption that its contribution to ΔTWS is limited. Consistent with previous studies (e.g. Bhanja et al., 2016; Thomas et al., 2017), this study applies time-series simulations of surface runoff from GLDAS LSMs as a proxy for ΔSWS in the absence of global-scale time-series monitoring of surface water storage changes in rivers, lakes, floodplains and reservoirs. Recognition of the problem of routing in the use of GLDAS LSM data for ΔSWS, identified by Reviewer 1, and its implications for the computation of ΔGWS will be made explicit in the revised manuscript. Together with this, we will expand related discussion of the performance of GHMs and LSMs related to GRACE ΔTWS as reviewed recently by Scanlon et al. (2018).

3. *The discussion related to the "narrative of global groundwater depletion" needs elaboration:*

- *Not only piezometric studies show that groundwater depletion can be very local; this is also true for <u>model-based estimates of groundwater depletion</u>. See for instance results from Wada et al. 2012 (Figure S5) https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2012GL051230 and De Graaf et al 2017 (Figure 11): https://www.sciencedirect.com/science/article/pii/S030917081630656X#fig0011*

  This means that at the aquifer scale anomalous rainfall may cause an overall increase in groundwater storage, while groundwater depletion may locally still persist. Thus, the "<u>narrative of global groundwater depletion</u>" pertains to "<u>groundwater depletion as a global phenomenon</u>".

R1 #3a. We thank Reviewer 1 for their argument that it is not only piezometry but also global-scale modelling that shows that groundwater depletion can be localised so that depletion can occur alongside accumulation in the same (large) aquifer system. The revised manuscript will incorporate evidence from GHMs explicitly in its discussion of the nature of groundwater depletion assessed globally.

- *The current consensus seems to be that global ΔTWS has been increasing between 1950-1995 by dam building, decreasing from 1995-2005 by groundwater depletion and has been increasing again since then by increased land water storage due to a climate-change induced increase in precipitation: see the review by Wada et al: https://link.springer.com/chapter/10.1007%2F978-3-319-56490-6_7. Yet, at the same time groundwater depletion at the current hotspots has persisted. How do your findings relate to these insights?*

R1 #3b. We thank R1 for raising an interesting point on the dynamic nature of global ΔTWS due to spatiotemporal variability in anthropogenic influences including climate change on land-water budgets (e.g. irrigation abstraction, construction of dams and reservoirs, trends in precipitation, and land-use change). Our findings on ΔTWS and ΔGWS apply specifically to the period (2002-2016) observed by GRACE. We note from the recommended review by Wada et al. (2017) that recent groundwater-storage depletion has made a net positive contribution to global sea-level rise. Further, as highlighted by R1, Reager et al. (2016) apply GRACE data from 2002 to 2014 to show a trend towards enhanced precipitation on the land under climate change. Given this trend and the observed intensification of precipitation on land under climate change (Allan et al., 2010; Westra et al., 2013; Myhre et al., 2019; Zhang et al., 2013), we may expect that groundwater recharge to many large-scale aquifer systems will increase under climate change in light of the statistical relationships found in this study between ΔGWS and extreme precipitation. We propose to update the discussion on this specific point in the revised manuscript.

4. *Line 146: I don't understand the 20 realisations. I would think: 3 GRACE products, 4 LSM estimates of ΔSMS and ΔSWS and one LSM with ΔSNS amount to 3x4x1 = 12 realisations? Or did you combine e.g. ΔSWS from one LSM with the ΔSMS from another? If you did this, this seems to be inconsistent as it would not preserve mass and overestimate the errors due to the LSM corrections.*

R1 #4. We thank Reviewer 1 for this query and will revise our explanation from where the 20 realisations derive. On lines 142-145 of the original manuscript, we write, "we apply 3 gridded GRACE products (CSR, JPL-Mascons, GRGS) and an ensemble mean of ΔTWS and individual storage component of ΔSMS and ΔSWS from 4 Land Surface Models (LSMs: CLM, Noah, VIC, Mosaic), and a single ΔSNS from Noah model (GLDAS version 2.1)." The breakdown of 20 realisations is given below with 12 realisations being the primary products, whereas the remaining 8 realisations derive from a combination of GRACE ΔTWS and different LSMs to demonstrate the range of uncertainty in the estimation of ΔGWS using GRACE-derived ΔTWS and GLDAS LSMs.

- 3 GRACE TWS x 4 LSMs (SWS, SMS) x 1 LSM (SNS) = 12 realisations
- CSR GRACE TWS x mean LSMs (SWS, SMS) x 1 LSM (SNS) = 1 realisation
- JPL GRACE TWS x mean LSMs (SWS, SMS) x 1 LSM (SNS) = 1 realisation
- GRGS GRACE TWS x mean LSMs (SWS, SMS) x 1 LSM (SNS) = 1 realisation
- Mean GRACE TWS x 4 LSMs (SWS, SMS) x 1 LSM (SNS) = 4 realisation
- Mean GRACE TWS x mean LSMs (SWS, SMS) x 1 LSM (SNS) = 1 realisation

Small remarks:

- *The first sentence of the introduction: Doell et al (2012) is only one model-based study providing these numbers. I would advise using less significant numbers based on an overview of estimates by Hanasaki et al (2018): https://www.hydrol-earthsyst-sci.net/22/789/2018/*

R1 #5. We appreciate Reviewer 1's suggestion and will incorporate this recommended study by Hanasaki et al. (2018) in the revised manuscript.

- *Lines 212-215: Trying out different smoothing parameters. I feel that the results of this exercise should be shown, at least in the Supplementary Information (SI). Perhaps report the statistics of the residuals for a number of settings of the smoothing parameters to justify the values chosen.*

R1 #6. The original analysis evaluated the effect of seasonal and trend smoothing windows in applying the STL (Seasonal-Trend Decomposition using Loess) decomposition method. In the revised manuscript, we will expand discussion in the Methodology of the sensitivity analysis that applied smoothing windows at various lengths; we will also include a new figure to the supplementary information in addition to the current STL figure in Fig. S37.

- *On a related note: Looking at some of the plots in the SI I see that residuals are often far from white. In the time series literature this would be seen as a serious model insufficiency. Some discussion on how this would affect results is warranted as well.*

R1 #7. We thank Reviewer 1 for spotting the fact that some lines (e.g. uncertainty envelop around the mean of time-series records) are cut-off by figure margins. In the revised supplementary information, we will reproduce all the time-series plots (from Figs S1 to S36) with a full range of values.

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