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Gravity Recovery and Climate Experiment (GRACE) detection of water storage changes in the Three Gorges Reservoir of China and comparison with in situ measurements

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[1] Water impoundment in the Three Gorges Reservoir (TGR) of China caused a large mass redistribution from the oceans to a concentrated land area in a short time period. We show that this mass shift is captured by the Gravity Recovery and Climate Experiment (GRACE) unconstrained global solutions at a 400 km spatial resolution after removing correlated errors. The WaterGAP Global Hydrology Model (WGHM) is selected to isolate the TGR contribution from regional water storage changes. For the first time, this study compares the GRACE (minus WGHM) estimated TGR volume changes with in situ measurements from April 2002 to May 2010 at a monthly time scale. During the 8 year study period, GRACE-WGHM estimated TGR volume changes show an increasing trend consistent with the TGR in situ measurements and lead to similar estimates of impounded water volume. GRACE-WGHM estimated total volume increase agrees to within 14% (3.2 km^3) of the in situ measurements. This indicates that GRACE can retrieve the true amplitudes of large surface water storage changes in a concentrated area that is much smaller than the spatial resolution of its global harmonic solutions. The GRACE-WGHM estimated TGR monthly volume changes explain 76% ($r^2 = 0.76$) of in situ measurement monthly variability and have an uncertainty of 4.62 km^3. Our results also indicate reservoir leakage and groundwater recharge due to TGR filling and contamination from neighboring lakes are nonnegligible in the GRACE total water storage changes. Moreover, GRACE observations could provide a relatively accurate estimate of global water volume withheld by newly constructed large reservoirs and their impacts on global sea level rise since 2002.

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1. Introduction

[2] The Gravity Recovery and Climate Experiment (GRACE) is a dedicated dual-satellite mission, launched in March 2002, to deliver monthly solutions of the spherical harmonic coefficients describing Earth's gravity field [*Tapley et al.*, 2004]. The temporal gravity changes in GRACE level 2 solutions are caused by a combination of redistribution of water, snow, and ice on land and in the ocean (ocean currents), postglacial rebound, and mass redistribution inside the Earth's crust and mantle and in the ocean after very large earthquakes. In general, the largest gravity signal observed in the GRACE solutions at seasonal time scales comes from changes in the distribution of water and snow on land [*Wahr et al.*, 1998]. So far, GRACE has already provided a wealth of new and useful hydrologic information [*Wahr et al.*, 2004; *Schmidt et al.*, 2006; *Syed et al.*, 2008]. GRACE observations of time-variable gravity fields have been widely used for estimating regional water storage variations in the Amazon [*Syed et al.*, 2005], Mississippi [*Rodell et al.*, 2004a; *Syed et al.*, 2005], Oklahoma [*Swenson et al.*, 2008], Ob [*Frappart et al.*, 2006], and the Yangtze [*Hu et al.*, 2006] river basins and for characterizing terrestrial moisture changes in the Canadian Prairie [*Yirdaw et al.*, 2008], groundwater withdrawal in India [*Rodell et al.*, 2009] and in California's Central Valley [*Famiglietti et al.*, 2011], glacier melting in Alaska [*Chen et al.*, 2006], and ice sheet mass loss in Greenland [*Velicogna and Wahr*, 2005, 2006] and Antarctica [*Velicogna et al.*, 2006; *Chen et al.*, 2009]. However, only a few of these studies compare GRACE satellite observations with in situ measurements to assess the accuracy of the GRACE solutions [e.g., *Rodell et al.,* 2004a; *Syed et al.*, 2005, 2007; *Swenson et al.*, 2006, 2008; *Yeh et al.*, 2006; *Longuevergne et al.*, 2010; *Famiglietti et al.*, 2011].

[3] The accuracy of GRACE estimates of water storage changes within a region depends on the GRACE measurement errors and contamination from mass variability in

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neighboring areas. Satellite measurement errors are the largest error component [*Swenson and Wahr*, 2002]. However, because of the lack of contemporaneous observations having the spatial coverage necessary to characterize terrestrial water storage variations at the GRACE spatial scale, evaluations of GRACE data are usually achieved through comparison with simulations from global water and energy balance models [*Chen et al.*, 2005; *Hu et al.*, 2006; *Schmidt et al.*, 2006; *Seo et al.*, 2006; *Wahr et al.*, 2006; *Syed et al.*, 2008], such as the H96 model [*Fan and Van den Dool*, 2004], the land dynamics model (LAD) [*Milly and Shmakin*, 2002], the WaterGAP Global Hydrology Model (WGHM) [*Döll et al.*, 2003], and the Global Land Data Assimilation System (GLDAS) [*Rodell et al.*, 2004b]. However, models have their own deficiencies and do not simulate anthropogenic water storage changes. Recently, *Swenson et al.* [2006] found a close agreement (root-mean-square difference (RMSD) of 20.3 mm) when directly comparing terrestrial water storage estimates from GRACE and from the combination of in situ measurements of soil moisture and groundwater in central Illinois. The combination of terrestrial observations with superconducting gravimeters and repeated absolute gravity measurements in Europe also offers another opportunity to evaluate temporal gravity field variations derived from GRACE [*Hinderer et al.*, 2006; *Neumeyer et al.*, 2008; *Crossley et al.*, 2009; *Weise et al.*, 2009].

[4] The impoundment of the Three Gorges Reservoir (TGR) in China can be viewed as a geophysical "controlled experiment" that is suitable for geophysical and geodetic studies [*Boy and Chao*, 2002]. The TGR is one of the largest hydroelectric reservoirs in the world. The volume and surface areas of impounded water in the reservoir can be obtained from a combination of dam level and topographic data [*Wang et al.*, 2005]. *Wang* [2000] simulates the surface vertical displacements caused by the filling of the TGR, and *Wang et al.* [2002] predict the induced surface horizontal displacements, gravity, and tilt changes. *Boy and Chao* [2002] even simulate the gravity changes related to different stages of the TGR water impoundment. *Wang et al.* [2007] use GRACE data to study the water storage changes for the upstream contributing areas of the TGR and compare to a hydrological model simulation. They conclude that the monthly water storage changes in these areas can be roughly determined from GRACE data, but they did not discuss the gravity and water storage changes caused by TGR water impoundment.

[5] TGR water impoundment has occurred during the time period since the 2002 launch of the GRACE mission. The volume of impounded water at maximum operational height (175 m above sea level) is 39.3 km^3. When spread over an area of 500 km $\times$ 500 km, a typical scale of analysis for GRACE studies, this volume equates to roughly 160 mm of equivalent water height, which is much larger than the estimated uncertainty of the monthly GRACE solutions at that resolution (17–38 mm depending upon whether or not correlated errors are removed from the solutions [*Swenson et al.*, 2006; *Swenson and Wahr*, 2006]). However, this mass change is concentrated on the much smaller TGR region, about 1000 km^2 of land area [*Wang*, 2000; *Wang et al.*, 2005]. *Zhong et al.* [2008] estimated an 8 mm yr^{-1} linear trend between April 2003 and January 2007 in the GRACE data caused by the reservoir filling as well as a 50 mm equivalent water height change after June 2003 within a region of 1.2×10^5 km^2.

[6] Ground measurements of TGR impounded water volume offer a unique opportunity to validate the temporal variations in water storage derived from GRACE observations. As far as we know, no previous studies compare the GRACE data with in situ reservoir volume change data, especially since the TGR was first filled to its near-full capacity in November 2008. Thus, this study tests the ability of GRACE unconstrained global solutions to detect gravity changes caused by TGR impounded water and evaluates GRACE estimates of the surface water storage changes against in situ measurements of TGR impounded water volume variations.

[7] GRACE mass anomalies in the GRACE footprint centered at the TGR mainly are a combination of (1) surface water (i.e., water stored in lakes, rivers, and reservoirs), (2) soil moisture, (3) groundwater, and (4) snow. At the seasonal time scale, the contribution of natural water storage (e.g., monsoon rainfall in this study) in the GRACE footprint is thought to dominate the GRACE total storage anomalies. In contrast, the anthropogenic surface water contribution from the TGR is expected to be the dominant factor affecting long-term variations of the GRACE solutions during the TGR impoundment and will be isolated from the natural variations simulated by a hydrological model. Therefore, from the GRACE total storage anomalies, we subtract simulated total water storage anomalies using a hydrological model that does not incorporate the TGR (e.g., WGHM), then convert the residual (GRACE − WGHM) equivalent water heights into volumes by multiplying by the footprint of our postprocessed GRACE solutions (i.e., $400 \times 400 = 1.6 \times 10^5$ km^2; see section 2.2). Finally, we compare these residual volumes with in situ TGR volume measurements. To summarize, our method consists of extracting the TGR signal whose spatial extent is smaller than the GRACE footprint but whose amplitude should be large enough to be detectable by GRACE. Hence, the implicit questions that we ask in this study are the following: can GRACE retrieve the true amplitudes of the TGR volume changes, even though their spatial extent is smaller than the resolution of the GRACE global gravity solutions? What is the uncertainty of such retrievals?

2. Study Area and Data Processing

2.1. Study Area and in Situ Data

[8] The Three Gorges Dam (TGD) currently stands at 185 m above sea level (~120 m above the downstream water level) and can hold 39.3 km^3 water, corresponding to a total inundated surface water area of about 976 km^2 along the middle reach of the Yangtze River and forming a stretch about 600 km long up to Chongqing and 1–2 km wide near the dam (Figure 1) [*Wang*, 2000]. The impoundment process has proceeded in three stages starting in June 2003, when the water level of the TGR rose from ~70 to 135 m and then reached 156 m on 27 October 2006 when the major construction of the dam (185 m) was finished (Figure 2). The water level reached 172.3 m for its first experimental maximum impoundment on 4 November 2008 and 171.4 m on 24 November 2009 and 174.91 on 25 October 2010. After 3 years of experimental maximum (~175 m)

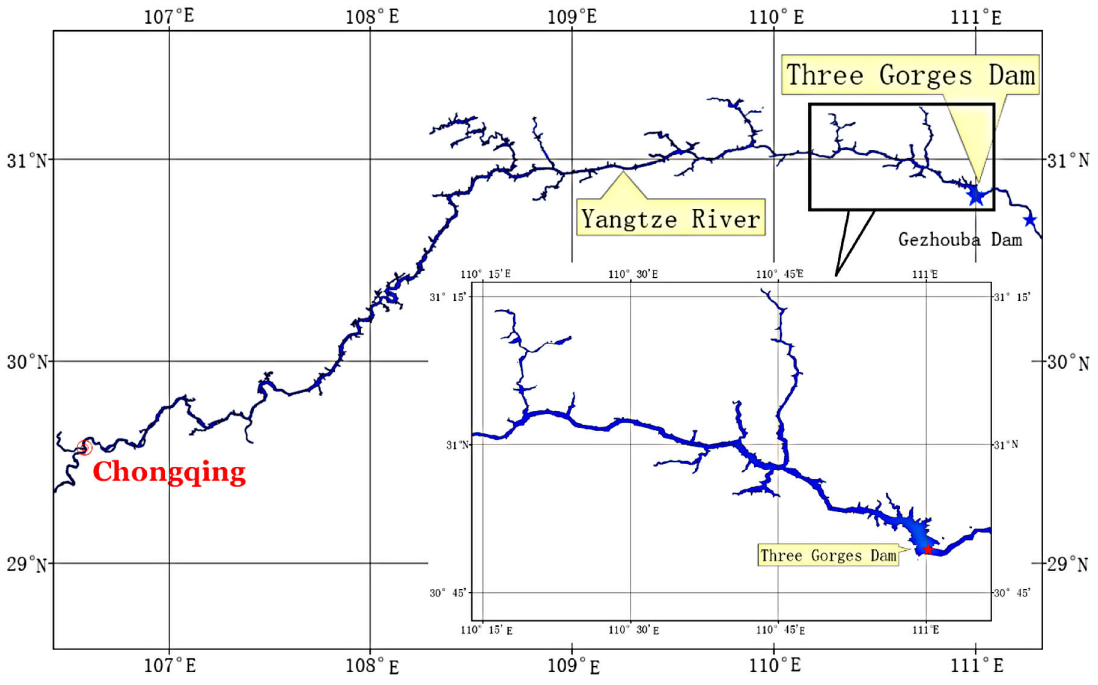

Figure 1. Study area and inundation map of China's Three Gorges Reservoir (TGR). At the maximum level (175 m), the impounded water stretches about 600 km along the Yangtze River from the TGD to Chongqing and covers about 976 km^2 on the basis of the NASA Shuttle Radar Topography Mission (SRTM) global elevation data (90 m spatial resolution). The inset inundation map is a close-up of the most downstream part of the reservoir at 175 m above sea level. About 40 km downstream from the Three Gorges Dam (TGD) is the first Yangtze River dam, Gezhouba Dam, which was first built in the late 1970s and whose second-phase project was completed in 1998. The total volumes of the Three Gorges and Gezhouba reservoirs are 39.3 and 1.6 km^3, respectively.

impoundment, reservoir levels in operational mode are ~175 m for power generation and navigation during winter months (from November to February), declining to 145–160 m with the gradual release of water for downstream irrigation and navigation in the spring (March–May) and for flood control during the monsoon season (June, July, and August). Impoundment begins again at the end of the flood season in September of each year.

[9] About 40 km downstream of the TGD is the oldest Yangtze River dam, the Gezhouba Dam, which was first constructed in the late 1970s and whose second phase was completed in 1998. The reservoir volume is ~1.6 km^3. The filling of this reservoir was completed before the GRACE mission. Thus, the impact of its water volume change on the GRACE gravity signal is relatively small (<4%) compared to the TGR.

[10] TGR water level, volume, inflow, and outflow information are obtained from the China Three Gorges Corporation (http://www.ctgpc.com.cn) and the Information Center of Water Resources (ICWR) (http://xxfb.hydroinfo.gov.cn). TGR volume and inflow data are reported four times daily (hourly in the flood season), and water level and outflow data are reported hourly. They are converted into monthly values by a simple arithmetic average. Uncertainties of the water level and volume data are 0.01 m and 0.1 km^3, respectively, according to the reported precision. Volume V (km^3) and water level H (m) data follow a power law relationship ($V = 0.2968 \times 1.0284^H$, $r^2 = 0.999$; Figure 2) when the water level is above 135 m. TGR volume data are not available for water levels less than 135 m and are then derived from water level data through this power law relationship. This study only uses the volume data. No groundwater data are available for use in this study.

[11] We also compared the reported TGR water volume data with volume values calculated from the inflow and outflow data and from the area and water level changes during reservoir filling from 145 to 172 m from September to November in 2008 and from September to October in 2009. Our calculated volume values (from both inflow-outflow data and area water level changes) have a linear fit with the reported volume data by r^2 of 1 and a mean absolute difference (MAD) of 0.1–0.3 km^3, which indicates that measured volume data errors are in the range 0.1–0.3 km^3 and are much smaller than the GRACE estimate uncertainties [*Swenson et al.*, 2006; *Swenson and Wahr*, 2006].

2.2. Grace Data

[12] We use the level 2 release 4 unconstrained GRACE solutions from April 2002 to May 2010 computed by the Center for Space Research at the University of Texas at Austin and provided as monthly sets of Stokes coefficients up to harmonic degree 60, corresponding to a 333 km spatial resolution. We replace the very large scale component of the gravity field (degree 2 zonal Stokes coefficient) by more accurate satellite laser ranging estimates [*Cheng and Tapley*, 2004]. We then convert the Stokes coefficients

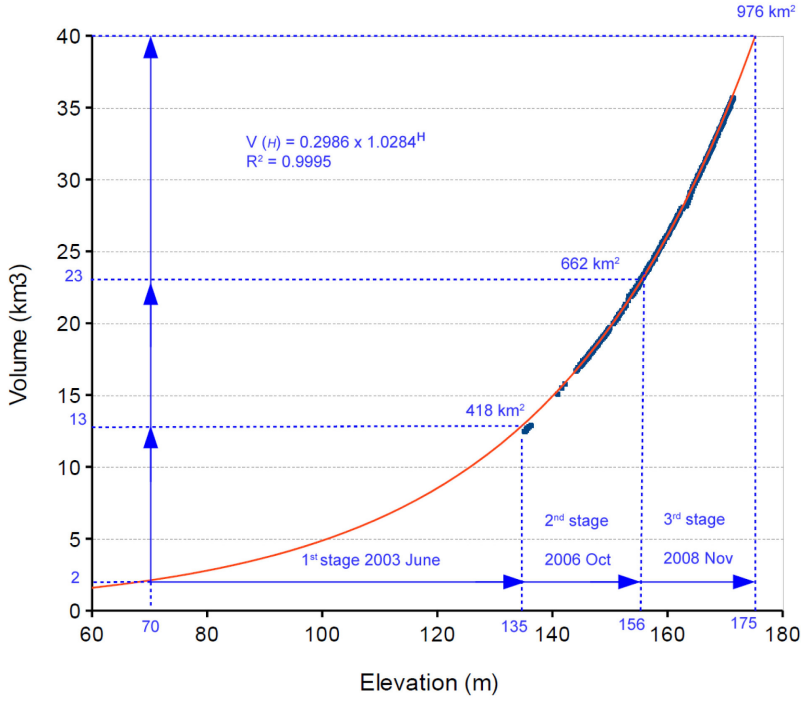

Figure 2. Power law relationship of in situ reported water volume and water level values in the TGR and the inundated area derived from SRTM digital elevation map data at water levels of 135, 156, and 175 m, which represent the three stages of TGR water impoundment that started in June 2003, October 2006, and November 2008.

defining the geopotential into equivalent water height anomalies [e.g., *Wahr et al.*, 1998].

[13] We apply the method of *Swenson and Wahr* [2006] to remove correlations among Stokes coefficients that produce north-to-south oriented stripes distinctive in raw GRACE spherical harmonic solutions. We use the same filter parameters as *Swenson and Wahr* [2006] that are explicitly provided by *Duan et al.* [2009]. We only keep the coefficients of degrees lower than 51, i.e., half wavelengths larger than 400 km, as it is not possible to decorrelate higher-degree coefficients. We do not apply any additional smoothing that would degrade the spatial resolution of our solutions, and we do not apply any scaling factor to our solutions. Whereas the decorrelation filter affects the regional hydrological signal, its impact on the TGR signal is likely to be negligible since the reservoir stretches mostly in the east-west direction, while the filter is designed to remove signals that are correlated in the north-south direction that is orthogonal to the reservoir axis [*Swenson and Wahr*, 2006].

[14] Our processed GRACE solutions agree with the publicly available level 3 GRACE solutions such as those from the University of Colorado (CU) at the 81% level with an $r^2 = 0.81$ (see auxiliary material Figure S1).[1] Our GRACE solutions are smoother than the CU ones with smaller amplitudes in winter and summer, particularly in fall 2004 since our GRACE decorrelated solutions are not scaled, in contrast to CU's level 3 solutions. The intrinsic resolution of our postprocessed GRACE solutions is about 400 km (~20,000/51), and the GRACE footprint size is thus 400 km × 400 km = 1.6×10^5 km^2. We compute the GRACE solutions on a 1° × 1° grid. The results we report represent the time series centered at 111°E, 31°N, which are assumed to represent water storage averaged over an area of 1.6×10^5 km^2 and are the optimal agreements with TGR in situ measurements compared to those at other grids.

2.3. Hydrologic Model Data

[15] We test different hydrological models to obtain the optimal simulation of the total water storage (TWS) changes without the reservoir storage: (1) the joint National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) global reanalysis project spanning from 1948 to present [*Kalnay et al.*, 1996] using a simple coupled soil model [*Mahrt and Pan,* 1984], (2) the WaterGAP Hydrological Model [*Döll et al.*, 2003; *Guentner et al.*, 2007], and (3) the Global Land Assimilation System [*Rodell et al.*, 2004b] using the Noah land surface model. GLDAS uses many ground and satellite observations to parameterize the Noah land surface model.

[16] WGHM is a conceptual model that is calibrated against discharge measurements [*Hunger and Döll*, 2008], whereas the GLDAS/Noah and NCEP/NCAR models are land surface models that are typically uncalibrated. The NCEP/NCAR model is a coupled land-atmosphere model with a simplified land component acting as a boundary condition, and the GLDAS/Noah and WGHM models are run in off-line mode and are forced by atmospheric data but have a more sophisticated land surface representation that is constrained by many ground and satellite observations.

[1]Auxiliary materials are available in the HTML. doi:10.1029/2011WR010534.

[17] GLDAS/Noah simulated TWS anomalies lag GRACE TWS anomalies by 1 month and show a very small mean annual variation (see auxiliary material Figure S2). NCEP predictions display a mean annual cycle that agrees quite well with that of GRACE, although their interannual variations are weak, as identified by *Rodell and Famiglietti* [1999], and therefore overestimate the soil moisture during the 2006 drought period. WGHM TWS anomalies are best correlated to GRACE, with their mean annual peak occurring in August, have a mean annual amplitude similar to GRACE, and display interannual variability, e.g., in 2006 August. As WGHM seems to more reliably simulate TWS interannual variations and agrees better with GRACE than NCEP/NCAR and GLDAS/Noah in the TGR area, we use WGHM TWS to extract the reservoir signal from the GRACE TWS solutions.

[18] The differences among model simulations can be explained by at least two factors. The first one is the precipitation data set used to force the model. WGHM is forced by a combination of Global Precipitation Climatology Centre monthly 1° precipitation, which includes rain gauge measurements and European Centre for Medium-Range Weather Forecasts analyses. On the other hand, GLDAS/Noah is forced by the 2.5° Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP) satellite products downscaled using Atmospheric General Circulation Model (AGCM) simulation outputs. NCEP/NCAR precipitations are AGCM outputs and are not assimilated by any observations. Precipitation errors are one of the largest causes of error in hydrological modeling [e.g., *Oki et al.,* 1999; *Ngo-Duc et al.*, 2005] and gauge-based products are more reliable than satellite and AGCM-derived products. In the TGR dam neighboring areas, errors in snow water equivalent due to inaccurate snowfall estimates are likely to contribute to the error budget as well.

[19] The second factor is the land surface model. As mentioned, the land surface parameterization of the WGHM and GLDAS/Noah models is much more sophisticated than that of the NCEP/NCAR model. For example, some storage components are sometimes missing in the NCEP/NCAR model, while surface water storages in rivers, lakes, wetlands, and some reservoirs as well as groundwater storage are simulated by WGHM. In the TGR area, WGHM predictions do not account for the reservoir impoundment because the TGR is not included in the Global Lakes and Wetlands Database used by WGHM [*Lehner and Döll,* 2004].

[20] Global monthly precipitation used here are CMAP from the Physical Sciences Division, Earth System Research Laboratory, NOAA, Boulder, Colorado (http://www.esrl.noaa.gov/psd/), available on a 2.5° global grid [*Xie and Arkin*, 1997]. A four-grid average in the TGR area is used in this study in order to match the GRACE resolution. The CMAP precipitation data are not used in the direct calculation or comparison with GRACE mass anomalies but are shown in order to help interpret the results since gauge data are only available in 2003–2008 for some reason. According to *Biemans et al.* [2009], the representation of seasonality at monthly scales from seven global precipitation products including CMAP is similar and has a precipitation uncertainty of 30% in a basin. The monthly CMAP precipitation data can explain near 90% of precipitation seasonality and 60% of monthly time series from gauge measurements in the TGR areas from 2003 to 2008 (see auxiliary material Figure S3).

3. Method

[21] TWS from WGHM are used to isolate the TGR signal from the GRACE solutions. Before subtraction from GRACE TWS, the WGHM TWS simulations are processed using the same method that was applied to process the GRACE level 2 solutions. We then convert the residual (GRACE − WGHM) equivalent water heights into volumes by multiplying by the footprint of our postprocessed GRACE solutions (i.e., 400 km × 400 km = 1.6×10^5 km^2). The residual volumes thus represent the TGR impoundment signal and are compared with in situ TGR volume measurements.

[22] The accuracy of GRACE solutions is usually assessed by comparison to model simulations or to in situ measurements that are spatially averaged over the same domain since GRACE solutions are averaged over regions that are larger than the GRACE footprint using an averaging kernel designed to minimize leakage [*Swenson and Wahr*, 2003; *Swenson et al.,* 2006; *Frappart et al.*, 2006; *Hu et al.*, 2006; *Velicogna and Wahr*, 2006; *Weise et al.*, 2009, *Rodell et al.*, 2009]. In this study, as mentioned, TWS from WGHM are used to isolate the TGR signal from the GRACE solutions, and the residual is compared to in situ measurements. Thus, we estimate the accuracy of both the GRACE global solutions and WGHM simulation.

[23] In order to estimate the combined uncertainties of GRACE and WGHM estimates of the TGR water volume, we choose eight pairs of the same months (November or December) of two distinct years, when the TGR volume is nearly the same, to compute GRACE-WGHM estimated reservoir volume changes. Thus, their RMSD or MAD may be taken as the uncertainty of GRACE-WGHM estimated reservoir volume changes.

[24] In addition, we compare the volume differences during optimal months (October, November, and December) when there is much less rainfall, little snow, and TGR is at the highest water level and during four periods, June 2002 to May 2003, June 2003 to May 2006, June 2006 to May 2008, and June 2008 to May 2010, which represent the prefilling and the first, second, and third stages of reservoir filling, respectively. These periods are chosen to cover multiples of complete years so that the averages are not biased by changes in seasonal time periods. So our last two stages start a few months earlier than the actual reservoir filling stages. The missing GRACE data in June and July 2002 and June 2003 are linearly interpolated using data from the neighboring months. The GRACE-WGHM estimated volume differences between two consecutive periods are then compared with the in situ measured TGR volume changes. A singular spectrum analysis (SSA) [e.g., *Ghil et al.,* 2002] with a 4 month correlation lag is used to low-pass filter the raw GRACE-WGHM by separating the long-period variations (contained in the first mode of the analysis) from the high-frequency stationary noise at periods smaller than or equal to 4 months. This filtering leads to a smoother time series that reduces 21% of the original variance while causing little change in the long-term variations (see auxiliary material Figure S4). Although this filter significantly improves the

agreement between GRACE-WGHM estimates and TGR measurements at the monthly scale, the corresponding comparison numbers used in this study are those calculated from the unfiltered data.

4. Results

4.1. Climatic Monthly Means

[25] Precipitation in the TGR area is mainly concentrated in May–August (~60% of annual total) and is well correlated with 2 month lagged GRACE TWS anomalies (Figure 3a). This suggests that precipitation is the controlling factor for total water storage variations in the summer months in the TGR area. GRACE-observed and WGHM-estimated total water storage anomalies have seasonal cycles similar both in amplitude and phase before 2006 (Figure 3a), with the annual peaks delayed by about 1 or 2 months with respect to the rainfall annual peak since water storage is correlated to cumulative precipitation. For the 2002–2005 period, when the TGR is only filled to the first stage at ~135 m with a reservoir water volume of ~13 km^3 (Figure 3a), the TGR outflow almost equals the inflow (except in June 2003, when TGR started its first filling stage) because the TGR remained at a nearly constant level until the second-stage filling that started in late 2006. Inflow, outflow, and GRACE TWS annual peaks all occur between July and September. In contrast, when the TGR is filled to ~172 m (~36 km^3) for the 2008–2010 period (Figure 3b), the outflow is smaller than the inflow during the filling months of September and October and larger than the inflow in the following months from January to May, when water stored in the reservoir is released for power generation and downstream irrigation and navigation, while creating storage for flood control for the following June to August flood season. The amount of water stored in the TGR is also reflected in the GRACE mass anomalies, whose 2008–2010 average is significantly larger than the 2002–2005 average and whose 2008–2010 seasonal variation amplitude is less than the 2002–2005 seasonal variation amplitude, with a secondary peak appearing in November when the TGR is at its full operational level (Figures 3a and 3b).

4.2. Comparison between GRACE and TGR Volumes

[26] The 2006 drought signal in the TGR area is present in the CMAP rainfall data and GRACE and WGHM TWS anomalies (Figure 4a). According to the NCEP reanalysis data (not shown), the snow water equivalent (SWE) in the TGR area is usually less than 3 mm in winter months, such as January and February (except in January of 2008, when SWE was 12 mm). Thus, SWE variation in the TGR area is only a small part of the total mass variations in winter months and is negligible in other months. Therefore, the optimal time for evaluating the GRACE solutions relative to the in situ measurements of water volume in the TGR area is in October, November, and December, when there is much less precipitation and little snow and TGR is at the highest water level.

[27] The GRACE time series for the TGR area before (Figure 4a) and after (Figure 4b) subtracting WGHM TWS anomalies displays an overall increasing trend correlated to the TGR three-stage filling. In contrast, WGHM TWS anomalies do not display any trend, indicating no storage increase in regional hydrology without considering the TGR. Thus, the increasing trend in the residuals (ΔGRACE – ΔWGHM) is related to the TGR impoundment (Figure 4b). The impounded water at each of the three TGR filling stages is estimated as the difference between the averaged water volumes computed for the following four consecutive periods, June 2002 to May 2003, June 2003 to May 2006, June 2006 to May 2008, and June 2008 to May 2010, which

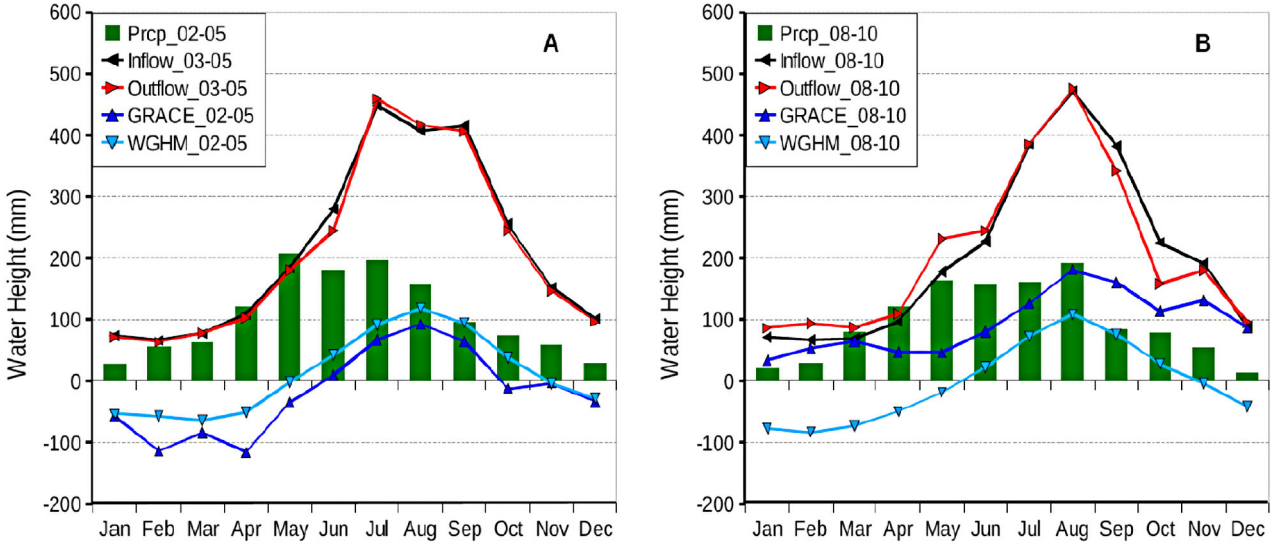

Figure 3. Climatic monthly mean precipitation from Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP), inflow, outflow, Gravity Recovery and Climate Experiment (GRACE), and WaterGAP Global Hydrology Model (WGHM) mass anomalies in equivalent water height (mm) in the TGR area computed for two periods: (a) 2002–2005 and (b) 2008–2010. The inflow and outflow are converted into equivalent water height (mm) within a month over an area of 400 km × 400 km centered at 111°E, 31°N. Original GRACE, WGHM, and precipitation data are displayed in Figure 4.

represent the prefilling and the first, second, and third filling stages, respectively (Figure 4b). To reduce uncertainties associated with modeling the regional hydrological signal, the comparison periods are chosen to cover multiples of complete years so that the averages are not biased by changes in seasonal time periods. A SSA low-pass filter reduces 21% of the GRACE-WGHM estimate variances and provides a smoother time series but causes little change in the long-term volume increases (Figure 4b). Although this filter significantly improves the agreement between GRACE-WGHM estimates and TGR measurements at the monthly scale (Figure 5), with r^2 values increasing from 0.66 and 0.76 to 0.81 and 0.91 for all data and for data in the optimal months (October–December), respectively, the

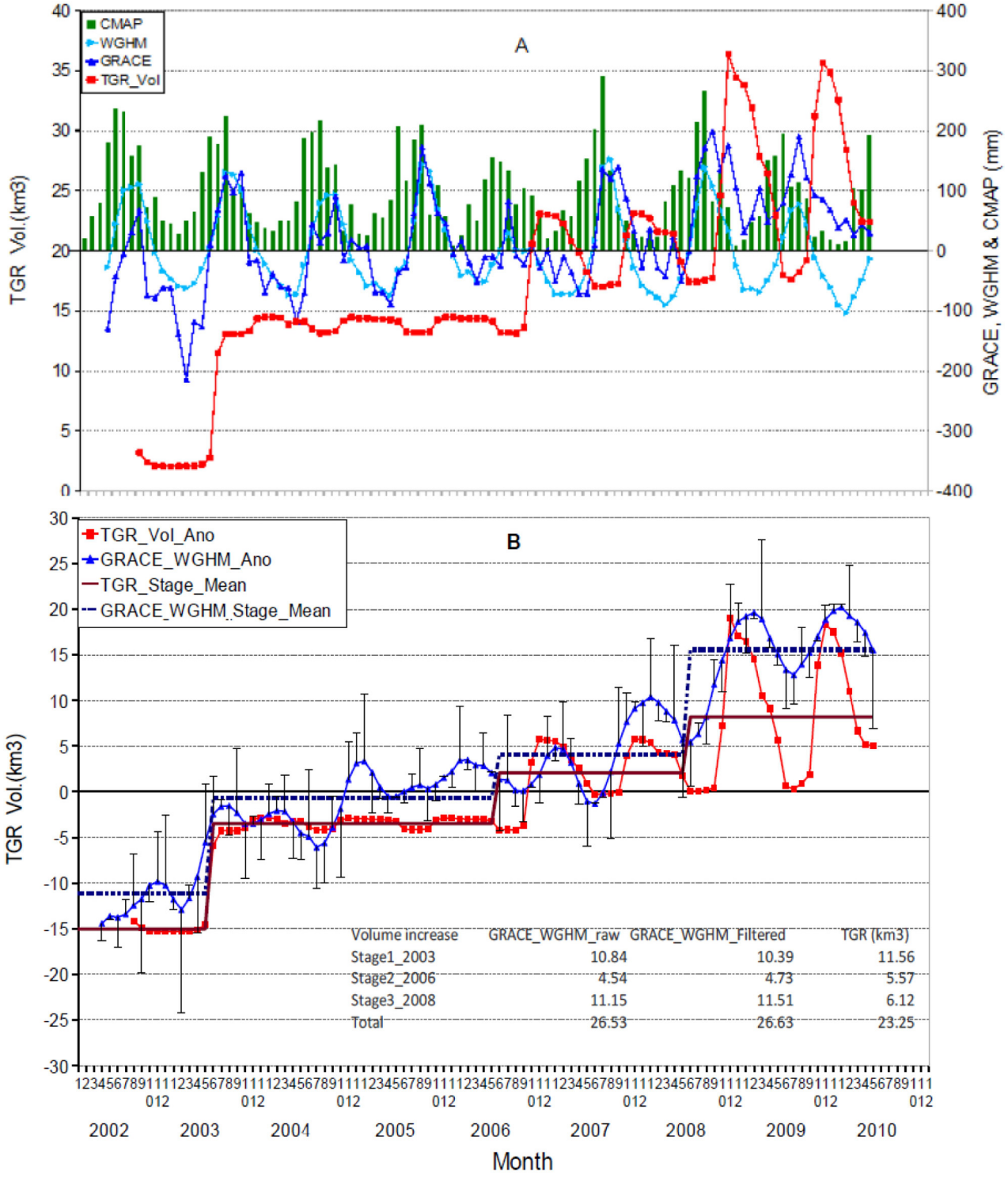

Figure 4

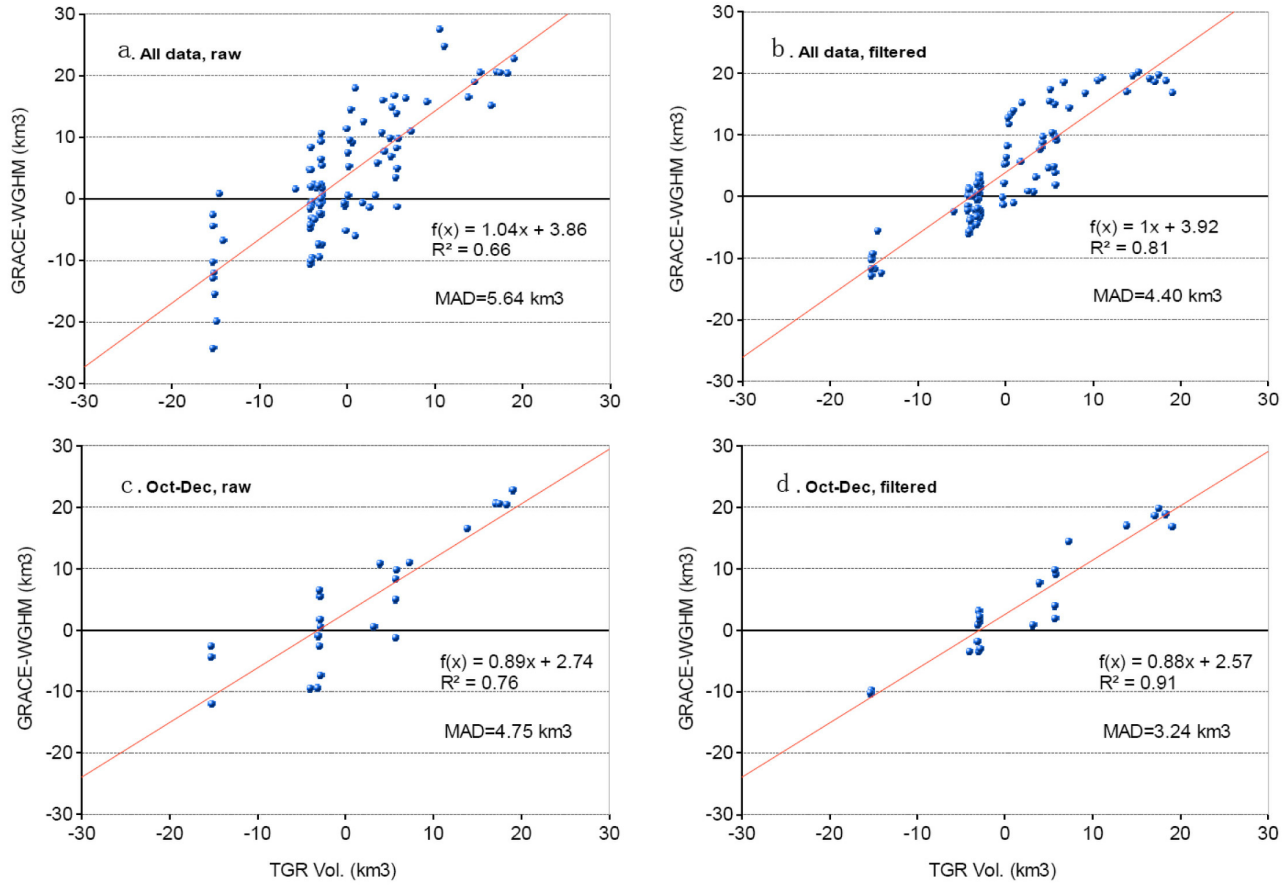

Figure 5. Comparison of raw and filtered GRACE-WGHM estimates of Three Gorges Reservoir's water storage changes with in situ measurements. A singular spectrum analysis (SSA) technique using a 4 month correlation lag is used to low-pass filter the raw GRACE-WGHM estimate by isolating the first mode from the high-frequency noise. Raw means that the GRACE-WGHM estimates are the original data, and filtered means that the GRACE-WGHM estimates are smoothed by the SSA technique. (a and b) All data from April 2002 to May 2010. (c and d) The optimal months of October, November, and December from 2002 to 2009.

corresponding comparison numbers and uncertainty analysis used in this study are conservatively preferred to those calculated from the unfiltered data.

[28] The impounded water volume during the first filling stage in June 2003 estimated from GRACE-WGHM and from TGR in situ data are 10.84 and 11.56 km^3, respectively. Both are fairly close to the 8 km^3 (50 mm) obtained by *Zhong et al.* [2008], who use a different processing strategy. GRACE-WGHM estimates (4.54 km^3) for the water volume increase during the second filling stage in 2006 are slightly less than TGR in situ data (5.57 km^3). GRACE-WGHM data (11.15 km^3) yield a much larger increase than TGR (6.12 km^3) in the third filling stage in 2008. This much larger increase in GRACE-WGHM mass anomalies might indicate a large quantity of discharge from the TGR to the underlying groundwater (i.e., leakage to neighboring areas and increased groundwater recharge from the bottom of the TGR) once the TGR has reached its maximum capacity.

Figure 4. (a) Monthly rainfall (mm) from CMAP, total water storages from WGHM (without considering TGR), GRACE mass anomalies over an area of 400 km × 400 km centered at 111°E, 31°N, and TGR in situ measurements of water volume (km^3). (b) GRACE-WGHM estimated surface water residuals (ΔGRACE − ΔWGHM) and TGR in situ water volume anomalies and their mean values for four periods: June 2002 to May 2003, June 2003 to May 2006, June 2006 to May 2008, and June 2008 to May 2010, which represent the prefilling and the first, second, and third stages of TGR water filling, respectively. These periods are chosen to cover a number of years so that the averages will not be biased by the hydrologic seasonal cycle. The error bars (Figure 4b) are the differences of raw GRACE-WGHM and filtered GRACE-WGHM estimates. GRACE and WGHM estimated water height anomalies are converted to volume anomalies by multiplying by a constant area of 400 km × 400 km. The volume increase in the inset table (Figure 4b) is the difference of mean volumes between two consecutive stages for both raw and filtered GRACE-WGHM estimates as well as for in situ estimates.

These losses from the TGR are not accounted for in the WGHM estimates. If we consider the reservoir long-term volume change, i.e., the difference between the first and last stages, the error is 3.2 km^3, or 14% relatively.

[29] After 2008 the TGR volume changes exhibit a seasonal cycle whose amplitude becomes stronger as the TGR water storage approaches maximum. A significant increase in correlation and amplitude match is found as the WGHM estimated regional total water storage is subtracted from the GRACE TWS, demonstrating that the TGR impounded water signal is embedded in the GRACE signal (Figure 4b). However, even though WGHM leads to the best agreement with GRACE TWS, the GRACE-WGHM estimated surface mass anomalies have greater variability than the TGR water volume changes. Soil moisture changes and floods caused by frequent heavy monsoonal precipitation in the summer months and SWE changes in winter months, which might increase the uncertainty of WGHM predictions, are likely the main factors explaining the larger difference (ΔGRACE − ΔWGHM − ΔTGR) during these months. For example, out of the 11 months with volume difference larger than 10 km^3 after June 2003, 6 months are in January and September. In January 2008, when a heavy snow fell in the area, the GRACE-WGHM surface water storage estimate is 11.42 km^3 larger than TGR in situ measurements.

[30] The GRACE-WGHM monthly mass anomalies explain 66% ($r^2 = 0.66$) of TGR in situ monthly measurements with a MAD of 5.64 km^3 when using all months since 2002, while they explain up to 76% ($r^2 = 0.76$) with a MAD of 4.75 km^3 when only considering the optimal months of October, November, and December in each year (Figures 5a and 5c). After applying the SSA low-pass filter, GRACE-WGHM estimates can explain 81% and 94% of the TGR in situ measurements and have MADs of 4.40 and 3.24 km^3 for all months and for the optimal months, respectively (Figures 5b and 5d).

[31] To assess uncertainties of GRACE-WGHM estimated monthly surface water changes, we analyze eight pairs of months (November or December) in different years when the TGR volume changes are near zero. Thus, the GRACE-WGHM estimated mass differences in these months can be used as an estimate of the GRACE and WGHM combined monthly uncertainty. During those periods, the MAD of water height and volume is 29 mm and 4.62 km^3, with RMSD of 30 mm and 4.83 km^3 (Table 1), respectively. After applying the SSA low-pass filter, GRACE-WGHM estimate uncertainties can reduce to 11 mm and 1.69 km^3 (MAD) or 13 mm and 2.06 km^3 (RMSD).These are fairly comparable to the reported GRACE uncertainties of 17 mm and 4.25 km^3 for solutions at 500 km resolution [*Swenson and Wahr*, 2006] and to the MAD values of 4.75 and 3.24 km^3 (filtered) for the optimal comparison periods shown in Figures 5c and 5d.

[32] Finally, Figure 6 shows the spatial pattern of GRACE-detected mass anomalies between the final stage (June 2008 to May 2010) and the prefilling stage (June 2002 to May 2003) in the TGR area. The mass (water height or volume) difference between the two stages is roughly 175 mm or 28 km^3, similar to estimates in Figure 4b (166 mm or 27 km^3 in an area of 400 km × 400 km). The positive mass anomalies to the northeast of the TGR may come from tens of newly constructed hydropower reservoirs in the Jianghan Plains in the past decade. The Danjiangkou Reservoir (32.55°N, 111.49°E) is the largest one of these reservoirs. Its first stage was completed in the 1970s. The second stage began in 2005 and will increase the regular water volume from 17.4 to 29.0 km^3 and flood season water volume from 7.6 to 12.7 km^3 after completion in 2012 [*Hu and Dong*, 2010].

5. Discussion

[33] In validating GRACE solutions against ground measurements, the spatial scale difference between the large footprint of GRACE data versus the local nature of in situ observations is a challenging and unavoidable problem. When we convert a GRACE water height anomaly into a water volume change, we multiply it by a constant area corresponding to our postprocessed GRACE footprint size of 400 km × 400 km = 1.6×10^5 km^2. This constant area corresponds to the minimum half wavelength that is embedded in our postprocessed unscaled GRACE solutions or to a maximum spherical harmonic degree of 51. Similarly, when we convert TGR volume into water height, we divide the water volume using the same constant area. The GRACE footprint size does not affect the relative agreement between GRACE-estimated volumes and TGR in situ measurements,

Table 1. Uncertainties of GRACE-WGHM Estimated Surface Water Storage Changes (ΔGRACE − ΔWGHM) in Eight Pairs of Months When in Situ TGR Volume Changes Are Near Zero[a]

	ΔTGR Volume (km^3)	Raw ΔGRACE − ΔWGHM − ΔTGR (mm)	Raw ΔGRACE − ΔWGHM − ΔTGR (km^3)	Filtered ΔGRACE − ΔWGHM − ΔTGR (mm)	Filtered ΔGRACE − ΔWGHM − ΔTGR (km^3)
Dec 2002 minus Nov 2002	−0.03	11.22	1.82	−2.55	−0.41
Nov 2004 minus Nov 2003	0.11	50.71	8.01	23.2	3.71
Nov 2005 minus Nov 2003	0.11	27.32	4.26	24.51	3.92
Nov 2005 minus Nov 2004	0.00	−23.39	−3.74	1.3	0.21
Nov 2007 minus Nov 2006	0.08	69.23	11.00	−3.33	−0.53
Nov 2009 minus Nov 2008	−0.71	36.06	6.48	−10.39	−1.66
Dec 2009 minus Dec 2008	0.44	−0.62	−0.54	4.65	0.74
Dec 2007 minus Dec 2006	0.03	6.90	1.08	14.47	2.31
Mean absolute difference		29	4.62	11	1.69
Root-mean-square difference		30	4.83	13	2.06

[a]Raw means that the GRACE-WGHM estimates are not smoothed by the singular spectrum analysis (SSA) low-pass filter, and filtered means that the GRACE-WGHM estimates are smoothed by the SSA low-pass filter in a 4 month time window.

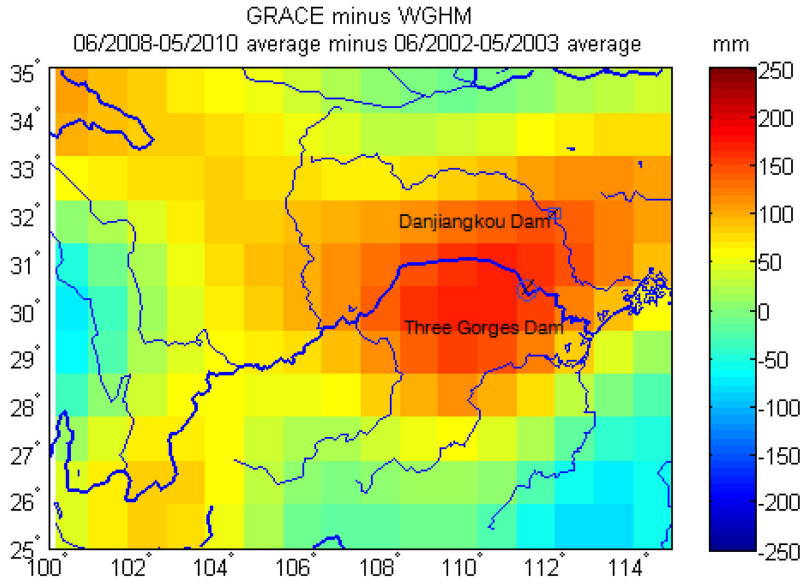

Figure 6. GRACE-WaterGAP (WGHM) estimated mass anomaly differences between the third (full) filling stage (June 2008 to May 2010) and the prefilling stage (June 2002 to May 2003) in the Three Gorges Reservoir area. The circle is the location of the Three Gorges Dam (reservoir), and the square is the location of the Danjiangkou Dam (reservoir). The blue lines are streams.

such as the r^2 value in Figure 5. Of course, it directly affects the GRACE estimated volumes, so that using a footprint size of 400 km × 400 km may underestimate the true TGR volumes. However, our GRACE estimated volumes generally have larger values than the in situ measurements. This invalidates the previous hypothesis and confirms the possibility of an increase in groundwater storage.

[34] Vertical separation of GRACE solutions is another challenging problem when comparing GRACE data with in situ measurements, which usually only include one or two components of the GRACE terrestrial TWS, e.g., soil moisture and groundwater storage [*Rodell and Famiglietti*, 2001; *Swenson et al.*, 2006, 2008; *Yeh et al.*, 2006], or surface water storage [*Frappart et al.*, 2008; this study]. Since we only have the in situ measurements of TGR water volume (surface water), we subtract the TWS anomalies (without a reservoir representation) simulated by WGHM (Figure 4b) from the GRACE TWS anomalies (implicitly containing the reservoir water storage changes) to estimate the TGR water volume variations. Thus, these residuals (GRACE minus WGHM) contain TGR volume changes that can then be compared to in situ observations. However, the uncertainties of GRACE and the model combine in the residuals. The combined uncertainties (MAD) of GRACE-WGHM estimates are 4.62 km^3/29 mm (Table 1). The uncertainties could be reduced to 1.69 km^3/11 mm after applying the SSA low-pass filter. Meanwhile, in the optimal comparison months from October to December, there are similar MADs (4.75 km^3 or 30 mm for raw GRACE-WGHM estimates and 3.24 km^3 or 20 mm for filtered GRACE-WGHM estimates) between GRACE-WGHM and TGR (Figures 5c and 5d). As stated in section 4.2, these estimates of the error in the GRACE-WGHM estimated TGR monthly volume anomalies are fairly comparable to the reported uncertainty (17 mm or 4.25 km^3) for similarly processed GRACE solutions of 500 km [*Swenson and Wahr*, 2006]. The lower error estimate given by *Swenson and Wahr* [2006] is because an additional 500 km Gaussian smoothing is applied to the decorrelated solutions, which is not the case in our study.

[35] Both spatial and temporal filters are used to process GRACE solutions and WGHM predictions. The spatial decorrelation filter applied by *Swenson and Wahr* [2006] is used to remove correlations among Stokes coefficients and therefore attenuate the meridional stripes distinctive in raw GRACE spherical harmonic solutions. The temporal SSA low-pass filter is used to remove the noise in the time series GRACE-WGHM estimates [e.g., *Ghil et al.*, 2002]. The SSA filter reduces 21% of the GRACE-WGHM estimate variances and provides a smoother time series but causes little change in the long-term averages (Figure 4b). Although this filter significantly improves the agreements between GRACE-WGHM estimates and TGR measurements at the monthly scale (Figure 5), the corresponding comparison numbers and uncertainty analysis used in this study are conservatively preferred to those calculated from the unfiltered data.

[36] In the third (last) filling stage from 2008 to 2010, GRACE-WGHM estimates (11.15 km^3) show a much larger mass change than TGR in situ measurements (6.12 km^3) (Figure 4b). While the difference (5 km^3) is of the same order as the monthly uncertainty estimated in this study (4.62 km^3) and in previous ones (17 mm or 4.25 km^3 [*Swenson and Wahr*, 2006]), it is 3 times the long-term error of 1.69 km^3 (Table 1) estimated after removing stationary high-frequency noise using a SSA low-pass filter, which allows us to assume that this difference might be related to TGR leaking to neighboring areas and increased groundwater recharge and atmospheric water vapor. The newly constructed hydropower reservoirs in the Jianghan

Plains in the northeast of the TGR in the past decade might also contribute to the observed mass increase (Figure 6). At present, we still do not know which components play a primary role and what their relative significance is to the TGR total water storage change. According to *Chao et al.* [2008], a 5% seepage rate into the ground is generally expected during the first year of a reservoir's life, which would amount to 2 km^3 for the TGR's first-year full-level storage. Seepage increases slowly with time, so the amount of leakage for the years following the last filling stage will not be detectable by GRACE. In order to explain the remaining 3 km^3, it would be worthwhile to study how much water is leaking to neighboring areas and increasing the groundwater recharge and storage due to the maximum storage in the TGR. Even though the quantities cited above (2 and 3 km^3) are very close to the estimated uncertainty of the GRACE-WGHM estimates and cannot be validated using the present GRACE solutions, a qualitative check of our assumptions of groundwater seepage and leakage of neighboring reservoirs is still conceivable.

[37] Last, this study shows that large mass changes that occur in a concentrated area, e.g., the water impoundment in the TGR area, are detectable by GRACE with the help of hydrologic modeling, even though the area is much smaller than the footprint of GRACE global harmonic solutions. However, the total mass changes from one or several reservoirs must be larger than the GRACE-model estimate uncertainties, 4.62 km^3, and must be distributed over an area larger than 1000 km^2 in this case. There are nearly 30,000 named artificial reservoirs with nominal capacity built in the 1900s, and those reservoirs retain a total of $\sim$10,800 km^3 water on land [*Biemans et al.*, 2011]. *Chao et al.* [2008] note that they have reduced the magnitude of global sea level rise by -30 mm at a rate of -0.55 mm yr^{-1} since the 1950s. The contribution of the TGR alone amounts to -0.11 mm yr^{-1} of sea level change between 2003 and 2008. This indicates that GRACE observations could provide a relatively accurate estimate of global water volume held by newly constructed reservoirs and their impact on global sea level rise since 2002 and could be used to evaluate the impact of global reservoir operations on seasonal variations of streamflow and global sea level.

6. Summary

[38] The TGR water impoundment represents a geophysical "controlled experiment" and offers a unique opportunity for conducting detailed geophysical and geodetic studies. Filling the TGR has occurred at the same time as the GRACE mission and therefore can be monitored from both space and ground. The vast amount (near 40 km^3) of water impounded in the TGR is much larger than the accuracy of the GRACE decorrelated solutions at spatial scales of 400 km and thus provides an important opportunity to assess the ability of GRACE to estimate surface water storage changes that occur below its intrinsic resolution but have large amplitudes. For the first time, this study compares the GRACE estimated reservoir volume changes with in situ TGR volume measurements from April 2002 to May 2010 at a monthly time scale. Since the TGR and regional hydrology signals are jointly measured by the GRACE satellites, a global hydrology model is used to isolate the TGR contribution. The WaterGAP model (WGHM) is selected because it predicts water storage interannual variations in the TGR area better than other models (e.g., GLDAS and NCEP/NCAR), such as the 2006 drought. Overall, the GRACE minus WGHM residuals show an increasing trend in TGR water storage in the different filling stages during the past decade and compare well with in situ TGR observations, i.e., GRACE solutions can retrieve the true amplitude of large mass changes happening in a concentrated area, e.g., the water impoundment in the TGR area, with the help of hydrologic modeling, even though such an area is much smaller than the resolution of GRACE global harmonic solutions. We compare the temporal volume differences during three optimal months and during four periods representing the three different TGR filling stages. For every period, GRACE-WGHM estimates are in fair agreement with TGR in situ measurements. The GRACE-WGHM estimate (26.53 km^3) of the annual mean impounded total water volume between the last and prefilling state is 14% larger than the in situ volume change (23.25 km^3), i.e., the uncertainty on long-term volume change is 3.2 km^3. GRACE-WGHM estimates agree with TGR in situ measurements in the first two filling stages and overestimate the third (last) fully filled stage. The GRACE-WGHM monthly reservoir volume changes could explain 76% ($r^2 = 0.76$) of in situ monthly volume measurements with a MAD of 4.75 km^3 in the optimal comparison months from October to December and have an uncertainty of 4.62 km^3 (MAD).

[39] GRACE estimated reservoir volume changes have much larger monthly variability than the TGR in situ measurements. All large (>10 km^3) differences (GRACE $-$ WGHM $-$ TGR) are positive values, mainly because of heavy rainfall in summer and snowfall in winter. In both cases, WGHM may underestimate soil moisture, water ponds, and snow, leading to an overestimate of reservoir volume change. In addition, our results suggest that reservoir leakage, i.e., groundwater recharge from the bottom of the filled TGR, and the influence of neighboring lakes are nonnegligible contributors to the regional mass changes observed by GRACE and could be quantified with further study. Moreover, GRACE observations could provide a relatively accurate estimate of global water volume withheld by newly constructed reservoirs and their impacts on global sea level rise since 2002 and could be used to evaluate the impact of global reservoir operations on seasonal variations of land surface streamflow and global sea level changes.

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