

This study provides a novel perspective on the information content of GRACE time variable gravity data for estimating continental water storage variations. The study analyzes the effect of spatially concentrated mass variations such as water storage change in lakes, reservoirs or rivers on the GRACE signal. A similar dedicated analysis has not been published before. The paper very nicely combines a comprehensive synthetic experiment with real-world applications. The results, highlighting the considerable effect on GRACE data of position and extent of concentrated mass variations within the area of interest, will have a high impact on future analyses of GRACE for hydrological applications. Also, results of several previous publications on the use of GRACE data for estimating water storage variations at regional scales may need to be reconsidered in the light of the outcomes of the present paper. I highly recommend publication of this study in HESS, given moderate revisions that should mainly help improving the quality of presentation, in particular with regard to the main findings of this study in terms of GRACE signal content with respect to concentrated mass variations.

Thank you very much for the constructive comments. For the sake of clarity, we better introduced the “point mass” problem with a methodological figure and associated discussion. Finally, we strengthened the “case studies” part with evaluation of uncertainties.

Major comments:

1) With the synthetic experiment (Chapter 3) (Figures 1, S1, S2) the study presents a highly valuable but complex analysis of the impacts of scale and location of mass variations and study area on the apparent GRACE signal. A condensed summary of the three main findings as given in Chapter 3 is commendable. Nevertheless, in addition to improved wording and explanation of figures, a slightly extended discussion of the results will help to better illustrate the wealth of outcomes of the analyses condensed in the figures 1, S1, S2 and their impacts for future studies (see also my minor comments below for details).

The authors believe that the three points highlighted are the most critical. In particular, this experiment clearly shows the impact of mass distribution on GRACE basin-wide average storage change. However, we extended the discussion section in the synthetic experiment (see text).

2) The applications to real-world examples in Chapter 4 take an inverse view as compared to the synthetic experiments. In the real-world example, one has a GRACE signal and tries to interpret it in terms of water storage variations, including in terms of concentrated mass such as reservoirs (the synthetic experiment provides a mass distribution and estimates its effect on GRACE).

2.1) It will be very helpful to make it crystal clear how to explain the GRACE signal when having some a-priori information on the distribution of mass within the study area. For example, the sentence in page 11142, line 13, “If the mass is assumed uniformly distributed ,... then estimated storage is twice that actually determined from GRACE ...” is misleading. What is the true value, what does GRACE see, in which case do we overestimate or underestimate with GRACE data, how to relate GRACE data to the point masses?

That was indeed not clear. The question of overestimation and underestimation depends on the point of view. Modified as :

“If the lake mass is assumed uniformly distributed over the Lower Nile basin then its impact on GRACE (170 mm between minimum and maximum, 69 km³) is twice the actual impact considering the spatial distribution of concentrated mass variations (80 mm, 32 km³, similar to what GRACE captures), as expected from Experiment 1. A consequence is that long-term variations in the lake contribution to water storage changes would be overestimated if uniform distribution was assumed.”

2.2) Similarly, the phrase in page 11141, line 27, is not fully clear. “Simple GRACE estimates will over-estimate average basin storage if the distribution is incorrectly assumed to be uniform ...”. What exactly does this mean? What is a “simple GRACE estimate”? Is it true if one says that that the real mass variations are smaller than those derived from GRACE if the spatial distribution is not uniform?

Right. Modified as:

Second, the signal produced by a concentrated mass tends to increase with concentration. If a point mass is located near the center of the basin and its distribution is incorrectly assumed to be uniform, GRACE estimates may over-estimate the actual mass storage by more than 50%.

The following sentence is added:

As a conclusion, considering actual mass distribution within a basin is necessary to accurately interpret water mass storage variations with GRACE.

2.3) Similarly, conclusions, page 11147, lines 16-18: “... the simple sum of reservoir storage underestimates their actual impact on GRACE by nearly 50%.” Not clear. Isn't it rather that GRACE overestimates by 50% (the observed reservoir storage should be the truth?)

Indeed. But as the groundwater contribution is not modeled, the following sentence is more adapted:

Reservoir storage changes during the recent drought (2006/10 – 2009/09) have been estimated ~27 km³ from satellite altimetry. However, the computed impact on GRACE is twice as important (45 km³) and accounts for ~ 50% of the TWS decline measured by GRACE. Assuming uniform reservoir storage distribution would have underestimated the reservoir contribution by 50% Both soil moisture (~50%) and predicted impact of reservoir (~50%) account for most of the TWS decline of 93 km³ during the 2007 through 2009 drought. While large variability in SMS among LSMs precludes reliable estimation of trends in GWS depletion during the drought, it is expected to be very limited.

2.4) Similarly, page 11144: “ Reservoir storage appears to explain about 50% of mass variations on GRACE ...” But we want to know the true storage variations?! Following Table 2, the true value is <30% when considering altimetry data.

This is true. The impact of reservoir is 50% of GRACE data (while the actual impact is <30%). Modified in the text :

In the Tigris-Euphrates basin, major reservoirs are located near the center of the basin; their impact on GRACE is larger than the simple sum of reservoir volume variations. Reservoir storage changes during the recent drought (2006/10 – 2009/09) have been estimated ~27 km³ from satellite altimetry. However, the computed impact on GRACE is twice as important (45 km³) and accounts for ~ 50% of the TWS decline measured by GRACE. Assuming uniform reservoir storage distribution

would have underestimated the reservoir contribution by 50% Both soil moisture (~50%) and predicted impact of reservoir (~50%) account for most of the TWS decline of 93 km³ during the 2007 through 2009 drought

3) The supplementary material is partly not self-explaining and references to it in the main text are rare. In my opinion, it will be helpful to include some paragraphs of text explaining the main approaches and findings, instead of (or in addition to) very condensed figure captions that do not provide enough information to grasp the overall message (in particular figures S3 and S4).

More text has been added, in the main article and in the supplementary material

Minor / detailed comments:

1) page 11135, line 7: “observable” instead of “observability”

OK

2) page 11135, line 19: Rodell et al. 2009

OK

3) There is some confusion throughout the paper what SMS stands for. It is introduced as soil moisture storage (page 11139, line 6-7), later on defined as soil moisture + snow (page 11139, line 17). For the Tigris- Euphrat, SMS is considered as an important storage compartment (Chapter 4.2). Does it include snow, a storage compartment which will be relevant in this basin? Table 2: Does SMS include snow? Which GLDAS model is used in table 2?

Indeed, this is not clear at all, but snow is considered in the analysis of the data. It has been précised throughout the manuscript. In table 2, the mean of all 4 models is considered.

4) page 11141, line 8: “Masses outside the basin yield a similar ABS to point masses inside the basin ...” Where can this be seen? Up to which distance does this hold?

More details in the analysis.

5) page 11141, line 11: Why does the degree 60 case lead to a decreasing ABS relative to the degree 50 case? Isn't it the reverse (more smoothing / more strict truncation for the 50 case)?

Not exactly. Truncation at degree 50 may be considered as a 400-km filter, which conserves full amplitude of Stokes coefficients for all degrees below 50. Conversely, a 300-km Gaussian smoother affects all degrees: at degree 30, Stokes coefficients are divided by a factor 2. As a whole, the impact of the 300-km Gaussian smoother is larger than the simple truncation at degree 50. To illustrate this point, please refer to figure 3 in Longuevergne et al., WRR 2010: GRACE hydrological estimates for small basins: Evaluating processing approaches on the High Plains Aquifer, USA.

6) page 11142, lines 3-4: Following my major comment 1), the authors may add some more explanations how location and spatial extent interact in the synthetic examples.

7) page 11142, lines 13-15: Assuming point and uniform distribution of mass among the basin, isn't it experiment 2 to refer to instead of experiment 1?

The lake is located at the basin edge, so its contribution to GRACE is limited to half the simple sum of reservoir volume variations. So, this is experiment 1.

8) Can the leakage from southern parts of the Nile basin be specified (page 11143, line15)?

Not really in this paper. Please check (Abdelsalam et al., 2008)

9) page 11143, line 23: what is the "reduced area"?

We meant that the lake has a small area, corrected.

10) page 11144, line 13: "reservoir storage" instead of "reservoir storage management"

OK

11) page 11146, line 22: " water storage" instead of "water level"

OK

12) page 11144, line 23: "reservoirs"

OK

13) Table 1 and others: column "Variability". Is it mean seasonal variability?

Variability is computed as the standard deviation of water storage, which indeed includes, especially, the seasonal variations. Included in the caption for Table 1

14) Fig. 1, Fig S1, S2: Specify that in each plot a mass of 1 km³ is used.

Added

15) Fig. 2: other (and less favourable) symbols for CSR and GRGS data (replace by error bars as in the other figures)

Well, figure 2 already shows a lot of curves and adding the errorbars for all months largely overloads the figure. For the sake of clarity, we do not include errorbars.

16) Fig. 2: Why has a 2.7 m water layer be used for the analysis?

2.7 m is the level variability of Aswan lake (Table 1), which is equivalent to 16 km³. Modified in the caption

17) Figure S1 caption: Delete twice "Experiment 1"

OK

18) Figure S1 caption:" as reduced to..." (?) "... normalized to ..."?

Indeed. Modified

19) Figure S3: suggestion to show SH spectra for area without point masses for comparison (and to illustrate the “signature of concentrated masses”).