An assessment of terrestrial water storage, rainfall and river discharge over Northern India from satellite data

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Terrestrial water storage (TWS) plays a key role in the global water cycle and is highly influenced by climate variability and human activities. In this study, monthly TWS, rainfall and Ganga–Brahmaputra river discharge (GBRD) are analysed over India for the period of 2003–12 using remote sensing satellite data. The spatial pattern of mean TWS shows a decrease over a large and populous region of Northern India comprising the foothills of the Himalayas, the Indo-Gangetic Plains and North East India. Over this region, the mean monthly TWS exhibits a pronounced seasonal cycle and a large interannual variability, highly correlated with rainfall and GBRD variations ($r > 0.8$) with a lag time of 2 months and 1 month respectively. The time series of monthly TWS shows a consistent and statistically significant decrease of about 1 cm year^{-1} over Northern India, which is not associated with changes in rainfall and GBRD. This recent change in TWS suggests a possible impact of rapid industrialization, urbanization and increase in population on land water resources. Our analysis highlights the potential of the Earth-observation satellite data for hydrological applications.

Keywords: Earth-observation satellites, rainfall, river discharge, terrestrial water storage.

TERRESTRIAL water storage (TWS), a measure of all forms of water stored above and underneath the Earth's surface comprises of water stored in lakes, reservoirs, rivers, depressions, soils, aquifers, etc. and plays an important role in the hydrological cycle and climate variability[1–3]. It is also crucial for sustainable water resources management and food security. The lack of sufficient *in situ* data and the complexity of modelling the processes governing TWS are major limiting factors for the accurate estimation of its variability. With the launch of the Gravity Recovery and Climate Experiment (GRACE) twin satellite mission in March 2002, jointly by the National Aeronautics and Space Administration (NASA) and the German Aerospace Center (DLR), it is now possible to produce a comprehensive global map of water mass changes with unprecedented accuracy[4,5]. GRACE uses a microwave ranging system, highly sensitive to detecting separation changes, to measure accurately changes in the speed and distance between two identical spacecraft flying in a polar orbit about 220 km apart. It is able to sense precisely a small variation in Earth's gravitation pull and provides a detailed map of Earth's gravity anomalies which are used to estimate changes in TWS[2]. It has the advantage that it senses water stored at all levels, including groundwater and thus offers a unique opportunity to characterize the water balance at regional and continental scales.

GRACE data have been used for a wide range of applications over the continents and more specifically over India. For instance, Vishwakarma *et al.*[6] recently studied GRACE-derived mass changes during two major flooding events in India – the 2005 monsoon flooding in Mumbai and nearby states, and the major flood in Bihar in 2008. Moreover, it has been observed that the groundwater is decreasing over India under global change scenario[7]. The unremitting decline of groundwater, a ubiquitous source of potable water and irrigated agriculture, over Northern India in the last decade was noticed using GRACE observations and hydrological model output data[8–10]. Rodell *et al.*[9] showed that dwindling of groundwater over northwest India was not consistent with the changes in rainfall and other components such as soil moisture, surface water, snow, glaciers and biomass. However, rainfall is supposed to be one of the major factors that impacts the interannual variability of TWS[11–13]. With the availability of reasonable homogeneous rainfall data from multisatellite estimates, it is now possible to adequately characterize the contribution of rainfall on TWS variability over India. Moreover, GRACE data have undergone thorough retrospective processing and now offer a data record of more than one decade.

In this study, we examine the variability of TWS over India at seasonal and sub-seasonal scales for a ten-year period (2003–2012) from recently released upgraded monthly GRACE land data along with the associated variability and changes of satellite-derived rainfall and altimeter-based Ganga–Brahmaputra river discharge (GBRD).

The processed GRACE monthly mass grids land data based on the RL05 special harmonics from the Center for Space Research (CSR) – University of Texas, Jet Propulsion Laboratory (JPL) and GeoForschungsZentrum Postdam (GFZ) solutions at 1° lat./long. are used. Various suitable filters such as destriping filter, 200 km wide Gaussian filter, and special harmonics filter cut-off at degree 60 are applied on this dataset. The post-processed

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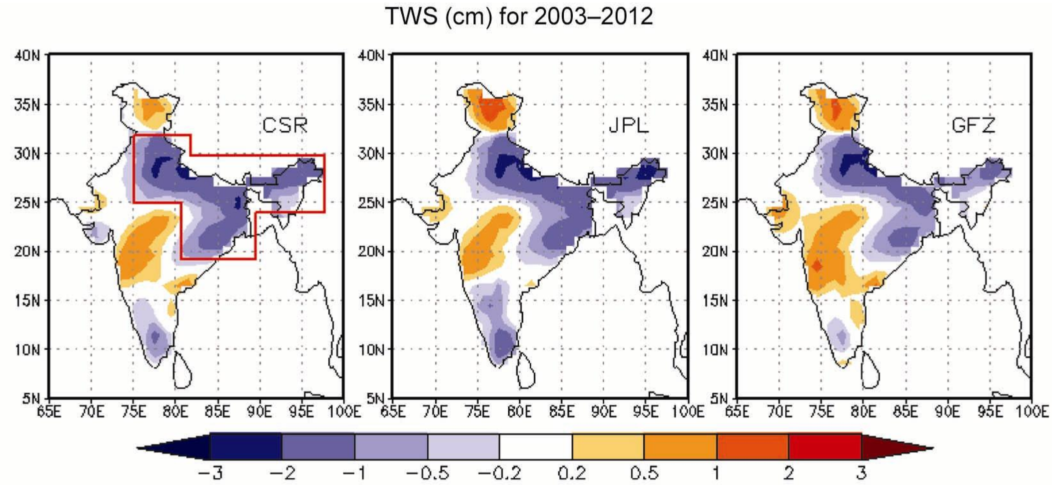

Figure 1. Spatial distribution of TWS from CSR, JPL and GFZ solutions over India averaged for 2003–2012. The red-coloured box shows the region used for detailed analysis in this study.

data are multiplied by scaling coefficients (provided with the dataset) which are independent of the GRACE data and intended to restore much of the energy removed by the filters to the land grids[5]. The monthly TWS data from 2003 to 2012 are used in this study. Data are missing for five months of June 2006, January and June 2011, May and October 2012 during the study period.

The monthly rainfall data used in this study are the Tropical Rainfall Measuring Mission (TRMM) Multi-satellite Precipitation Analysis (TMPA)-3B43. This rainfall product provides a reasonably good estimate of high-resolution (0.25° lat./long.) quasi-global precipitation from a variety of contemporary satellite-borne precipitation-related sensors and used for a wide range of applications[14]. This rainfall product recently underwent major revisions and consequently version 7 (V7) product was released, which performs better than its predecessor version 6 (ref. 15). TMPA-V7 product also performs better than other multisatellite rainfall products such as Climate Prediction Center Morphing (CMORPH), Naval Research Laboratory (NRL)-blended, and Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks (PERSIANN) over India[16]. Here, we use TMPA-3B43 research monitoring product V7 from 2003 to 2012. As the spatial resolution of TWS data is 1° lat./long. grid, the rainfall data are resampled in the same resolution and land-only data over India are considered.

We also use the monthly GBRD derived from a suite of radar altimeters, including Topex-Poseidon, ERS-2, Envisat and Jason-2 (refs 17, 18). In order to develop this database, *in situ* river discharge data measured at two gauging stations in Bangladesh (Hardinge (Ganges) and Bahadurabad (Brahmaputra)) are combined with altimetry water-level heights to estimate the Ganga–Brahmaputra continental freshwater flux into the Bay of Bengal. First, using a large sample of *in situ* river height measurements coming from the Bangladesh Water Development Board, altimeter-derived water levels over the Ganga and the Brahmaputra were thoroughly evaluated[17,18]. For instance, using Jason-2 observations, the uncertainty for both rivers was found to be less than ~ 4% of the annual peak-to-peak variations of the two rivers[18]. Finally, the combined Ganga–Brahmaputra monthly discharges meet the requirements of acceptable accuracy (15–20%) with a mean error of ~ 17% for the period 1993–2012. The Ganga–Brahmaputra monthly discharge at the river mouths shows a marked interannual variability with a standard deviation of ~ 12,500 $m^3 s^{-1}$, much larger than the dataset uncertainty.

The spatial distribution of mean TWS averaged for 2003 to 2012 from CSR, JPL and GFZ solutions is shown in Figure 1. TWS from these three solutions shows similar characteristics over India; however there is slight magnitude difference among them. Two areas of positive TWS, one located over the Northern hilly region (Jammu & Kashmir) and another over the west-central part of India, are seen. Moreover, two zones of negative TWS are also observed in the three solutions. Among them, one is over south peninsular India and another covering a large area of the country, including the foothills of the Himalayas, the Indo-Gangetic Plains and North East India (shown with red boundaries in Figure 1). In this large area, one of the most populous and industrialized regions of India, TWS shows negative values up to –3 cm. In the following, we focus our study on this region with maximum TWS decrease.

Figure 2 shows the mean monthly variations of TWS, rainfall and GBRD over the region of interest for the period 2003–2012. Lower TWS is observed in May; then it starts increasing from June, reaches a peak in September and gradually decreases during the dry season. All the three solutions show similar variations. This region receives considerable rainfall during pre-monsoon season (March–May) with maximum rainfall during July under

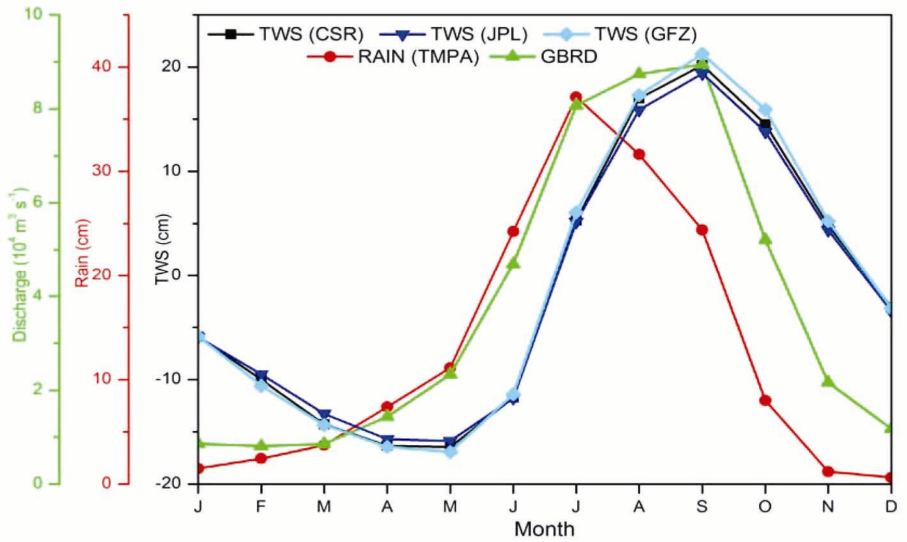

Figure 2. Monthly variations of mean TWS, rainfall and river discharge over Northern India.

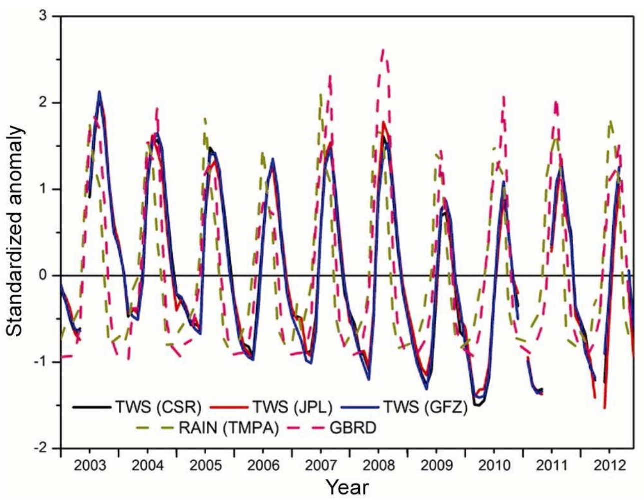

Figure 3. Interannual variations of standardized anomaly of TWS, rainfall and river discharge over Northern India.

the influence of peak southwest monsoon, which then decreases. The GBRD also shows a peak from July to September. Monthly mean variations in TWS, rainfall and GBRD clearly indicate a strong seasonality and confirm a strong relationship among them over this region.

The interannual variations of standardized anomalies of monthly TWS, rainfall and GBRD for the study period are shown in Figure 3. The standardized anomaly is computed by dividing the anomaly of individual months by their respective standard deviation based on the 10-year period data, defined by eq. (1) below.

$$\text{Standardized anomaly} = \frac{x_i - x}{\sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - x)^2}}, \quad (1)$$

where x_i is the value for a particular month, x the mean, and N (= 120 for this study) is the number of months for the study period. Standardized anomaly removes the influence of spread from data and is a dimensionless quantity.

The three solutions of GRACE-derived TWS show a similar variability with excellent agreement among them. Rainfall and GBRD also show close variability with TWS, but with certain lead/lag time. The lead/lag correlations of rainfall versus TWS, GBRD versus TWS, and rainfall versus GBRD are presented in Figure 4. TWS has the maximum correlation with rainfall, $r = 0.84$, with a lag time of two months, whereas it has peak correlation with GBRD, $r = 0.87$, with a lag time of one month. Rainfall and GBRD are also well correlated with a lead time of one month over the maximum TWS decrease region, which is commensurable with the earlier study by Papa *et al.*[17].

Finally, the changes in TWS over the maximum decrease region are examined for the study period. The time series of monthly TWS averaged over the region of interest (shown in Figure 1) is illustrated in Figure 5. It clearly shows a statistically significant decrease in TWS of ~0.1 cm month^{-1} (in all the three GRACE solutions). However, the associated rainfall over this region and GBRD do not exhibit any significant change during the same period. The changes in TWS, rainfall and GBRD are also investigated for the each month separately (Table 1). Whereas TWS consistently decreases irrespective of the season, rainfall and GBRD show almost no statistically significant changes during that period (despite showing negative and positive magnitudes of linear trend), except during October for rainfall (slight decrease) and in December and January for GBRD (increase). As already pointed out by Rodell *et al.*[9] for northwestern India groundwater, our analysis also reveals a consistent decrease in TWS over Northern India, which is not attributed to any rainfall changes. Thus, our study

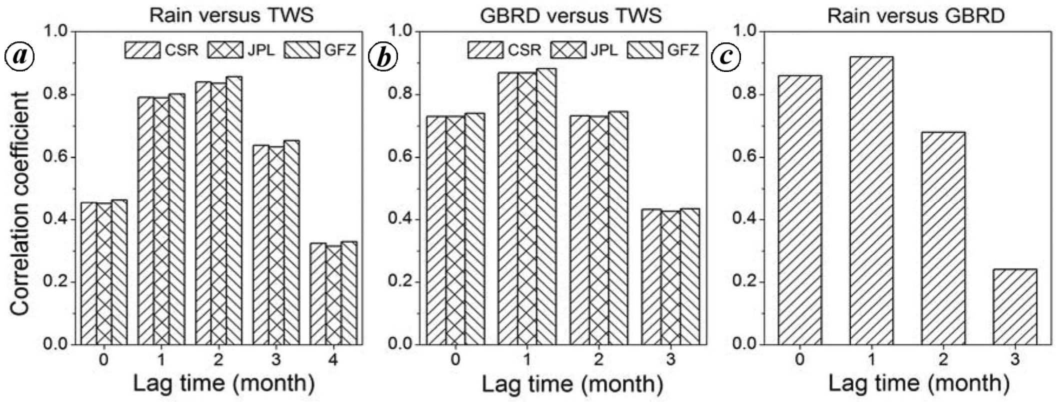

Figure 4. Lag correlations between (***a***) rainfall and TWS, (***b***) discharge and TWS, and (***c***) rainfall and discharge over Northern India.

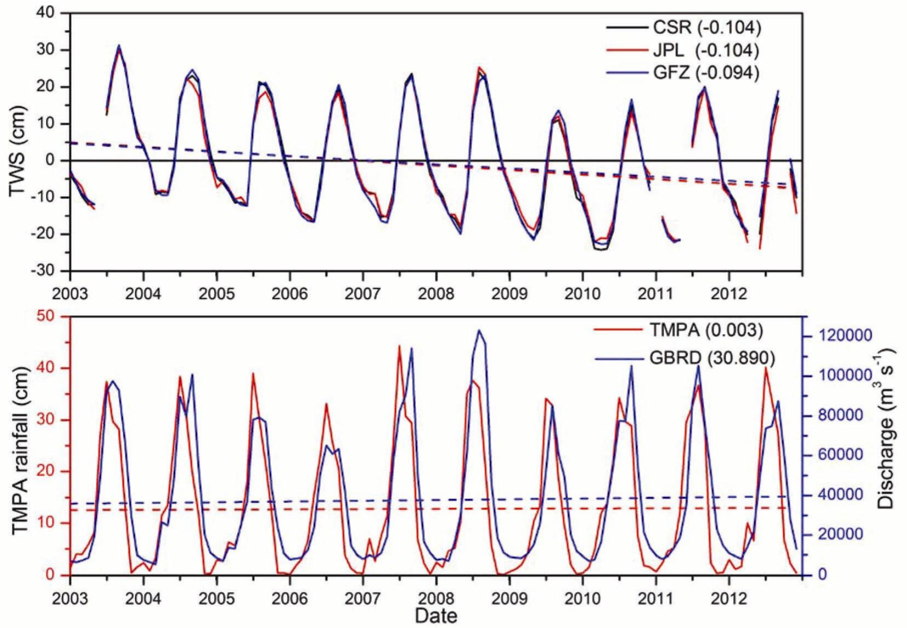

Figure 5. Time series of monthly TWS, rainfall and river discharge over Northern India for 2003–2012. Linear trends are shown by dashed lines and trend values are given in parentheses. The TWS trend values are statistically significant at 95% level, whereas the trend values of rainfall and GBRD are not statistically significant.

suggests that this decrease in TWS may possibly be associated with the effects of rapid urbanization, increasing population, agriculture expansion and industrialization.

Monthly TWS, rainfall and GBRD derived from the earth-observation satellite data are analysed over India for a 10-year period ranging from 2003 to 2012. The mean TWS showed a decrease over a large region of Northern India consisting of the foothills of the Himalayas, the Indo-Gangetic Plains and NE India. The mean monthly TWS over this region of maximum decrease exhibits a large seasonality in agreement with rainfall and GBRD variations. The interannual variability of monthly TWS, rainfall and GBRD indicates a close relationship among them. The TWS is highly correlated with rainfall and GBRD with a lag time of 2 months and 1 month respectively. In addition, the time series of monthly TWS shows a consistent and statistically significant decrease over Northern India, irrespective of the season, which is not associated with any observed changes in rainfall and GBRD. It suggests that this decrease in TWS may possibly be associated with the effects of human activities in a region facing rapid urbanization, increasing population, agriculture expansion and industrialization. The study clearly points out the need for accurate and long-term satellite-derived observations to monitor water resources, help in their better management and plan the necessary decision to cope with such anomalous decrease in TWS over a highly populated region. Our analysis will also be useful for future studies such as the one over Punjab and Gujarat which are experiencing problems with groundwater

Table 1. Linear trends of terrestrial water storage, rainfall and river discharge over Northern India for the period 2003–2012

Month	TWS (CSR)	TWS (JPL)	TWS (GFZ)	Rain (TMPA)	GBRD
January	**–1.057**	**–1.013**	**–1.188**	–0.046	**334.224**
February	**–1.313**	**–1.301**	**–1.461**	–0.175	204.285
March	**–1.467**	**–1.420**	**–1.448**	–0.130	20.897
April	**–1.485**	**–1.526**	**–1.439**	0.092	–152.952
May	**–1.773**	**–1.524**	**–1.682**	–0.120	78.079
June	**–2.246**	**–2.180**	**–1.500**	–0.036	–509.509
July	**–2.118**	**–2.255**	**–2.005**	–0.263	–1228.261
August	**–1.496**	**–1.742**	**–1.392**	0.612	427.921
September	**–1.207**	**–1.134**	**–1.146**	0.458	–538.079
October	**–1.870**	**–1.824**	**–1.732**	**–0.824**	–7.085
November	**–1.541**	**–1.389**	**–1.339**	0.143	36.812
December	**–1.723**	**–1.653**	**–1.367**	–0.022	**447.206**
Annual	**–1.528**	**–1.533**	**–1.418**	–0.026	–73.122

The units of TWS and rainfall trends are in cm $year^{-1}$ and that of river discharge is in $m^3 s^{-1} year^{-1}$. The trend at 95% significance level is indicated in bold.

extraction. Needless to say, more accurate discharge data from the recently launched Satellite with Argos and AltiKa (SARAL) satellite and advanced rainfall data from the synergistic use of INSAT-3D and Global Precipitation Mission (GPM) Core Observatory would essentially provide continued and improved database for hydrological and water resources management applications.

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