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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.

Mohammad Shamsudduha et al.

m.shamsudduha@ucl.ac.uk

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Response to Anonymous Referee 2 (AR2)

Numbered responses are given below each comment:

[AR2] This study evaluates, for the Upper Nile Basin over the 2003-2012 period, several estimates of terrestrial water storage (TWS) as processed from the Gravity Recovery and Climate Experiment (GRACE) retrievals with in situ and model-derived estimates of its individual terms: surface water storage (SWS), soil moisture storage (SMS), and groundwater storage (GWS). The authors reach interesting conclusions, namely 1) the pre-processing of GRACE greatly affects estimated annual TWS amplitude and, most

notably, reconcilability with bottom-up approaches and 2) uncertainty in GRACE TWS and model-derived prevents a reasonable inference of GWS variation in these aquifers. While I appreciate the scientific value of this work, I find this manuscript confusing at times in its logic, and lacking rigor regarding how methods and some quantities are defined. Therefore, I recommend resubmission only after the authors have made a substantial rewriting effort to improve the clarity of the presented results.

[G0] We greatly appreciate the critical comments of the Anonymous Referee #2 (AR2) and their recognition of the important conclusions of the manuscript.

Responses to general comments [G1-G3]

[AR2] "In situ ΔTWS" is used throughout the manuscript, but this term is quite misleading: as defined in Eq. (1) and then L379-381, this quantity is the sum of ΔSWS, ΔGWS, and ΔSMS estimates. While the two former terms are indeed estimates based on situ measurements, ΔSMS is averaged from simulations with three gridded hydrological models at 0.25 resolution (Sect 3.1.3 and L580-581). This is of particular importance since the whole study is about attempting to reconcile estimates of storage compartments across approaches and scales. I suggest using something like "bottom-up ΔTWS" instead.

[G1] We thank AR2 for their critical comment here. We agree and will adapt their proposed nomenclature, "bottom-up ΔTWS", in the revised manuscript to make the distinction clearer.

[AR2] The method section is rather long, in particular the description of GRACE datasets retrievals and the applied methodology in sections 3.1.2, 3.2.1 and 3.2.2. While I understand the authors want to present the remaining datasets (ΔSWS, ΔSMS . . .) before detailed how ΔTWS is being processed, sect. 3.2.1 and sect 3.2.2, are even frankly confusing at times, e.g., when the ΔTWS scaling methodology is explained (L357-363, see specific comments) and then discussed again (L387-397) so that in the end I am not sure what was used for the study.

[G2] We appreciate that the description of various datasets and the method section are long and keep them separate under two sub-sections, Datasets (3.1) and Methodologies (3.2). The apparent confusion in the application of scaling factors may derive from the fact that we conducted additional scaling experiments only for the ensemble mean ΔTWS of 3 GRCTellus GRACE products (CSR, JPL, GFZ). These additional scaling experiments were conducted in an attempt to reconcile GRCTellus GRACE ΔTWS with 'bottom-up ΔTWS'. As per responses S7 and S17 to AR1, we will clarify the selected methodologies for scaling factors in sections 3.2.1 and 3.2.2 in a revised manuscript.

[AR2] TWS sometimes appears instead of ΔTWS (e.g. L79-86). While this be should a mere technical comment, in some cases TWS would actually be more accurate in the general sense (i.e. the concept of storage), e.g. when discussing reduction in volumetric storage in the whole basin (e.g., L537-539 where "ΔTWS" is used).

[G3] We thank AR2 for their comment here and will revise the use of 'TWS' and 'ΔTWS' accordingly in a revised manuscript.

Responses to specific comments [S1 to S3]:

L21-22: It would be more accurate to say that the authors "test the phase and amplitude of three GRACE ΔTWS estimates derived from 5 commonly-used gridded products [. . .]".

[S1] We thank AR2 for their critical comment and suggestion here. We agree with AR2 and will employ suggested edits in the revised manuscript.

L123: What is the actual time span of the "unintended experiment": 2004-2006 (like stated here)? 2005-2006 (e.g., L553)? 2003-2006 (most of the manuscript)? The authors should delimit this period consistently across the main text, the tables, the figures, and the supplementary materials.

[S2] Agreed, we will use the time span of 2003-2006 to indicate the "unintended experiment" throughout the revised manuscript.

L169-173: The authors should comment on the large discrepancy between these two lake area estimates. In addition, why do the authors report the HydroSHEDS area value as being from this study in Table 1?

[S3] We thank AR2 for their suggestion here and will include in a revised manuscript a statement highlighting the large discrepancy between the delineated area of LVB reported by UNEP (2013) and both Awange et al. (2014) and this study, which employs the HydroSHEDS boundary shapefiles for LVB and LKB.

L357-363: The authors first state that they spatially aggregate the unscaled ΔTWS signal over the study region in order to have a time series, but then say that the scaling factors are applied to each grid of the GRACE mesh, therefore it is done before spatial aggregation? Please clarify.

[S4] Yes, gridded scaling factors were applied to corresponding grid cells for ΔTWS before the spatial aggregation over LVB and LKB in order to generate time-series data. We will revise the texts in order to clarify this point.

L395-397: Along with the regionally-averaged gain factor, why did the authors not also test the third method described L392-394?

[S5] We do neither possess nor access monthly scaling factors to conduct the third scaling experiment and will clarify this point in the revised manuscript.

L415-418: A lag of 2-3 months between lowest rainfall and lowest ΔTWS is also well noticeable, while ΔSMS respond more quickly to rewetting after the driest month ($\sim$1 month) and ΔSWS is slower ($\sim$4 months lag after minimum rainfall).

[S6] We appreciate this comment and will expand our discussion of seasonal hydrological responses to rainfall that include dam operations.

L432-434: Figs. S5 to S7 are relative to the entire Victoria Nile Basin and not Lake Kyoga Basin, I do not see how the authors can derive the observation that "GRACE-derived ΔTWS signals are strongly correlated in both LVB and LKB (see supplemen-

tary Figs. S2–S7)". The same applies L441-444. Maybe the figures were unintentionally swapped with relative to LKB?

[S7] Agreed, to be corrected in a revised manuscript.

L446-447: This sentence is misleading since only 3 ΔTWS estimates are used shown, albeit derived from 5 different GRACE products.

[S8] Agreed, as per responses S11 (AR1) and S1 (AR2), we will revise the text.

L449-456: The authors might already mention that only ΔGWS shows an increase in 2005-2006, as later discussed in the Discussion section.

[S9] We thank AR2 for this comment. We provide an explanation of the apparent rise in ΔGWS in lines 554-557.

L457-458: A support supplementary figure with time series for LKB would help. Is it what Fig. S9 should have been (instead of describing the Victoria Nile Basin)? If so, the authors should add a reference to Fig. S9 here, and replace "[. . .] (see supplementary Figs. S8–S9)." by "[. . .] (see supplementary Figs. S8–S9)." in L456, and caption of Fig. S9 should read "LKB", instead of "VNB".

[S10] Agreed, LKB is mistakenly labelled as Victoria Nile Basin. We will correct this in a revised supplementary document.

L465-466: I am not sure what the authors mean, how could the TWS signal miss one of its component, unless it refers to a water transfer within the system? All the more that even if mention of LVB-driven water balance of LKB is given on L175-177, this point is not picked up later in the Discussion section. Is it related to the substantial variability of ΔTWS deriving from ΔSMS in in LKB as compared to LVB? Could the authors expand their idea?

[S11] We appreciate that GRACE detects all mass changes, whether they are natural or anthropogenic, and regret the confusion caused by our statement, "GRACE ΔTWS

is unable to explain natural variability in in situ ΔTWS in LKB though this may be explained by the fact that SWS in Lake Kyoga is influenced by dam releases from LVB". As per response S14 (AR1), further discussion of signal leakage from Lake Victoria into Lake Kyoga will be made in the revised manuscript in which we will report on our leakage analysis showing 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.

L476-477: Why scaling down ΔSWS rather than using the rescaled ΔTWS presented right above (L474-476) to disaggregate ΔGWS?

[S12] As per response G3 to AR1, to estimate ΔGWS from GRACE ΔTWS, we applied a '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. R1 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. R1 bottom). We agree with AR2 that current description of application of scaling factors, both conventionally and unconventionally is insufficiently clear and will be substantially improved in the revised manuscript.

L526-527: This sentence essentially repeats L517-518, with typos (see Technical comments).

[S13] Agreed, lines 526-527 will be deleted in a revised manuscript.

L529: The measurement error is not necessarily only a bias (systematic) is there are random components; Swenson and Wahr (2006) seem to keep this broader definition.

[S14] We applied measurement and leakage errors from Landerer and Swenson (2012); reference to Swenson and Wahr (2006) is incorrect and will be corrected in the revised manuscript.

L541-548: Would not it be more correct to say that the choice of ΔSMS from LSMs contributes to uncertainty in estimating bottom-up ΔTWS (termed in situ in the manuscript, see General Comments), and consequently comparing it to GRACE ΔTWS, rather than uncertainty "GRACE analysis"? In addition, the order of sentences in this paragraph leaves me with the impression that this study did not bring any improvement to estimating bottom-up ΔTWS, while most of the manuscript uses this estimate as a benchmark to test GRACE ΔTWS products. In order to avoid finally leaving the reader with "how reliable is this ΔTWS reconciliation then?", the authors should maybe remind in the discussion that ΔSWS is by far the largest contributor in LVB at least, somewhat limiting the propagation of ΔSMS uncertainty.

[S15] We agree with this argument of AR2 that ΔSWS is by far the largest contributor to ΔTWS in the LVB and is dominated by an accurately observed ΔSWS signal of 81 km3, limiting the propagation of ΔSMS uncertainty. We will consequently revise the discussion to reflect this important argument as it relates to statements about uncertainty in GRACE products relative to a 'bottom-up' ΔTWS.

L616-617: This should probably be stated already in the Discussion.

[S16] We thank AR2 for this suggestion.

Technical corrections:

L101: SSA is not used anywhere else in the manuscript of supplement.

[T1] Agreed, "(SSA)" will be deleted in a revised manuscript.

L527: Likely typos, maybe "[. . .] priori information from LSMs contributes to adding uncertainty to ΔTWS signals".

[T2] Agreed, this statement will be deleted in a revised manuscript.

Figs. 5 and 6: What are the dashed vertical lines in the top panels and the horizontal dashed line in the bottom panels?

[T3] Agreed, we will delete the vertical line which separates the two periods (2003-2006, 2007-2012). The dashed horizontal line indicates the mean rainfall for the period of 2003-2012; this detail will be made clear in the figure captions (Figures 5 and 6) in the revised manuscript.

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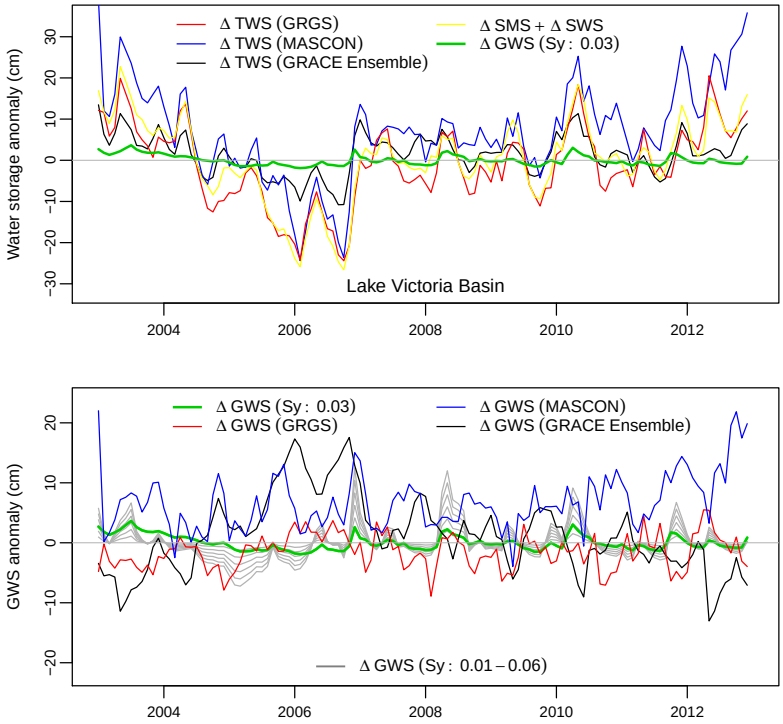

Fig. 1. Figure R1. Time-series records of GRACE ΔTWS, sum of in-situ ΔSWS and ΔSMS, and in-situ ΔGWS for LVB (top); and estimated ΔGWS (bottom). Gridded scaling factors applied to GRCTellus and JPL-Mascons.