Long-term Total Water Storage Change from a SAtellite Water Cycle (SAWC) reconstruction over large south Asian basins

Reviewer 2

COMMENTS

- **This paper explains how to estimate the total water storage change of a large basin using GRACE estimates by satellite. The water conservation equation is used to have an independent constraint, and uses satellite estimates of precipitation and evaporation together with a direct measure of river discharge near the mouth of the river. These complementary measures have to be at the monthly scale, as this is the temporal resolution of the GRACE estimates. The methodology is applied to four large basins in India and Indochina and the methodology is able to produce estimates that compare well with GRACE observations. I find the paper and the methodology interesting and the results of application, since they allow to monitor the water status of large basins with very little in-situ observations (essentially only a discharge measurement is needed). The paper is clearly written and well organized.**
- Thank you for your appreciation on this work.

- **My questions, being a meteorologist, are about the determination of the precipitation and evaporation by satellite. In the integration part, three sources are used for precipitation. More than providing the references, nothing is said about the characteristics of these data sets, how are they produced, what are the differences between them, which is the uncertainty for each of them, and how is the total uncertainty obtained. Similarly, more information about the ET databases should be provided.**

- Thank you for this remark. These global precipitation and ET database are widely used in remote sensing community (Rodell et al., 2015; Pan et al., 2012; Sahoo et al., 2011; Zhang et al., 2017; Munier et al., 2014; Pellet et al., 2018, 2019), but more information are needed in this section. The manuscript specifies some characteristics of these datasets for P, E and TWSC, and cite some inter-comparison studies in which uncertainty assessments can be found:

1. *Precipitation, P - All these datasets are global datasets widely used in the community. GPCP and TMPA use the same algorithm Threshold Matched Precipitation Index (TMPI) to estimate instantaneous precipitation from multiple satellites by combining high-quality passive micro-wave observations and infrared data and differ only in the use of gauge analyses (GPCC) to obtain calibrated estimates. While TMPA is based on inverse random-error variance weighting, GPCP assumes that the precipitation distribution estimated from combined satellite estimates is optimal and uses the gauge observations only for debiasing. The MSWEP dataset merges the highest quality precipitation data sources available as a function of timescale and location. It uses a combination of rain gauge measurements, the two previous satellite datasets, and reanalysis. These datasets have been compared in terms of uncertainties and performance in (Sun et al., 2018). It should be noted that these datasets are not independent of each other but represent the best up-to-date precipitation estimates for hydrological studies.*

2. *Evapotranspiration, E - The Global Land Evaporation Amsterdam Model (GLEAM-V3B, Martens et al., 2016; Miralles et al., 2011), uses Priestley and Taylor 1972 (Priestley and Taylor, 1972) empirical energy-based equation to calculate the reference evapotranspiration and separately estimate the different components of land evaporation: transpiration, bare-soil evaporation, interception loss, open-water evaporation and sublimation. GLEAM uses reanalysis (vA) or satellite (vB) precipitation inputs. The global observation-driven Penman-Monteith-Leuning (PML, Zhang Yongqiang et al., 2016) evapotranspiration introduced by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) and the MODIS Global Evapotranspiration Project (MOD16, Mu et al., 2011) are both evapotranspiration estimates based on Penman-Monteith equations (PENMAN, 1948; Monteith, 1965). We choose these three datasets due to their different equations of parametrization for the evapotranspiration. Inter-comparison of global evapotranspiration algorithms and datasets can be found in (Michel et al., 2016).*

3. *Total Water Storage Change (TWSC), ΔS - Another MASCON solution exists : the CSR-MASCON solution. The MASCON solutions from CSR and JPL differ in their processing: while JPL solution is based on the explicit estimation of mass anomalies at specific mass concentration block location using the analytical partial derivatives of the inter-satellite range-rate measurements (Watkins et al., 2015), the CSR developed MASCON solution is first based on a Spherical decomposition of the inter-satellite range-rate measurements that is truncated spatially at the location of mass concentration (Save et al., 2016). The two solutions have been compared to the spherical solutions in terms of uncertainty in both min-max range and trend in (Scanlon et al., 2016; Save et al., 2016). We choose here the JPL solution because it is more independent of the spherical solution.*

Characterizing the uncertainties of satellite-retrieved products is a difficult task (see the answer to the next comment). In this study, the precipitation and evapotranspiration uncertainties are derived from the literature (Munier et al., 2014). All datasets describing a water components have the same uncertainty and the resulting uncertainty of ensemble mean is derive assuming the independence of the sources. This simplification is usually done: (Pan et al., 2012; Munier et al., 2014; Pellet et al., 2018, 2019). This is now clearer in the manuscript where the Simple Weighting (i.e. arithmetic average) estimate and its uncertainty are introduced in Section 2.2.1.

$$P_{SW} = \frac{1}{p-1} \sum_{i=1}^{p} \frac{\sum_{k \neq i} (\sigma_k)^2}{\sum_k (\sigma_k)^2} P_i. \tag{1}$$

This equation is valid when there is no bias error in the P_is (thanks to the preliminary bias correction) and is optimal when the errors ϵ_i are statistically independent from each other. This expression is valid for the other water components. The variance of the P_{SW} uncertainties is then given by:

$$\sigma_{P_{SW}} = \frac{1}{(p-1)^2} \sum_{i=1}^{p} \left(\frac{\sum_{k \neq i} (\sigma_k)^2}{\sum_k (\sigma_k)^2} \right)^2 \sigma_i^2. \tag{2}$$

• I believe that the paper would benefit of related precipitation and evaporation maps and a discussion in depth of the uncertainties of the terms of water closure budget (P, ET, D). The last paragraph of subsection 2.2.1, or Table 3, only give the values imposed for the uncertainties, not how they are obtained. Also subsection 2.3.4 is vague on the subject.

- Thank you for this comment. Uncertainty analysis at grid scale is beyond the scope of this study which focus on the basin scale, however particular analysis on precipitation (resp. evapotranspiration) uncertainties can be found in (Sun et al., 2018) (resp. (Michel et al., 2016)). These references have been added in section 2.2.1. The following specification are now clearer in the text : *"Characterizing the uncertainties of satellite-retrieved products is a difficult task. Such characterizations are generally product, and site, specific. Some studies (Pan et al., 2012; Sahoo et al., 2011; Zhang et al., 2017) estimate the a priori uncertainty of particular water component based on the spread among the various estimates. In our case, this approach would not take into account the fact that our precipitation estimate are not independent. Finally, the values considered here are derived from (Munier et al., 2014) in which the authors reviewed the literature on this topic. Compared to this study, the partitioning of uncertainty between P and E has been modified to allow larger uncertainty in P since all P datasets are dependent with each others. As the objective of the current study is to reconstruct GRACE TWSC, the approach assumes low error in the GRACE estimate."*

Noted that Table 3 does not give *a priori* uncertainty value but provided uncertainty estimates computed *a posteriori* as the distance between the original datasets and the reference (our new estimate). This is why the various original products have different *a posteriori* uncertainty even if a same *a priori* uncertainty was specified. This is now clearer in the text.

- **On the other hand, ISBA-CTRIP and GLDAS are used as evaluation tools. Being these utilities models themselves, it is unclear if the results are good enough for validation in this area of the world. More details should be provided about the quality of these models in this region so that it appears legitimate to use it as a validation tool, discussing at least their uncertainties.**

- Thank you for this remark. We prefer to state "evaluation" with ISBA instead of "validation" in section 3.2 since validating TWSC over the long time period (1980-2015) is a difficult task. Often, this type of evaluation is performed by comparing to other independent estimates. For instance, Figure 4 shows that ISBA can simulate more accurately the TWSC than GLDAS. The following statement has been aded to the manuscript : *"Finally, the discrepancy between simulated TWSC from ISBA and GLDAS can be explained by the representation of aquifers in these two models. While a two-dimensional diffusive groundwater scheme in ISBA represents unconfined aquifers process (Vergnes and Decharme, 2012; Vergnes et al., 2012),* *the Noah land model used in the GLDAS simulations did not include surface and groundwater storage. Therefore, the simulated mean seasonal cycle and the inter-annual variability of the TWSC is improved in ISBA (Decharme et al., 2019). On the contrary, deviations from GRACE TWSC can thus be expected with GLDAS simulated TWSC (Syed et al., 2008). Based on the results presented in Figure 4, we decided to compare SAWC estimate only to ISBA over long time period".* Nevertheless, none of these models included anthropogenic effect and this is also now discussed.

• **Furthermore, having a better description of the rationale in Section 3, more specifically in subsection 3.2, may be of help for the reader. In subsection 3.1 all the available sources (GRACE, SAWC, ISBA and GLDAS) are compared and it is stated that SAWC fits best with GRACE, admitting that it is by construction. Then, in subsection 3.2, it retains ISBA for the further comparison considering that it performs better than GLDAS. In this part a discussion on the uncertainties of all methods is missing.**
- See previous answer for the rational in Section 3. The manuscript now justifies the ISBA comparison.

• **For a non-specialist, the paper is interesting and the methodology seems powerful**
- Thank you, we hope that the revised manuscript will answer your concerns.

References

Decharme, B., Delire, C., Minvielle, M., Colin, J., Vergnes, J., Alias, A., SaintMartin, D., Séférian, R., Sénési, S., and Voldoire, A. (2019). Recent Changes in the ISBACTRIP Land Surface System for Use in the CNRMCM6 Climate Model and in Global OffLine Hydrological Applications. *J. Adv. Model. Earth Syst.*, 11(5):1207–1252.

Michel, D., Jiménez, C., Miralles, D. G., Jung, M., Hirschi, M., Ershadi, A., Martens, B., Mccabe, M. F., Fisher, J. B., Mu, Q., Seneviratne, S. I., Wood, E. F., and Fernández-Prieto, D. (2016). The WACMOS-ET project - Part 1: Tower-scale evaluation of four remote-sensing-based evapotranspiration algorithms. *Hydrol. Earth Syst. Sci.*, 20(2):803–822.

Monteith, J. L. (1965). Evaporation and environment.

Munier, S., Aires, F., Schlaffer, S., Prigent, C., Papa, F., Maisongrande, P., and Pan, M. (2014). Combining data sets of satellite-retrieved products for basin-scale water balance study: 2. Evaluation on the Mississippi Basin and closure correction model. *J. Geophys. Res.*, 119(21):12,100–12,116.

Pan, M., Sahoo, A. K., Troy, T. J., Vinukollu, R. K., Sheffield, J., Wood, and F, E. (2012). Multisource estimation of long-term terrestrial water budget for major global river basins. *J. Clim.*, 25(9):3191–3206.

Pellet, V., Aires, F., Mariotti, A., and Fernández-Prieto, D. (2018). Analyzing the Mediterranean Water Cycle Via Satellite Data Integration. *Pure Appl. Geophys.*, 175(11).

Pellet, V., Aires, F., Munier, S., Fernández Prieto, D., Jordá, G., Arnoud Dorigo, W., Polcher, J., and Brocca, L. (2019). Integrating multiple satellite observations into a coherent dataset to monitor the full water cycle - Application to the Mediterranean region. *Hydrol. Earth Syst. Sci.*, 23(1).

PENMAN, H. L. (1948). Natural evaporation from open water, hare soil and grass. *Proc. R. Soc. Lond. A. Math. Phys. Sci.*, 193(1032):120–145.

Priestley, C. and Taylor, R. (1972). On the Assessment of Surface Heat Flux and Evaporation Using Large-Scale Parameters. *Mon. Weather Rev.*, 100(2):81–92.

Rodell, M., Beaudoing, H., L'Ecuyer, T., Olson, W., Famiglietti, J., Houser, P., Adler, R., Bosilovich, M., Clayson, C., Chambers, D., Clark, E., Fetzer, E., Gao, X., Gu, G., Hilburn, K., Huffman, G., Lettenmaier, D., Liu, W., Robertson, F., Schlosser, C., Sheffield, J., and Wood, E. (2015). The Observed State of the Water Cycle in the Early 21st Century. *J. Clim.*, pages 8289–8318.

Sahoo, A. K., Pan, M., Troy, T. J., Vinukollu, R. K., Sheffield, J., and Wood, E. F. (2011). Reconciling the global terrestrial water budget using satellite remote sensing. *Remote Sens. Environ.*, 115(8):1850–1865.

Save, H., Bettadpur, S., and Tapley, B. D. (2016). High-resolution CSR GRACE RL05 mascons. *J. Geophys. Res. Solid Earth*, 121(10):7547–7569.

Scanlon, B. R., Zhang, Z., Save, H., Wiese, D. N., Landerer, F. W., Long, D., Longuevergne, L., and Chen, J. (2016). Global evaluation of new

GRACE mascon products for hydrologic applications. *Water Resour. Res.*, 52(12):9412–9429.

Sun, Q., Miao, C., Duan, Q., Ashouri, H., Sorooshian, S., and Hsu, K. (2018). A Review of Global Precipitation Data Sets: Data Sources, Estimation, and Intercomparisons. *Rev. Geophys.*, 56(1):79–107.

Syed, T. H., Famiglietti, J. S., Rodell, M., Chen, J., and Wilson, C. R. (2008). Analysis of terrestrial water storage changes from GRACE and GLDAS. *Water Resour. Res.*, 44(2).

Vergnes, J.-P. and Decharme, B. (2012). A simple groundwater scheme in the TRIP river routing model: global off-line evaluation against GRACE terrestrial water storage estimates and observed river discharges.

Vergnes, J.-P., Decharme, B., Alkama, R., Martin, E., Habets, F., and Douville, H. (2012). A Simple Groundwater Scheme for Hydrological and Climate Applications: Description and Offline Evaluation over France. *J. Hydrometeorol.*, 13(4):1149–1171.

Watkins, M. M., Wiese, D. N., Yuan, D.-N., Boening, C., and Landerer, F. W. (2015). Improved methods for observing Earth's time variable mass distribution with GRACE using spherical cap mascons. *J. Geophys. Res. Solid Earth*, 120(4):2648–2671.

Zhang, Y., Pan, M., Sheffield, J., Siemann, A., Fisher, C., Liang, M., Beck, H., Wanders, N., MacCracken, R., Houser, P. R., Zhou, T., Lettenmaier, D. P., Ma, Y., Pinker, R. T., Bytheway, J., Kummerow, C. D., and Wood, E. F. (2017). A Climate Data Record (CDR) for the global terrestrial water budget: 1984-2010. *Hydrol. Earth Syst. Sci. Discuss.*, (April):1–40.