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Water budget closure based on GRACE measurements and reconstructed evapotranspiration using GLDAS and water use data for two large densely-populated mid-latitude basins

Meixia Lv, Zhuguo Ma *, Xing Yuan, Meizhao Lv, Mingxing Li, Ziyan Zheng

CAS Key Laboratory of Regional Climate-Environment for Temperate East Asia, Institute of Atmospheric Physics, Chinese Academy of Sciences, 40 Qi-jia-huo-zi, Chaoyang District, Beijing 100029, China

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ABSTRACT

The GRACE-derived terrestrial water storage change (TWSC) provides an unprecedented opportunity to close the terrestrial water budget. However, it remains challenging to achieve the balance without the consideration of human water use (e.g., irrigation and inter-basin water diversion) for the estimation of other water budget terms such as the evapotranspiration. In this study, the terrestrial water budget closure is tested over the Yellow River Basin (YRB) and Changjiang River Basin (CJB, also called Yangtze River Basin) of China. First, the evapotranspiration is reconstructed using the GLDAS-1 land surface models, the high quality observation-based precipitation, naturalized streamflow, and the irrigation water (hereafter, ET_{recon}). The ET_{recon}, evaluated using the mean annual water-balance equation, is of good quality with the absolute relative errors less than 1.9%. The total basin discharge (R_{total}) is calculated as the residual of the water budget among the observation-based precipitation, ET_{recon}, and the GRACE-TWSC. The difference between R_{total} and the observed total basin discharge is used to evaluate the budget closure, with the consideration of inter-basin water diversion. After the ET reconstruction, the mean absolute imbalance value reduced from 3.31 cm/year to 1.69 cm/year and from 15.40 cm/year to 1.96 cm/year over the YRB and CJB, respectively. The estimation-to-observation ratios of total basin discharge improved from 180.8% to 86.8% over the YRB, and from 67.0% to 101.1% over the CJB. The yearly timescale is the finest temporal scale for the analysis in this study due to the data limitation of naturalized streamflow, irrigation water, and water diversion. The proposed ET reconstruction method is applicable to other human-managed river basins to provide an alternative estimation.

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1. Introduction

The launch of the Gravity Recovery and Climate Experiment (GRACE) satellite has been responsible for the emergence of GRACE hydrology studies (Syed et al., 2008; Yirdaw et al., 2008; Zaitchik et al., 2008; Wang et al., 2011). As a horizontally and vertically integrated quantity, the GRACE-derived terrestrial water storage change (TWSC) is regarded as a perfect fit for water budget studies (Rodell and Famiglietti, 1999). The basin-scale terrestrial water budget closure has been investigated by several studies (Syed et al., 2005; Sheffield et al., 2009; Gao et al., 2010; Sahoo et al., 2011; Pan et al., 2012; Long et al., 2015b) using Eq. (1) assuming no lateral groundwater flow across a river basin boundary (Wan et al., 2015):

$$R_{total} = P - ET - \Delta S/\Delta t \quad (1)$$

where $\Delta S/\Delta t$ (cm/t) represents the terrestrial water storage change that is calculated from the GRACE terrestrial water storage anomaly (TWSA) (e.g., $\frac{\Delta S}{\Delta t} \approx \frac{\mathrm{TWSA}(t)-\mathrm{TWSA}(t-1)}{\Delta t}$, Long et al., 2014), P (cm/t) is precipitation, and ET (cm/t) is actual evapotranspiration. The R_{total} (cm/t) inferred from Eq. (1) is taken to represent the total basin discharge, which includes not only the surface water but also the groundwater (Syed et al., 2005). Then, the water budget closure can be evaluated using the difference between R_{total} and the observed total basin discharge.

However, it has been found that the terrestrial water budget is not necessarily closed from currently available water budget terms (Table 1) (Sheffield et al., 2009; Gao et al., 2010; Sahoo et al., 2011; Pan et al., 2012; Long et al., 2014; Penatti et al., 2015). Due to the errors from different sources of satellite data, Sheffield et al. (2009) claimed that it is presently impossible to achieve water budget closure from remote sensing only, which was also noted by Gao et al.

* Corresponding author.
E-mail address: mazg@tea.ac.cn (Z. Ma).

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Table 1
Summary of key studies on the terrestrial water budget closure test using GRACE-derived terrestrial water storage change (the current paper is added for completeness). *R* is estimated total basin discharge which is compared with measured streamflow, *P* is precipitation, *ET* is evapotranspiration, and TWSC is terrestrial water storage change.

Study	Study basins	Data sources	Water budget closure
1. Sheffield et al. (2009)	Mississippi River basin	1. *P* (remote sensing, TMPA and CMORPH products) 2. *ET* (remote sensing, Penman-Monteith) 3. TWSC (GRACE) $R = P - ET - \text{TWSC}$	*R* was greatly overestimated due mainly to the high bias in *P*.
2. Gao et al. (2010)	9 major US river basins	1. *P* (remote sensing, TMPA, CMORPH, and PERSIANN) 2. *ET* (remote sensing, MODIS) 3. TWSC (GRACE) $R = P - ET - \text{TWSC}$	*R* was generally overestimated due to excessive *P* and underestimation of combined *E*.
3. Sahoo et al. (2011)	10 global river basins (Mackenzie, Yukon, Mississippi, Danube, Lena, Chang Jiang, Mekong, Niger, Murray-Darling, and Amazon)	1. *P* (remote sensing, GPCP, TRMM, CMORPH and PERSIANN) 2. *ET* (remote sensing, Penman–Monteith, Priestley–Taylor, and Surface Energy Balance System) 3. TWSC (GRACE) $R = P - ET - \text{TWSC}$	The water budget closure was not achieved with errors of the order of 5–25% of mean annual *P*. A constrained ensemble Kalman filter was used to close the water budget.
4. Pan et al. (2012)	32 major global river basins (including Yellow and Changjiang River basins)	1. *P* (in situ observations) 2. *ET* (in situ observations, remote sensing retrievals, LSM simulations, and global reanalyses) 3. TWSC (GRACE and LSM simulations) $R = P - ET - \text{TWSC}$	Water balance errors were resolved using the constrained Kalman filter technique.
5. Syed et al. (2005)	Amazon and Mississippi River basins	Combined Land-Atmosphere Water Balance using ECMWF. $R = -\frac{\partial S}{\partial t} - \frac{\partial W}{\partial t} - div Q$ $\partial S/\partial t$ is TWSC from GRACE	Overestimation and underestimation of *R* coexisted.
6. Oliveira et al. (2014)	3 largest river basins in the Brazilian Cerrado	1. *P* (remote sensing, TRMM) 2. *ET* (remote sensing, MOD16) 3. TWSC (GRACE) $R = P - ET - \text{TWSC}$	*R* was overestimated due mainly to the overestimation of TRMM rainfall.
7. Armanios and Fisher (2014)	Usangu sub-basin of the Rufiji basin in Tanzania	1. *P* (remote sensing, TRMM) 2. *ET* (remote sensing, SRB/MODIS/AIRS-driven) 3. TWSC (GRACE) $R = P - ET - \text{TWSC}$	*R* was poorly correlated to available ground data and generally underestimated.
8. Wang et al. (2014)	Australian continent areas (with mean annual runoff < 10 mm/year)	1. *P* (remote sensing, TRMM) 2. *ET* (remote sensing, MODIS) 3. TWSC (GRACE) $\text{TWSC} = P - ET$	GRACE-TWSC was much less than *P*–*ET* over areas with mean annual runoff < 10 mm/year.
9. Long et al. (2015b)	Changjiang (Yangtze) River basin	1. *P* (remote sensing, TMPA) 2. *ET* (remote sensing, MOD16 and AVHRRNDVI-based) 3. TWSC (GRACE) $\text{TWSC} = P - R - ET$	Between the GRACE-TWSC and water budget estimated TWS change, the mean bias is 1.17 cm/month, and the RMSD is 1.46 cm/month.
10. Penatti et al. (2015)	Upper Paraguay River Basin	1. *P* (remote sensing, TRMM) 2. *ET* (remote sensing, MOD16) 3. TWSC (GRACE) $R = P - ET - \text{TWSC}$	*R* was greatly overestimated due mainly to the underestimation of *ET*.
11. This study	Yellow and Changjiang (Yangtze) River basins	1. *P* (in situ measurements and MSWEP) 2. *ET* (reconstructed using LSMoutput and water use data) 3. TWSC (GRACE) $R = P - ET - \text{TWSC}$	The estimation-to-observation ratios of *R* improved from 180.8% to 86.8% and from 67.0% to 101.1% over the YRB and CJB, after the *ET* reconstruction.

Note: TMPA: Tropical Rainfall Measuring Mission (TRMM) Multi Satellite Precipitation Analysis. CMORPH: CPC MORPHing technique. PERSIANN: Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks. GPCP: Global Precipitation Climatology Project. MODIS: Moderate Resolution Imaging Spectrora diometer, SRB: surface radiation budget, AIRS: Atmosphere Infrared Radiation Sounder. *W*: precipitable water. divQ: vapor flux divergence. ECMWF: European Centre for Medium-Range Forecasts.

(2010) and Penatti et al. (2015). Besides the natural instrumental errors, the human interventions (e.g., irrigation and inter-basin water diversion), which affect the terrestrial hydrological cycle (Long et al., 2015b; Lv et al., 2016) significantly over some river basins, have been paid little attention in the water budget closure analysis (Table 1). Panday et al. (2015) investigated the impacts of land cover change on water-balance key components (i.e., discharge, evapotranspiration, and soil moisture) based on numerical modeling and satellite observations of GRACE and MODIS, but they did not discuss human water use and whether the water budget is closed. Tang et al. (2013a) reported that the water diversion, reservoir regulation, and coal transport affect the mass variations largely in North China, but they also did not investigate these anthropogenic impacts on water budget closure. The necessity of considering irrigation and inter-basin water diversion in the water budget closure tests lies in the following two aspects.

First, water diversion can increase uncertainties in river basin outflows (Long et al., 2014). However, the inferred R_{total} from Eq. (1), which assumes no inter-basin water diversion, is usually compared with the in-channel streamflow at the basin outlet directly (Syed et al., 2005; Sheffield et al., 2009; Gao et al., 2010). As a result, there is a mismatch between the inferred R_{total} and the measured total basin discharge, and the terrestrial water budget cannot be closed without the consideration of the inter-basin water diversion.

Second, the irrigations are not well represented in currently available evapotranspiration (*ET*) products that are usually based

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