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Hydrology and Earth System Sciences
Discussions

Interactive comment on "Recent changes in terrestrial water storage in the Upper Nile Basin: an evaluation of commonly used gridded GRACE products" *by* Mohammad Shamsudduha et al.

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Response to Anonymous Referee 1 (AR1)

Numbered responses are given below each comment:

[AR1] This study aims to estimate the TWS change and its individual components in the Upper Nile Basin using GRACE, LSMs and in situ observations. Actually, similar studies have been done in this region by Awange et al. [2013], Awange et al. [2014], and Nanteza et al. [2016]. So, the main point is whether this manuscript can bring enough new knowledge based on new/updated data or methods. Different from previous studies, three different GRACE products (gridded level-3 GRCTellus, JPL mascon

and constrained GRGS products) were compared and validated with in situ TWS observations in this study. However, the detailed scaling process used in this study is still unclear for me (see detailed comments below). I also suspect that whether limited 6 monitoring well observations can represent actual large-scale GWS variations in the study region.

Responses to general comments [G1 to G3]:

[G1] We thank the Anonymous Referee #1 (AR1) for their comments on the manuscript. We are pleased that the reviewer has recognised the central difference between this study and previous studies in the region that include: (1) application of commonly used gridded GRACE products rather than a single GRACE product; and (2) an evaluation of these gridded products to represent the phase and amplitude of changes in terrestrial water storage in the Upper Nile Basin including a large and well-constrained change in surface water storage from 2003 to 2006.

[AR1] Especially, all three well observations in the LVB are located near the Lake Victoria. The representativeness of these wells is questionable. In addition, there are some obvious typos in the manuscript.

[G2] We agree with AR1 that the representivity of a limited number (6) of monitoring wells in the region is questionable. These daily monitoring records have been selected from a larger database of groundwater-level monitoring records in Uganda on the basis of the completeness and quality of their records from 2003 to 2012. Unfortunately, several time-series records from Uganda were excluded due to unexplained errors and substantial gaps; the location of the several monitoring wells also resided outside of the studied basins. Long time-series records of groundwater levels over the period from 2003 to 2012 from western Kenya, northern Tanzania, Rwanda and Burundi have not been identified despite intensive investigations carried out by The Chronicles Consortium, https://www.un-igrac.org/special-project/chronicles-consortium.

In the supplementary information of the revised manuscript, we will include plots of all employed piezometric observations that inform in situ ΔGWS (Fig. R1). In the Lake Kyoga Basin, piezometric records from 3 sites show consistency in the seasonality and amplitude of groundwater storage changes plotted as monthly groundwater-level anomalies relative to the mean for the period from 2003 to 2012; further details of these oscillations are described by Owor et al. (2009). In the Lake Victoria Basin, groundwater-level records from 2 sites (Entebbe, Nkokonjeru) are similar in their phase and amplitude, and are influenced by changes in the level of Lake Victoria as demonstrated by Owor et al. (2011). The groundwater-level record from Rakai represents local semi-arid conditions that exist within catchment areas (e.g. River Ruizi) draining to the western shore of Lake Victoria in Uganda. Although there are differences in the phase of groundwater-level fluctuations between the semi-arid site at Rakai and both Entebbe and Nkokonjeru (as well as the 3 sites in the Lake Kyoga Basin), amplitudes are similar.

[AR1] GWS estimation from GRACE: Based on my understanding on the manuscript, ΔGWS= the rescaled GRACE ΔTWS (sf=1.7 for GRCTellus, sf=? for JPL mascon) minus scale-down ΔSWS (sf=0.11 for GRCTellus and sf=0.39 for JPL mascon) minus simulated ΔSMS. Why so-called a scale down of ΔSWS was used rather than the original ΔSWS (EWH, based on equation 2, Line 317)? In fact, the ΔGWS estimation from GRACE (GRCTellus, JPL mascon and GRGS) was not given in detail. I would suggest the authors explain it in a paragraph in 3.2.2.

[G3] We thank the AR1 for this critical comment on the estimation of ΔGWS derived from GRACE datasets.

First, GRACE ΔTWS time-series records were generated for LVB and LKB following a conventional approach by: (i) selecting $1^\circ \times 1^\circ$ grids within the basin boundary, (ii) applying gridded scaling factors to the corresponding ΔTWS grids; and (iii) taking the average of time-series records of scaled ΔTWS grids over the basin. For GRCTellus products (CSR, JPL, GFZ), we applied scaling coefficients derived from CLM4.0 land surface model provided by Landerer and Swenson (2012). Similarly, gridded scaling

factors were applied to JPL-Mascons product provided by Wiese et al. (2015). No scaling factors were applied to GRGS GRACE. On the specific question of 'rescaled GRACE ΔTWS', we did not apply a single multiplicative scaling factor of 1.7 to GRCTellus ΔTWS (CSR, JPL, GFZ products) to generate a basin-wide time-series data.

Two separate, unconventional scaling experiments were conducted in an attempt to reconcile GRCTellus TWS with in-situ (i.e. now 'bottom-up') TWS only for the Lake Victoria Basin (LVB). Under the first experiment, we applied a single multiplicative scaling factor of 1.7, informed by the lowest RMSE, in order to 'scale up" the GRCTellus ensemble mean of ΔTWS data. In the second experiment, we 'scaled down' SWS in the LVB, recognising that ΔSWS is the largest contributor to ΔTWS in the LVB. As stated on lines 399 to 404 in the current manuscript, "GRACE ΔTWS analyses commonly apply the same scaling factor as ΔTWS to all other individual components (Landerer and Swenson, 2012). We apply spatially-averaged scaling factors representative of (1) Lake Victoria and its surrounding grid cells (experiment 1: s=0.71; range 0.02−1.5), and (2) the open water surface of Lake Victoria without surrounding grid cells (experiment 2: s=0.11; range 0.02−0.30)."

To estimate ΔGWS from GRACE ΔTWS (following the conventional scaling approach outlined above), we applied the 'scaled down' SWS in the LVB because the amplitude of monthly anomalies of ΔSWS+ΔSMS substantially exceed ΔTWS, particularly for the GRCTellus GRACE ΔTWS signal (Fig. R2 top). This discrepancy is pronounced over the period from 2003 to 2006, and produces steep, rising trends in the estimated GRACE-derived ΔGWS (i.e. GRACE ΔTWS - (ΔSWS+ΔSMS)) when borehole-derived (in situ) estimates of ΔGWS are declining and of much lower amplitude (Fig. R2 bottom).

We agree with AR1 that current description of application of scaling factors, both conventionally and unconventionally is insufficiently clear and will be substantially improved in the revised manuscript.

Responses to specific comments [S1 to S20]:

(1) Line 240, CRS should be CSR.

[S1] Agreed, to be corrected in revised manuscript.

(2) Line248-249: GRCTellus datasets are provided as 1X1 grids, but ∼111 km is not the so-called spatial resolution of GRACE. At least, in some place of the manuscript, the authors should emphasize that the real resolution of GRACE is about 300 km, rather than that provided by these level-3 products.

[S2] We thank AR1 for their point of clarity on the resolution of GRACE products. In the revised manuscript, we will state clearly the spatial resolution of GRACE footprint (∼300 km) in section 3.1.2.

(3) Line 254, the citation Geruo et al., 2013 should be A et al. 2013. This is also a mistake in some other papers. Actually, A is his family name and Geruo is his forename.

[S3] Agreed, to be corrected in revised manuscript.

(4) Line 287, the citation (CSR, 2016) was not shown in the References. If there is no publication about it, maybe the authors can provide the website link where the information was available.

[S4] Agreed, to be corrected in revised manuscript.

(5) Line 405, JLP should be JPL. For GRGS, whether scaling factor was applied?

[S5] Agreed, JPL will be corrected in revised manuscript; no scaling factors were applied for GRGS product.

(6) Line 310, Fig.s should be Figs. [S6] Agreed, to be corrected in revised manuscript.

(7) Line 394, if I understand it correctly, gridded scale factors from Landerer et al. were not used in this study finally. The authors applied a single scaling (1.7) actually. Based on Figure S1 and the authors' experiment (Fig. S10b), the factors are highly

underestimated by Landerer et al. in the LVB.

[S7] We applied the gridded scaling factors, provided by Landerer and Swenson (2012) to derive the GRACE ∆TWS time-series data in the two basins. Under additional scaling experiments applied solely to GRCTellus, a single, multiplicative scaling factor of 1.7 was applied in an attempt to reconcile large differences between GRACE ∆TWS and the in-situ (now 'bottom-up') ∆TWS.

(8) In 3.2 Methodologies, how to estimate GWS using GRACE in detail? I would suggest the authors explain it in a paragraph in 3.2.2.

[S8] As per response G3, the estimation of ∆GWS from GRACE will be stated explicitly in a revised section of 3.1.2.

(9) Line 434, "in both LVB and LKB (see supplementary Figs. S2–S7)." The captions of Figs. S5-S7 are "over the Victoria Nile Basin". Does the Victoria Nile Basin mean the LKB? The caption of Figure S9 also contains "in VNB".

[S9] Agreed, to be corrected in revised manuscript.

(10) Line 436, simulated ∆SWS should be simulated ∆SMS?

[S10] Agreed, to be corrected in revised manuscript.

(11) Line 446, "all 5 GRACE ∆TWS and in situ ∆TWS time-series records". There are only 4 curves in each panel of Figure 7.

[S11] Agreed, in the revised manuscript, the text will be revised to "all 3 ∆TWS time-series records from 5 GRACE products".

(12) Line 449, "the period of 2004 to 2006", but in table 3, "2003-2006". This kind of inconsistency occurs several times in the manuscript.

[S12] Agreed, to be corrected as "2003 to 2006" throughout the revised manuscript.

(13) Line 464, "see supplementary Table S1". No correlation estimates in table S1 in

fact.

[S13] Agreed, we will correct the text in the revised manuscript. No correlation estimates are provided in the supplementary Table S1, which reports variances explained by linear regression.

(14) Line 465-466, "GRACE ∆TWS is unable to explain natural variability in in situ ∆TWS in LKB though this may be explained by the fact that SWS in Lake Kyoga is influenced by dam releases from LVB". GRACE can detect all mass changes including both natural and anthropogenic variability, but can not disaggregate individual components. If in situ ∆TWS includes all mass change signals, it should be consistent with the GRACE estimate, no matter mass change is natural or anthropogenic. I suspect that the lower correlation in the LKB might be caused by the smaller area of LKB and larger leakage errors from the surrounding regions (including LVB).

[S14] We appreciate that GRACE detects all mass changes whether they are natural or anthropogenic. We also appreciate the explanation suggested by AR1 and provide calculations to support this assertion. In the current manuscript (lines 532 to 536), we briefly discuss the leakage from Lake Victoria into the adjacent basin but we will expand this discussion and report that our leakage analysis shows that GRACE signal leakage into LKB from LVB, which is 3 times larger, is 3.4 times bigger for both GRCTellus GRACE and GRGS products.

(15) The caption of Table S1, no "variablility (i.e., variance, cmËĘ2)" in the table. In the caption, what is the meaning of 120 cmËĘ2 and 24 cmËĘ2? The variances of in situ ∆TWS?

[S15] Yes, the values of 120 and 24 cmˆ2 are variances in in-situ ∆TWS for LVB and LKB respectively. The table legend will be correctly in the revised manuscript.

(16) Line 473-477, GRACE-derived ∆TWS was rescaled to recover the actual mass change. But, why the scaling down process was needed to remove ∆SWS for estimat-

ing ∆GWS? If rescaled ∆TWS time series was used to estimate ∆GWS, maybe the authors should use in situ ∆SWS (equation 2) rather than scaling down ∆SWS. I also cannot understand the caption of Figure 8. Why a scaling down process of SWS is needed for disaggregating GWS from GRACE-derived rescaled TWS (Line 399-405).

[S16] See above response to the general comment G3.

(17) Line 399-405, were these factors calculated from the product of Landerer and Swenson 2012 (Figure S1)? Note that this product should be used for recovering TWS rather than only for SWS. In line 402, s=0.71 for experiment 1. But in caption of Figure S10, s=0.77 for experiment 1.

[S17] Yes, as per response G3 and S7, gridded scaling factors provided by Landerer and Swenson (2012) were used to generate ∆TWS time-series records for LVB and LKB. However, under the scaling experiments undertaken on the ensemble mean of 3 GRCTellus GRACE products (CSR, JPL, GFZ), several multiplicative scaling factors were applied to observed ∆SWS time-series data (s=0.71 and s=0.11 in experiment 1) and ∆TWS (s=1.7 in experiment 2), guided by RMSE, in an attempt to reconcile substantial differences between GRCTellus GRACE ∆TWS and bottom-up ∆TWS.

(18) Section 3.1.3, GLDAS does not assimilate surface water, which is an important TWS component in the study region. Whether the absence of surface water process will highly affect the accuracy of simulated soil moisture from GLDAS? Maybe the authors can try to use WGHM model which considers the surface water. In Figure S12, the authors compared many LSMs except WGHM, which simulates all TWS components. If the authors removed ∆SMS from WGHM, maybe there will be a better agreement between in situ well observations and GRACE-based ∆GWS, although the representativeness of these wells is also questionable.

[S18] We thank AR1 for their suggestion of the use of WGHM to test GRACE-derived ∆GWS but this is beyond the scope of the current study and we will consider such experiments in future studies.

(19) Line 1117, cantered should be centered.

[S19] Agreed, to be corrected in revised manuscript.

(20) Figure 8, what is the criterion of selecting Sy?

[S20] The explanation for the applied range of Sy values is currently given in lines 334-338.

References:

Landerer, F. W., and Swenson, S. C.: Accuracy of scaled GRACE terrestrial water storage estimates, Water Resour. Res., 48, W04531, 2012.

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Wiese, D. N., Yuan, D.-N., Boening, C., Landerer, F. W., and Watkins, M. M.: JPL GRACE Mascon Ocean, Ice, and Hydrology Equivalent Water Height JPL RL05M.1. Ver. 1, PO.DAAC, CA, USA, 2015.

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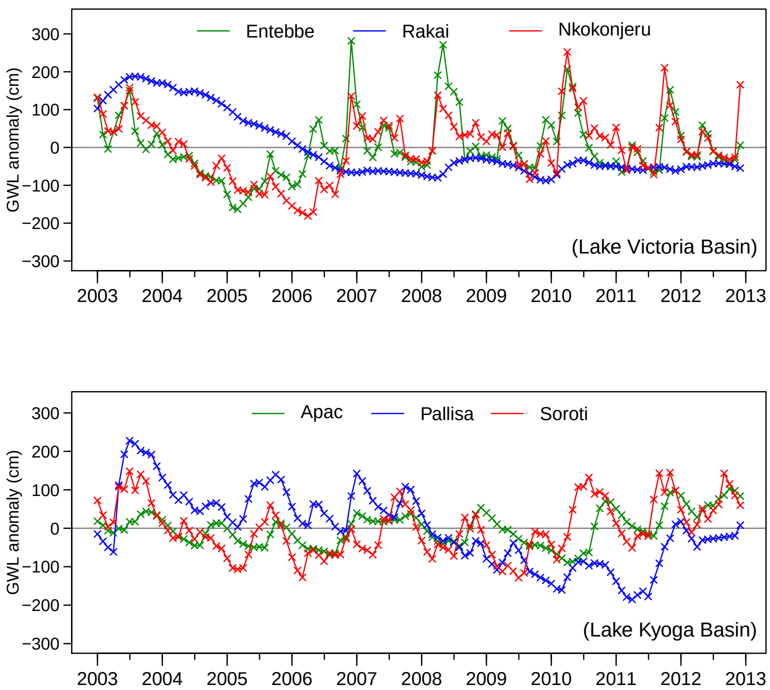

Fig. 1. Figure R1. Time-series records of monthly anomaly of groundwater-level monitoring records at three stations in LVB (top), and records at three stations in LKB (bottom).

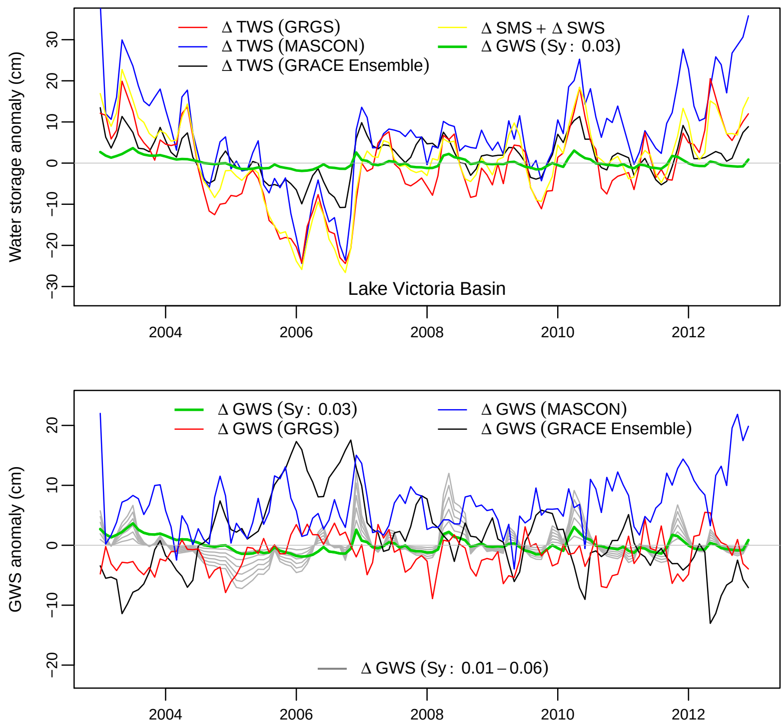

Fig. 2. Figure R2. Time-series records of GRACE ΔTWS, sum of in-situ ΔSWS and ΔSMS, and in-situ ΔGWS for LVB (top); and estimated ΔGWS (bottom). Gridded scaling factors applied to GRCTellus and JPL-Mascons.