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Groundwater Storage Changes: Present Status from GRACE Observations

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Abstract Satellite gravity measurements from the Gravity Recovery and Climate Experiment (GRACE) provide quantitative measurement of terrestrial water storage (TWS) changes with unprecedented accuracy. Combining GRACE-observed TWS changes and independent estimates of water change in soil and snow and surface reservoirs offers a means for estimating groundwater storage change. Since its launch in March 2002, GRACE time-variable gravity data have been successfully used to quantify long-term groundwater storage changes in different regions over the world, including northwest India, the High Plains Aquifer and the Central Valley in the USA, the North China Plain, Middle East, and southern Murray–Darling Basin in Australia, where groundwater storage has been significantly depleted in recent years (or decades). It is difficult to rely on in situ groundwater measurements for accurate quantification of large, regional-scale groundwater storage changes, especially at long timescales due to inadequate spatial and temporal coverage of in situ data and uncertainties in storage coefficients. The now nearly 13 years of GRACE gravity data provide a successful and unique complementary tool for monitoring and measuring groundwater changes on a global and regional basis. Despite the successful applications of GRACE in studying global groundwater storage change, there are still some major challenges limiting the application and interpretation of GRACE data. In this paper, we present an overview of GRACE applications in groundwater studies and discuss if and how the main challenges to using GRACE data can be addressed.

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1 Introduction

Groundwater storage is a vital resource to sustain agricultural, industrial, and domestic activities both in populous countries such as China and India, and in arid regions lacking adequate alternative water resources (e.g., the Middle East and North Africa). Groundwater, as an important component of the global water cycle, also plays a key role in the global water cycle's connections with climate change. Groundwater storage change is controlled by the balance between recharge (i.e., inflow into the groundwater body, or aquifer, from the soil or surface water reservoirs) and discharge (i.e., outflow from the groundwater to surface water systems) or groundwater abstractions (Freeze and Cherry 1979). Extended drought and/or excessive groundwater abstractions can lead to groundwater depletion and regional water resource scarcity and pose significant impacts on the ecosystem and economic and social developments (Foster and Loucks 2006; Rodell et al. 2009; Gleeson et al. 2010; Famiglietti 2014).

During the past few decades, intensive groundwater pumping, especially for agricultural irrigation, has led to dramatic declines of groundwater levels in many parts of the world, which in some places can be as much as up to 100–200 m (Rodell and Famiglietti 2002; Wang et al. 2006; Scanlon et al. 2012a, b; Famiglietti 2014). Due to the extremely slow process of groundwater recharge, excessive depletion of groundwater resources in those regions will not be fully restored in the foreseeable future. Groundwater depletion not only results in insufficient water to support sustainable local economic development, but also increases energy consumption as more energy is required to pump groundwater from greater depths below the surface, increasing demand on an already constrained energy supply (Konikow and Kendy 2005). Groundwater depletion can also lead to significant land subsidence, which, in extreme cases as in the San Joaquin Valley of California, has reached values of 1.2 m, impacting pipelines and transport systems. Other regions with severe subsidence include Bangkok, Thailand (Giao and Nutalaya 2006) and Jakarta, Indonesia (Abidin et al. 2008), increasing flood risks.

Monitoring and understanding groundwater storage changes, especially the long-term variability, are critical for maintaining sustainable economic development and healthy ecosystems, and better understanding the global and regional hydrological cycles and climate change. Despite their importance to freshwater supplies, groundwater resources are often poorly monitored, and accurate quantification of groundwater storage change has been difficult due to insufficient in situ groundwater level observations (Famiglietti et al. 2011). Even though in some regions in developed countries (such as the USA and Australia) monitoring well networks can be dense, quantifying regional groundwater storage changes from well data is still complicated by uncertainties in aquifer storage coefficients to convert water level changes to storage volumes (Rodell et al. 2007). Inadequate spatial and temporal coverage of monitoring networks is also a general issue. Additional complications include data formatting and inconsistencies, and human and mechanical monitoring, and recording errors. Furthermore, restrictive data sharing policies (due to political reasons) in other parts of the world may also limit studies of groundwater storage change using in situ well data.

Uncertainties in groundwater recharge estimates from water budgets in land surface models, e.g., the WaterGAP Global Hydrology Model (WGHM) can be large, particularly in semiarid regions (Döll et al. 2012). The primary discharge mechanism is often groundwater pumpage estimates, often based on country estimates from the Food and Agricultural Organization (FAO), also highly uncertain. In addition, limited in situ observations of groundwater levels reduce the reliability of the simulated groundwater storage (GWS) changes, especially at long timescales (Döll et al. 2012). These parameters are often unknown or difficult to quantify on a large regional basis. Therefore, accurately modeling long-term GWS change or groundwater depletion is challenging.

The Gravity Recovery and Climate Experiment (GRACE) is the first dedicated satellite time-variable gravity mission and provides an alternative and unique approach for monitoring large-scale mass changes in the Earth system (Tapley et al. 2004). Since its launch in March 2002, GRACE has been measuring global gravity changes on a monthly basis, with unprecedented accuracy (Wahr et al. 2004). Earth gravity changes are caused by mass redistribution within different components of the Earth's system, including the atmosphere, ocean, hydrosphere, cryosphere, and solid Earth. GRACE-observed gravity changes can be used to infer terrestrial water storage (TWS, the sum of snow water equivalent, surface water, soil water, and groundwater storage) changes, given that other geophysical causes of gravity change can be estimated and removed (e.g., Wahr et al. 2004; Chen et al. 2009). As atmospheric and oceanic contributions to gravity change have been removed in GRACE data processing using estimates from numerical models (Bettadpur 2012), over non-glaciated land areas, GRACE-observed mass changes mostly reflect TWS changes. Therefore, when water storage changes in snow, surface water reservoirs, and soil are known, GRACE gravity measurements provide an alternative and complementary tool for quantifying GWS changes over large regions.

GRACE time-variable gravity data have been successfully used to quantify long-term GWS changes in different regions over the world, including the northwest India (NWI) (Rodell et al. 2009), the High Plains Aquifer (HPA) (Scanlon et al. 2012b) and Central Valley in the USA (Famiglietti et al. 2011), the North China Plain (NCP) (Feng et al. 2013), the Middle East (Voss et al. 2013), and southern Murray–Darling Basin (MDB) in Australia, where groundwater storages have been significantly depleted in recent years (or decades) (Leblanc et al. 2009, 2012). In a commentary article, Famiglietti (2014) discussed the groundwater crisis which many parts of the world are facing in the recent decade through GRACE-observed groundwater depletions in some major aquifers or regions in the world. In this paper, we present an overview of the present status of monitoring GWS changes using GRACE time-variable gravity measurements, outline major challenges when using GRACE data in groundwater studies, and discuss if and how these challenges can be addressed.

2 Groundwater Depletion from GRACE

GRACE time-variable gravity fields are represented by spherical harmonic coefficients and can be used to estimate mass redistributions. However, a major challenge in estimating mass changes using GRACE gravity solutions is the well-known non-uniqueness of gravitational inversion for a 3D Earth (Chao 2005). In most GRACE applications, people have assumed that GRACE-observed gravity changes are mostly caused by mass redistribution on the Earth's surface (or close to the surface). This assumption appears valid in most parts of the world and over a wide range of timescales. The surface mass density change ($\Delta\sigma(\theta,\lambda)$ in kg/m^2) can be computed as (Wahr et al. 1998),

$$\Delta\sigma(\theta,\phi)=\frac{M_{\mathrm{E}}}{4\pi a^2}\sum_{l=2}^{N}\sum_{m=0}^{l}\frac{2l+1}{1+k_l}W_l\widetilde{P}_{lm}(\cos\theta)\times[\Delta C_{lm}\cos(m\phi)+\Delta S_{lm}\sin(m\phi)],\qquad(1)$$

where θ and λ are geocentric colatitude and longitude, respectively, a is Earth's mean radius (6.371×10^6 m), and M_{e} is the mass of the Earth (5.97219×10^{24} kg); $\widetilde{P}_{lm}$ are the fully normalized associated Legendre functions of degree l and order m, and ΔC_{lm} and ΔS_{lm} are GRACE gravity spherical harmonics coefficient change. $W_l=W_l(r)$ is the normalized Gaussian weighting function (with a maximum weight of 1), dependent on a chosen averaging radius (r).

GRACE satellite gravimetry is the first satellite remote sensing technique that is directly applicable to the assessment of large-scale GWS changes (Yeh et al. 2006; Swenson and Wahr 2006; Rodell et al. 2007). Over non-glacialized land areas, GRACE observes the total water mass change within a vertical column, including the atmosphere, terrestrial water, and solid Earth. Even when mass changes in the atmosphere and solid Earth can be removed using estimates from numerical models, GRACE itself cannot separate the different components of TWS changes. Therefore, water storage changes in snow, surface water reservoirs, and soil have to be estimated from other independent data source(s), such as land surface models (LSMs) in order to use GRACE to quantify GWS change (Rodell and Famiglietti 2002).

$$\Delta\mathrm{TWS}=\Delta W_{\mathrm{soil}}+\Delta W_{\mathrm{snow}}+\Delta W_{\mathrm{surface\_reservoir}}+\Delta\mathrm{GWS}\qquad(2)$$

or

$$\Delta\mathrm{GWS}=\Delta\mathrm{TWS}-\left(\Delta W_{\mathrm{soil}}+\Delta W_{\mathrm{snow}}+\Delta W_{\mathrm{surface\_reservoir}}\right)\qquad(3)$$

The top panel of Fig. 1 shows the long-term TWS changes (in cm/year equivalent water height) observed by GRACE for the period January 2005 and December 2009. The reason for picking up the period of 2005–2009 is to illustrate some of the strong groundwater depletion signals during that particular period such as those in southern MDB and Central Valley. At each grid point, the TWS rate is determined by an unweighted least squares fit of GRACE TWS changes calculated from the GRACE release-5 (RL05) gravity solutions provided by the Center for Space Research (CSR), University of Texas at Austin. We selected this 5-year period to better illustrate some significant long-term regional TWS and GWS changes during this particular time span. Some of the GRACE-observed long-term TWS changes may simply reflect water storage changes in surface water reservoirs, snow, and soil (SSS). After the total SSS water storage changes (shown in the middle panel of Fig. 1) estimated from the WGHM (version 2.2) (Güntner et al. 2007) have been subtracted from GRACE TWS changes, the residual changes should represent GWS changes over non-glacial regions (Fig. 1c). Some of the prominent mass change features such as those over the Greenland, Canadian Arctic Archipelago, and southern Alaska apparently represent ice mass losses during the studied period.

As the uncertainty of model-estimated SSS water storage change is unknown, some of the derived "groundwater" changes may be introduced by errors in model SSS estimates and/or GRACE TWS estimates. However, GRACE measurements have indeed captured some interesting long-term regional groundwater changes over the world that can be verified by either in situ groundwater level data or analysis of precipitation data. GRACE-

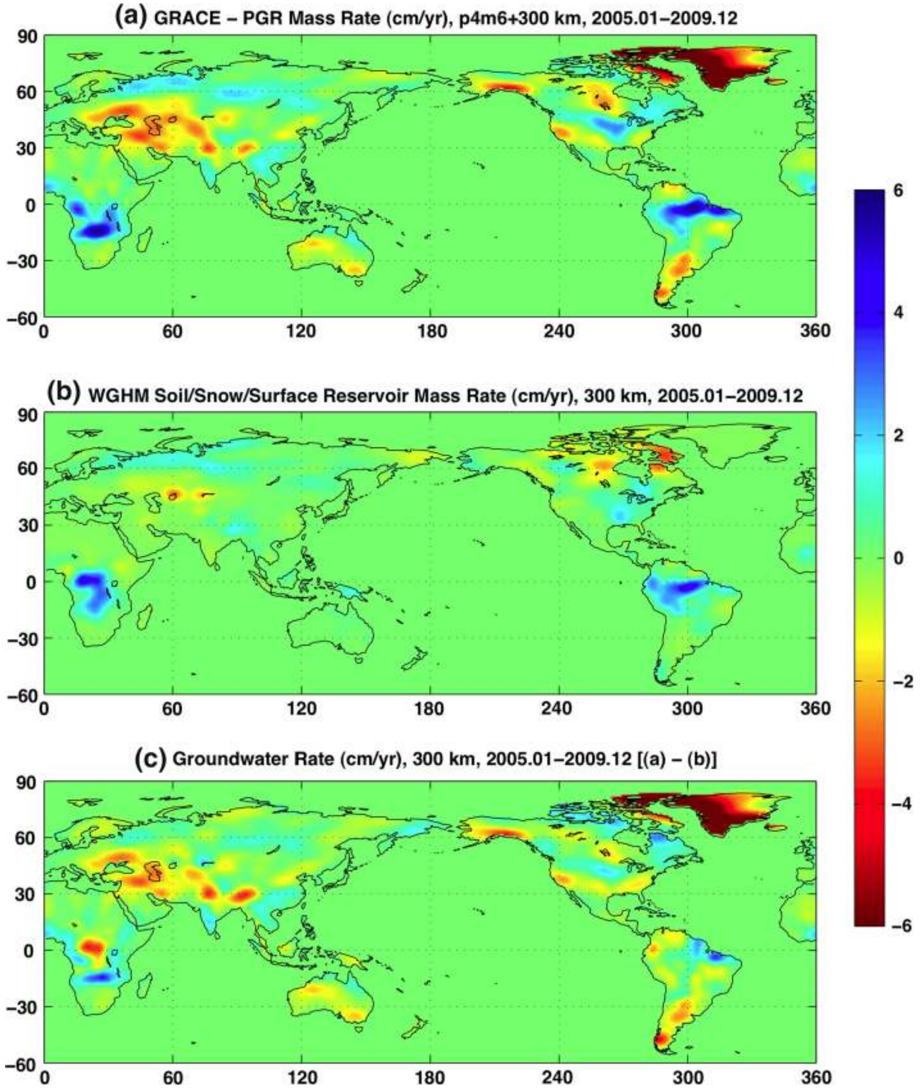


Fig. 1 **a** GRACE-observed TWS changes (in cm/year equivalent water height) for the period January 2005–December 2009. The post-glacial rebound (PGR) effect is removed using model estimates (Geruo et al. 2013). **b** Water storage changes in soil, snow, and surface reservoirs from WGHM for the same 5-year period. **c** "Groundwater" storage changes from GRACE-WGHM, i.e. (**a**–**b**). Decorrelation filter and 300 km Gaussian smoothing were applied to GRACE data, and 300 km Gaussian smoothing was applied to WGHM data

observed long-term regional groundwater changes include significant groundwater depletion in northwest and northern India (Rodell et al. 2009; Tiwari et al. 2009; Chen et al. 2014), the Middle East (Voss et al. 2013; Joodaki et al. 2014), California's Central Valley (Famiglietti et al. 2011; Scanlon et al. 2012a), and the southern MDB in Australia (Leblanc et al. 2009, 2012; Chen et al. 2015a), and lower groundwater depletions in the NCP in China (Feng et al. 2013) and HPA in the USA (Strassberg et al. 2009; Scanlon et al. 2012b; Famiglietti and Rodell 2013).

Fig. 2 **a** GRACE-observed “groundwater” storage change rates (in cm/year of equivalent water height) for ▶ the period January 2005–December 2009, same as Fig. 1c, but enlarged for the Southeast Asia region. **b** and **c** Comparisons of GRACE-observed TWS change, WGHM model estimates of SSS water change, and GWS change from GRACE to WGHM (in cm equivalent water height) for the period January 2003–December 2012, for two points (**a**) A and (**b**) B marked by *white triangles* on Fig. 2a

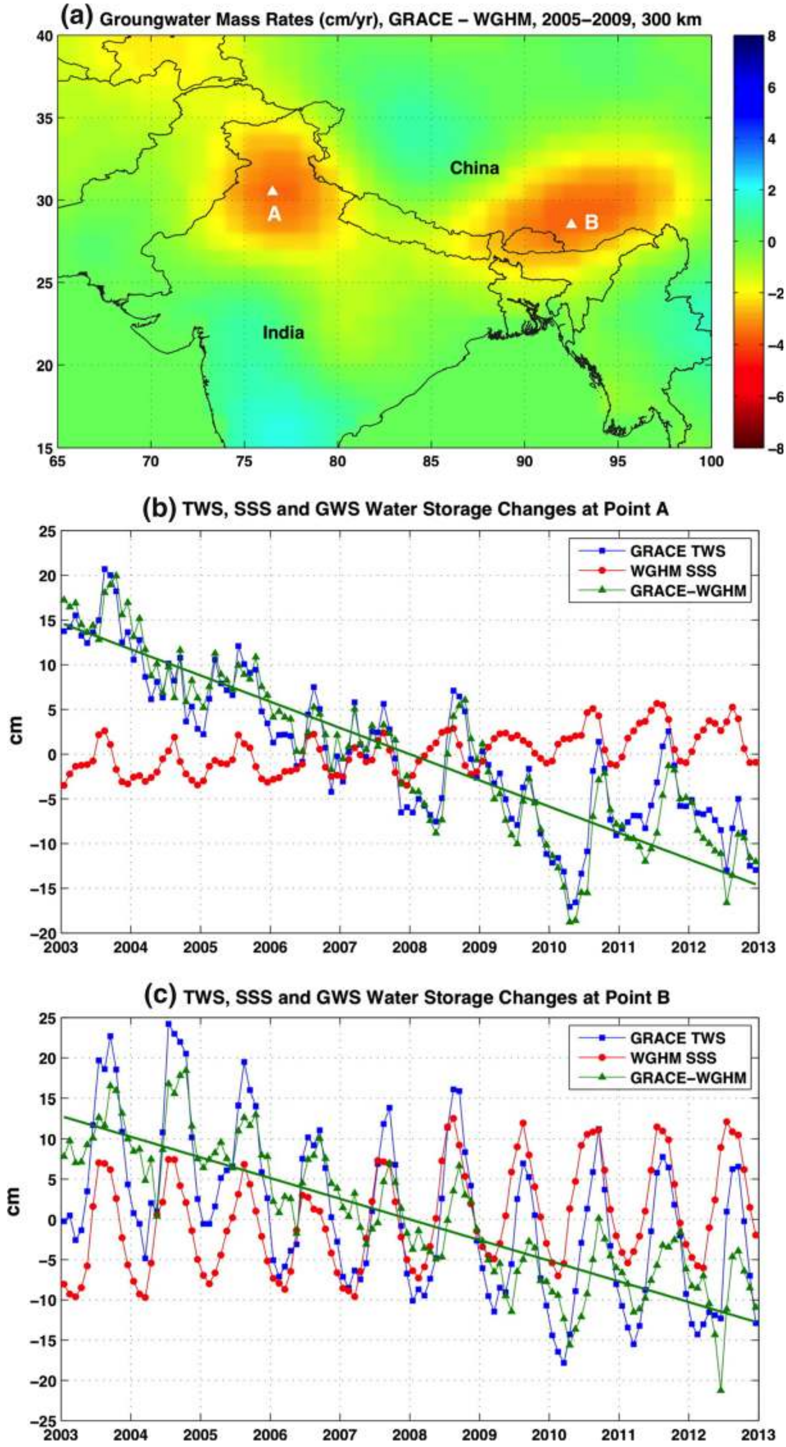
An alternative to applying Eq. (3) with modeled SSS data is to incorporate GRACE TWS observations into a land surface model via data assimilation and allow the model to separate the TWS components (Zaitchik et al. 2008). This approach is only appropriate if the model explicitly represents groundwater storage. Currently, most LSMs do not. This technique has been applied successfully to isolate groundwater storage changes from soil water and snow water storage changes and to apply the results for drought monitoring in North America (Houborg et al. 2012) and Europe (Li et al. 2012), but to date it has not been used for assessing long-term groundwater trends.

2.1 Groundwater Depletion in North West India

Rodell et al. (2009) and Tiwari et al. (2009) combined GRACE TWS estimates and soil and snow water estimates from the Global Land Data Assimilation System (GLDAS) hydrological model (Rodell et al. 2004) and found that TWS decreased significantly in the Ganges–Brahmaputra river basins (northwest and north India) during the period August 2002–October 2008. As precipitation in the region was close to the normal level during the period, the GRACE-observed TWS decrease was not related to drought but to GWS depletion due to groundwater pumping for irrigation and domestic consumption. The estimated groundwater depletion rate averaged over the Indian states of Rajasthan, Punjab, and Haryana is 17.7 ± 4.5 km^3/year (4 ± 1 cm/year) over the period August 2002–October 2008 (Rodell et al. 2009), and the estimated rate for a broader region covering north India (from northwest to northeast) can be up to 54 ± 9 km^3/year (2 cm/year; Tiwari et al. 2009) during the same period.

Using an extended record of GRACE measurements combined with Global Land Data Assimilation System (GLDAS) snow and soil water storage estimates, and a different method for correcting leakage bias of GRACE estimates, Chen et al. (2014) reassessed the groundwater depletion rate in the NWI region. The newly estimated groundwater depletion rate is 20.4 ± 7.1 km^3/year (2.4 ± 0.59 cm/year) averaged over the 10-year period January 2003–December 2012. However, during the first 5 years (2003–2007), the newly estimated rate (29.4 ± 8.4 km^3/year; 3.5 ± 0.70 cm/year) is significantly larger than previous estimates for roughly the same period. The difference is attributed to the improved treatment of leakage effects through global forward modeling and extended studied region (which is different from the three state regions defined in Rodell et al. 2009). The groundwater depletion in NWI occurred in a broad region that includes neighboring Punjab Province of Pakistan (especially northern Punjab) (see Fig. 1 of Chen et al. 2014).

GRACE-observed groundwater depletion in the NWI region is corroborated by groundwater recharge and consumption data from the Indian government (Rodell et al. 2009). Northern India is one of the most populous regions in the world. Excessive groundwater pumping for agricultural irrigation and domestic consumption in response to the growing demand for water has exceeded the replenishable groundwater supply, causing a steady decreasing of the water table (Tiwari et al. 2009). Analyses of precipitation data and model-predicted water storage changes in surface reservoirs and subsurface soil (plus snow if applicable) indicate that annual precipitation in NWI generally has been at normal


(a) Groungwater Mass Rates (cm/yr), GRACE – WGHM, 2005–2009, 300 km
China
India
A
B
40
35
30
25
20
15
65
70
75
80
85
90
95
100
8
6
4
2
0
−2
−4
−6
−8
(b) TWS, SSS and GWS Water Storage Changes at Point A
GRACE TWS
WGHM SSS
GRACE−WGHM
cm
25
20
15
10
5
0
−5
−10
−15
−20
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
(c) TWS, SSS and GWS Water Storage Changes at Point B
GRACE TWS
WGHM SSS
GRACE−WGHM
cm
25
20
15
10
5
0
−5
−10
−15
−20
−25
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013

levels (Rodell et al. 2009; Chen et al. 2014), and model-predicted SSS water storages have not shown any decreasing trends. This further indicates that GRACE-observed water storage decreases in the NWI region most likely (see Fig. 2) represent GWS changes. Leakage from ice melting of nearby mountain glaciers may also affect GRACE-estimated groundwater depletion in this region; however, the effect is relatively small and estimated to be ~ -3 km^3/year (Rodell et al. 2009), well within the estimated uncertainty level (Chen et al. 2014).

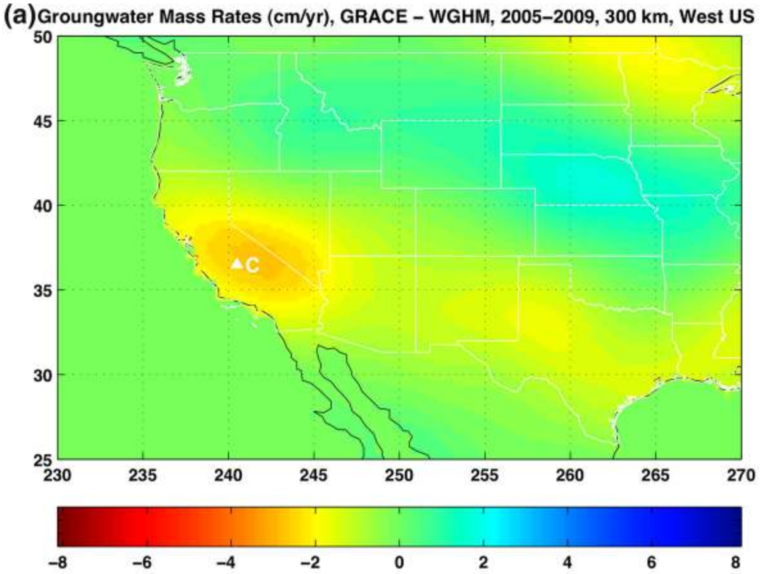
Interpretation of GRACE-observed mass loss in NWI may be more complicated than previously represented over the period 2005–2009; GRACE-observed mass loss extends over a broader region that covers parts of northeast India, Bangladesh, and southwest China, with the center of mass loss actually in southwest China. Furthermore, the region also covers part of the Himalayan mountain glaciers. The spatial pattern of this mass loss signal may vary when using different time spans of GRACE data, but nevertheless the contributors to this mass loss may include groundwater depletion in northeast India, northern Bangladesh, and southwest China, Himalayan mountain glaciers melting, and additional SSS water storage changes that are not correctly modeled in the WGHM. The southwest China region has experienced extended drought in the past decade, which may have contributed to GRACE-observed water storage decrease in this broad region.

2.2 Groundwater Depletion in the California Central Valley

Another interesting groundwater depletion signal observed by GRACE is in the Sacramento and San Joaquin River Basins in California (see Fig. 3), which encompass the Central Valley and its underlying groundwater aquifer system. The Central Valley is the most productive agricultural region in the USA, growing more than 8 % of the food produced in the USA (Faunt 2009). With limited surface water resources, groundwater has been a major water supply for agricultural activities in the Central Valley region. Excessive groundwater pumping has led to steady decreasing water tables (Faunt 2009; Famiglietti 2011; Scanlon et al. 2012a, b) and also to significant ground subsidence (Galloway et al. 1999) in the region.

Combining GRACE gravity measurements, snow water equivalent data from the National Operational Hydrologic Remote Sensing Center, in situ surface water storage estimates for the 20 largest reservoirs in the river basins, and soil moisture estimates from GLDAS (Rodell et al. 2004), Famiglietti et al. (2011) concluded that the Sacramento and San Joaquin River Basins lost water at a rate of 4.8 ± 0.4 km^3/year during the period October 2003–March 2010 and determined (based on additional observations and hydrological model information) that the majority of the water losses were due to groundwater depletion in the Central Valley. Scanlon et al. (2012a, b) extended the analysis of long-term GWS change in the Central Valley region by comparing GRACE estimates with in situ well measurements and showed that over the drought period from April 2006 through September 2009, GRACE data (minus SNODAS SWE, in situ surface water reservoir storage change, and GLDAS soil moisture estimates) indicate a groundwater depletion rate of 7.7 ± 0.7 km^3/year, agreeing very well with in situ well data estimate of 7.7 ± 0.1 km^3/year.

The significantly larger groundwater depletion rate from Scanlon et al. (2012a, b) is mostly the result of selecting a different time span (April 2006 and September 2009) from that (October 2003 to March 2010) used in Famiglietti et al. (2011). The Sacramento and San Joaquin River Basins (and the encompassed Central Valley) experienced a major



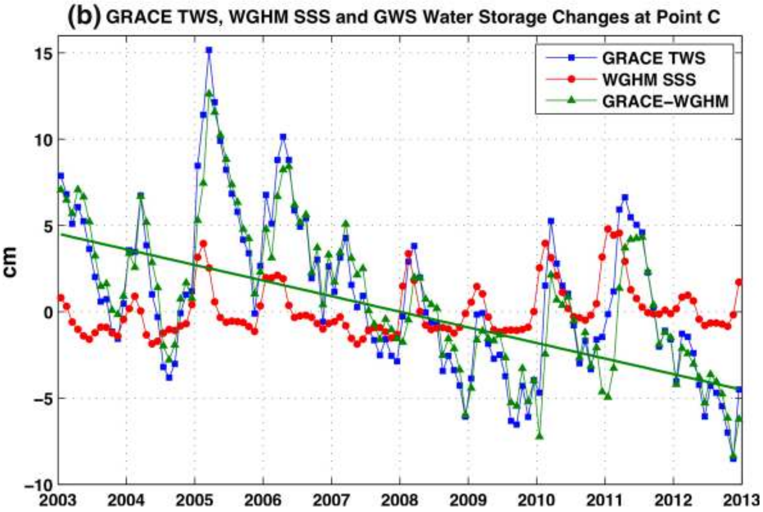


Fig. 3 **a** Estimated GWS change from GRACE to WGHM (in cm/year of equivalent water height) over the period January 2005–December 2009, same as Fig. 1c, but enlarged for the western and mid-western USA **b** Comparison of GRACE-observed TWS change, WGHM model estimates of SSS water change, and GWS change from GRACE to WGHM (in cm equivalent water height) for January 2003 through December 2012, for point C marked by *white triangle* on Fig. 3a

drought during the period October 2006 through March 2010, which caused greater groundwater depletion than the overall average (see Fig. 3b). Using different GRACE gravity solutions and different data processing methods also contributed to the discrepancy.

The groundwater depletion in the Central Valley is expected to continue. The western USA, especially California, is experiencing one of the most severe droughts on record.

This devastating extreme drought will surely increase further groundwater demand in the Central Valley for agricultural irrigation and domestic use. Studies based on climate model predictions show clear links between this mega drought and global climate change and suggest that it may become a chronic event (Swain et al. 2014; Diffenbaugh et al. 2015).

2.3 Groundwater Depletion in Southern Murray–Darling Basin

The MDB is a large drainage basin (area ~1.06 million km^2) in the interior of south-eastern Australia (see Fig. 4a), covering about one-seventh of the continent. It supports almost three-quarters of the country's irrigated land and generates about 30 % of the national income derived from agriculture (van Dijk et al. 2007). Australia is the second driest continent after Antarctica, with mean annual precipitation of ~450 mm (over the past century) (Lavery et al. 1997). Many parts of Australia have suffered from extended drought conditions (Leblanc et al. 2009), except for tropical northern and northeastern regions. Chronic drought conditions and excessive groundwater extraction for agricultural, industrial, and domestic consumption contribute to depletion of groundwater storage in regions such as the MDB (Tularam and Krishna 2009).

Australia is generally arid with relatively small seasonal hydrological variations (Awange et al. 2011). However, GRACE satellite gravity measurements still proved useful for estimating basin or large regional-scale TWS and GWS changes in Australia (e.g., Leblanc et al. 2009; Rieser et al. 2010; Awange et al. 2011). The MDB experienced a severe drought, termed the Millennium Drought (2001–2009; van Dijk et al. 2013), during which available in situ groundwater level measurements showed an alarming drop in groundwater storage in the southern MDB (Leblanc et al. 2012).

By analyzing in situ well data, Leblanc et al. (2009) showed that between 2001 and 2007, GWS in the MDB region lost 104 ± 40 km^3 (or 17 ± 7 km^3/year). The in situ estimates agree well with estimates from GRACE gravity measurements (combined with GLDAS snow and soil water estimates) for the period 2003–2007. Leblanc et al. (2012) extended the study to cover a longer time span and indicated that, over the period August 2002–December 2010, GRACE-estimated groundwater depletion in the southern MDB is ~18 ± 1.3 km^3/year.

In a recent study, Chen et al. (2015a) carried out a new analysis of in situ groundwater level measurements (from a network of 1395 boreholes) and indicated that, over the 20-year period (1993–2012), groundwater storage in the southern MDB and adjacent coastal regions in Victoria, Australia, has been declining steadily, until a trend reversal around 2010 attributed to two wet seasons in 2010 and 2011. The average groundwater depletion rate is estimated to be 3.4 ± 1.4 km^3/year for 1993–2012 (4.0 ± 1.7 km^3/year for 1993–2009). During the 10-year overlapping period (2003–2012) with the GRACE mission, GRACE-estimated groundwater changes (after WGHM SSS water storage estimates have been removed) agree remarkably well with in situ well data. The new GRACE estimate of groundwater depletion rate in the broad southern MDB region is ~17.2 ± 4.7 km^3/year for the period 2005–2009. After groundwater recharge in the past few wet seasons, the estimated overall groundwater rate is significantly reduced. Annual GWS changes are strongly correlated with precipitation anomalies, but the magnitudes of anomalous precipitation and groundwater storage suggest that only about 20 % of anomalous precipitation contributes to groundwater recharge. The strong correlation suggests that this significant groundwater depletion is primarily related to drought plus groundwater pumping for agricultural and domestic consumption (Chen et al. 2015a).

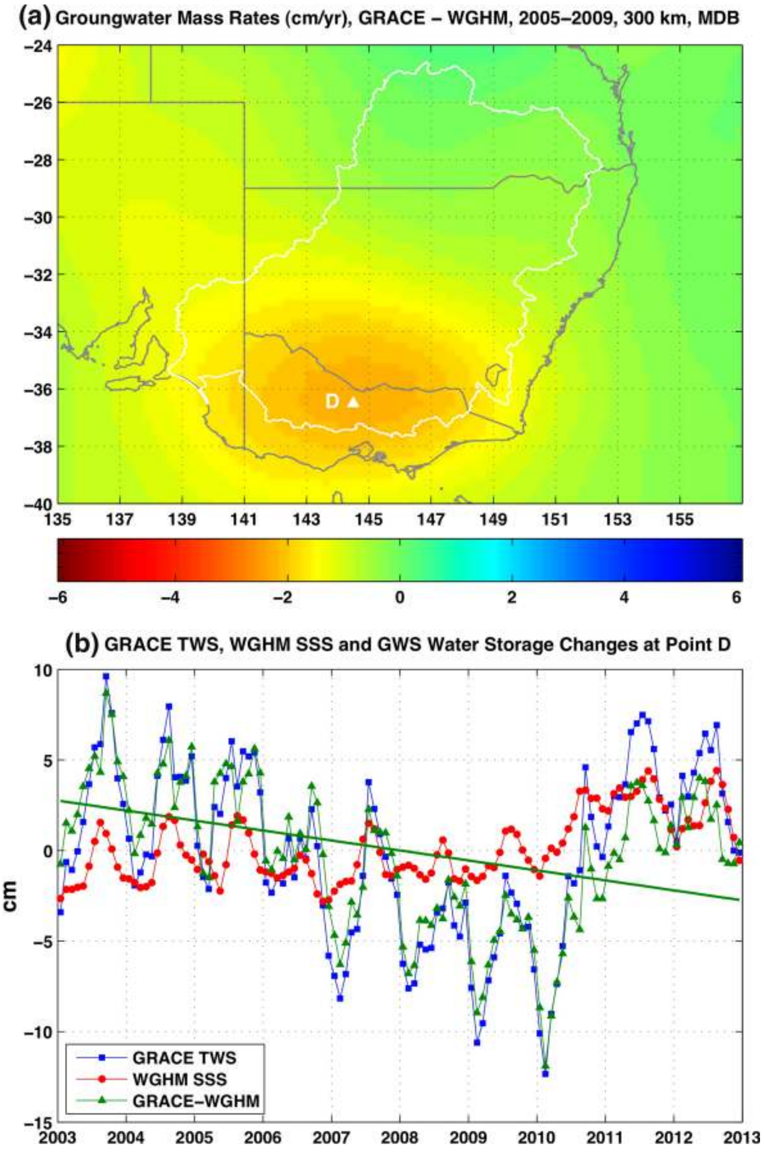


Fig. 4 **a** GRACE-observed groundwater rates (in cm/year equivalent water height) for the period 01/2005 through 12/2009, same as Fig. 1c, but enlarged for the MDB and surrounding regions in Australia. **b** Comparisons of GRACE-observed TWS change, WGHM model estimates of SSS water change, and GWS change from GRACE to WGHM (in cm equivalent water height) for the period January 2003–December 2012, for point D marked by *white triangle* on Fig. 4a

2.4 Groundwater Depletions in Other Regions

GRACE also captured groundwater depletion in other regions over the world, including the Middle East, NCP in China and HPA in the USA (Fig. 1c). The groundwater depletion signal in the Middle East appears also very significant, comparable to those in northwest and northeast India (at least over the 5-years period illustrated in Fig. 1c). After removing contributions from snow, canopy storage, and soil moisture storage using estimates from the GLDAS Variable Infiltration Capacity (VIC) model and contributions from five major surface water bodies—Lake Van, Lake Daryace (Lake Urmia), Lake Tharthar, the Assad Reservoir, and the Qadisiyah Reservoir using in situ measurements—Voss et al. (2013) show that the north-central Middle East is losing groundwater at an average rate of 13 ± 1.5 km^3/year for the period January 2003–December 2009. A similar study (Joodaki et al. 2014), using GRACE TWS estimates and the Community Land Model (CLM) 4.5 LSM estimates, shows that the largest groundwater depletion in the Middle East is occurring in Iran, with a loss rate of 25 ± 3 km^3/year during the period 2003–2012. GRACE-observed significant Iranian groundwater loss is supported by in situ well data (Joodaki et al. 2014). After the CLM4.5 model predicted natural variations in groundwater is removed from GRACE estimates, anthropogenic pumping contributions are estimated to be 14 ± 3 km^3/year, over half of the total groundwater loss. The large difference in the estimates of the two studies is due to different coverages of the studied regions, different time spans, and different LSMs used in the studies.

The NCP in North China is one of the largest irrigated areas in the world and is subjected to intensive groundwater-based irrigation. Combining GRACE gravity measurements and model estimates of snow water and soil moisture, Feng et al. (2013) showed that, over the period 2003–2010, the NCP region lost a significant amount of groundwater with an average rate of 8.3 ± 1.1 km^3/year (2 cm/year). However, other independent assessments from the Groundwater Bulletin of China Northern Plains (GBCNP) indicate that groundwater depletion rate in shallow aquifers in the plain for the same time period was only ~2.5 km^3/year. The large discrepancy in groundwater depletion estimates may reflect contributions of groundwater depletion from deep confined aquifers in the NCP and piedmont regions of North China, which is detectable by GRACE but difficult to quantify using in situ observations (Feng et al. 2013).

The HPA (450,000 km^2) is ranked first among aquifers in the USA for total groundwater withdrawals (Maupin and Barber 2005). A previous assessment (McGuire 2009) based on measured groundwater data shows that high recharge in the northern HPA enables sustainable withdrawals, whereas lower recharge in the central and southern High Plains has resulted in focused depletion of groundwater. Extrapolation of the current depletion rate suggests that 35 % of the southern HPA may be unable to support irrigation within the next 30 years (Scanlon et al. 2012b). Despite the large amount of groundwater withdrawn from the HPA, quantification of long-term groundwater depletion using GRACE has been more complicated, due to the irregular shape and south–north orientation of the aquifer and difficulty in accurate separation of HPA groundwater signal from surrounding TWS changes. However, a few previous studies (Strassberg et al. 2009; Longuevergne et al. 2010) show that GRACE-estimated GWS changes are highly correlated with those from detailed groundwater level monitoring data, indicating that GRACE is capable of detecting long-term GWS in the HPA region (Rodell and Famiglietti 2002). Through analyzing GRACE data and GLDAS Noah model estimates for the period 2003–2013, a recent study (Breña-Naranjo et al. 2014) shows persistent declines in groundwater storage across the HPA at an average rate of 12.5 ± 0.4 km^3/year.

3 Major Challenges in Monitoring Groundwater Change Using GRACE

3.1 Uncertainty of SSS Water Storage Changes

As GRACE can only measure the total water mass change (assuming atmospheric and solid Earth signals have been removed using model estimates), independent determination of SSS water storage changes plays a key role in separating the GWS contribution from GRACE-observed TWS change. Any uncertainty or bias in SSS water storage estimates will directly translate into errors in GRACE GWS estimates (through Eq. 3; see Rodell and Famiglietti 2002). Although there are limited snow cover and water level measurements of surface reservoirs available, adequate in situ soil moisture (SM) measurements on large regional or basin scales are not available in most regions. Furthermore, calculations of snow water equivalent (SWE) water from remote sensing measurements of snow cover are often subject to large uncertainty. Hence, removal of SWE and SM storage changes from the GRACE TWS is generally done using output for these storage changes from LSMs or global hydrological models (Rodell et al. 2007, 2009), such as the GLDAS (Rodell et al. 2004), WGHM (Güntner et al. 2007), and the CLM (Oleson et al. 2013).

The accuracy of LSM-based estimates of SM and SWE variations depends on the quality of the input meteorological data and the ability of the model to simulate physical processes. Water storage changes in surface reservoirs (lakes, manmade reservoirs, and rivers) can be estimated from limited available in situ observations (Rodell and Famiglietti 2001; Famiglietti et al. 2011; Scanlon et al. 2012). Comparisons between estimates from two different models (e.g., GLDAS and WGHM) can provide an approximate of the level of uncertainty of model-estimated SSS variability.

Figure 5 shows the comparisons of long-term SSS trends for the 10-year period from 2003 to 2012, predicted by GLDAS Noah and WGHM. Significantly large discrepancy exists between the two model predictions (even at long-term timescales), and the magnitudes of the differences (shown in Fig. 5c) are at the same level as the signals themselves. Apparently, the large discrepancy is not due to the absence of a surface reservoir component in the GLDAS model, but mostly attributed to the uncertainty of modeled SWE and SM estimates. Much progress is required before LSMs can accurately model long-term trends in SWE and SM. Fortunately, in some of the regions studied, where groundwater storage has experienced significant depletion in recent years (e.g., NWI, HPA, Central Valley, and NCP), model-predicted SSS trends and uncertainties are relatively small and largely do not affect GRACE-estimated groundwater rates. Additionally, precipitation and other measurements can be used to help diagnose likely SSS water storage changes and the possible uncertainties of model predictions (Rodell et al. 2009; Chen et al. 2014).

3.2 Uncertainties in GRACE TWS Storage Changes

Limited by the coarse spatial resolution of GRACE measurements (at ~200–500 km), accurate quantification of subregional TWS and/or groundwater storage changes is challenging. The spatial resolution of GRACE time-variable gravity solutions is mostly controlled by two factors: (1) the altitude of the GRACE satellites (~450 km now) and the distance (~220 km) between the twin satellites and (2) the need for spatial filtering (or smoothing) to suppress strong spatial noise in GRACE data (i.e., stripes and other residual noise) to extract reliable mass change signals. The high degree and order terms of GRACE spherical harmonic coefficients are mostly dominated by noise. Therefore, appropriate

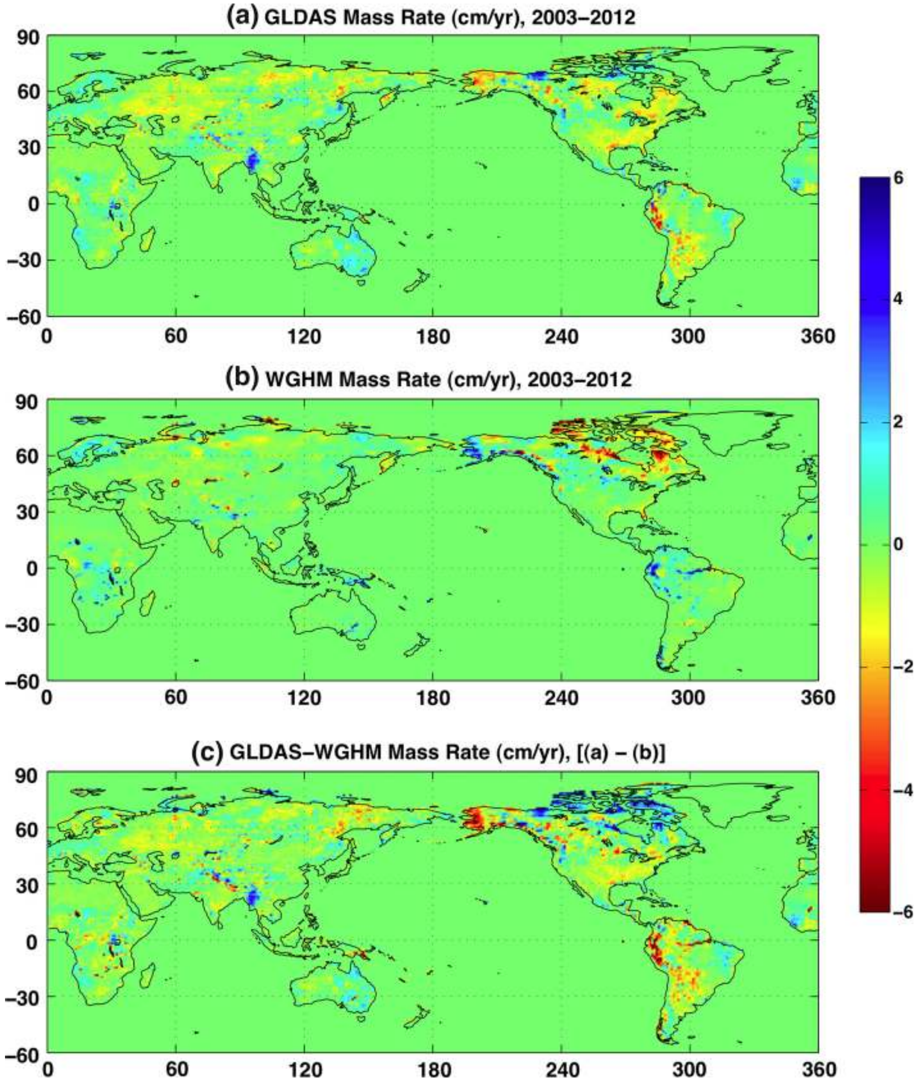


Fig. 5 **a** GLDAS SSS rates (in cm/year equivalent water height; water in surface reservoirs, a minor component, is not included in GLDAS) over the period January 2003–December 2012. **b** WGHM SSS rates during the same 10-years period. **c** GLDAS-WGHM SSS rates, i.e. (**a**) minus (**b**). No smoothing or truncation has been applied to the model SSS data

spatial filtering, such as decorrelation filtering (Swenson and Wahr 2006) and/or Gaussian smoothing (Jekeli 1981), is needed to reduce noise.

Truncation of GRACE time-variable gravity solutions (at degree and order 60) and use of spatial filtering or smoothing degrade the spatial resolution and dampen the retrieved magnitude of GRACE-observed mass changes. Experiments shown in Fig. 6 demonstrate these effects through simulations using WGHM-simulated long-term TWS changes due to excessive groundwater withdrawal or pumping in certain regions, e.g., NWI and NCP. The

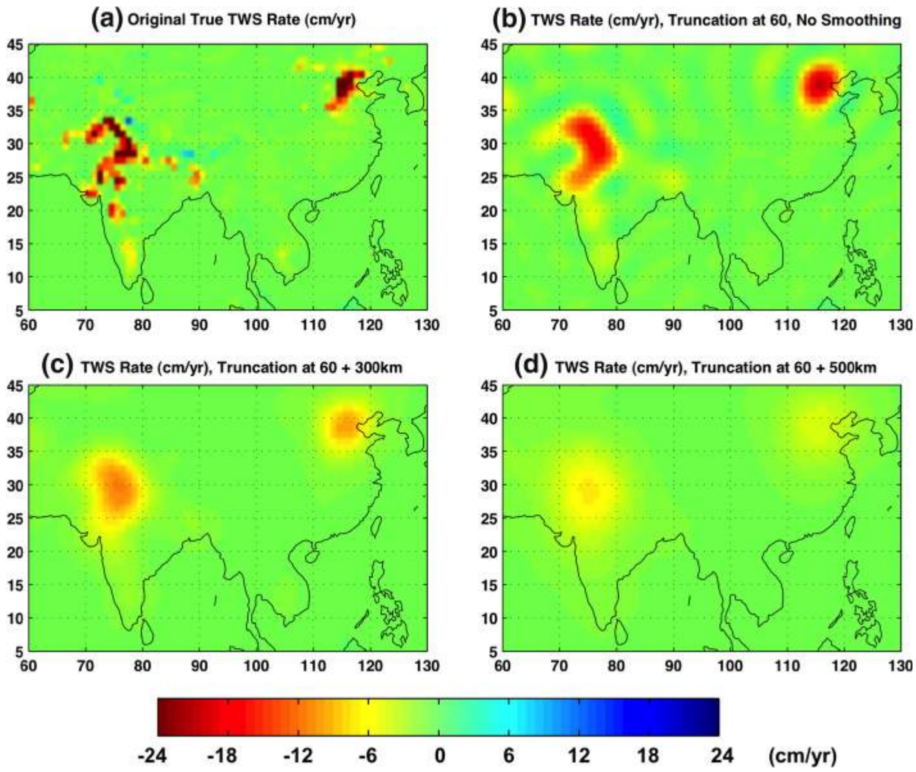


Fig. 6 WGHM-predicted long-term TWS mass rates (in cm/year equivalent water height change) at each grid point (on 1° × 1° grids) in part of Asia in 4 different cases: **a** true model prediction from WGHM; **b** model prediction with only truncation (at degree and order 60) applied; (3) model prediction with truncation and 300 km Gaussian smoothing applied; and (4) model prediction with truncation and 500 km Gaussian smoothing applied

four panels in Fig. 6 show WGHM-predicted long-term TWS rates at each grid point (on 1° × 1° grids) in part of Asia in four different cases: (a) true model prediction; (b) model prediction with only truncation (at degree and order 60) applied; (3) model prediction with truncation and 300 km Gaussian smoothing applied; and (4) model prediction with truncation and 500 km Gaussian smoothing applied.

Truncation alone (Fig. 6b) results in significant leakage (i.e., signal spread outside original area) and attenuation of signal amplitude, relative to the original true signal (Fig. 6a). After truncation at degree and order 60 (same as used in GRACE RL05 monthly solutions) and 300 km Gaussian smoothing, the magnitudes of TWS changes in the NWI and NCP regions have been reduced to less than 50 % of the true signal. After 500 km Gaussian smoothing, the magnitudes of TWS rates are further attenuated to only ~20–30 % of the true signal. Leakage and attenuation effects depend not only on the degree and order (60 here) of the truncation and scales of spatial filtering or smoothing, but also on the spatial pattern and distribution of the true mass change. Nevertheless, to accurately quantify long-term variations in TWS or groundwater storage using GRACE time-variable gravity data, leakage and attenuation biases in GRACE estimates have to be effectively reduced. This is a challenging task, which requires both a thorough understanding of GRACE leakage and attenuation effects and their dependency on temporal and spatial spectra of GRACE-observed TWS changes, and accurate knowledge of how to quantify and reduce leakage and attenuation biases.

There are a number of methods that can help reduce the leakage bias. Scale factors can be used to correct the bias in GRACE values (Velicogna and Wahr 2006). Scale factors can be estimated from model-estimated TWS storage changes by comparing model-predicted TWS values with the same model estimates after truncation and filtering (Chen et al. 2005; Landerer and Swenson 2012). However, the scaling factor method may only be valid for restoring seasonal amplitude and not for restoring the amplitudes of secular trends, as it is generally believed that seasonal TWS variability (or at least its spatial patterns) can be reliably simulated by LSMs, while interannual trends are commonly not well represented. The success of this method relies on whether the model used represents well the correct spatial patterns of the signal. Long-term TWS and groundwater changes are either absent or mostly not well modeled in the hydrological models, and therefore, the scale factor method is not recommended for multi-year and long-term timescales, unless people can construct good synthetic data models that can faithfully represent long-term TWS and groundwater storage change.

Forward modeling has proved to be an effective tool for accurately quantifying leakage effects and to obtain unbiased estimates of regional mass changes using GRACE gravity data. This method has been originally developed for studying long-term ice melting rates of polar ice sheets (e.g., Chen et al. 2006, 2009; Wouters et al. 2008) and mountain glaciers (e.g., Chen et al. 2007), when the locations of ice mass changes are approximately known (which are considered constrained experiments). The forward modeling method has later been extended to global scales with no constraints in the studies of global sea level rise (e.g., Chen et al. 2013) and regional groundwater depletion (e.g., Chen et al. 2014). In the forward modeling approach, iterative numerical simulations are used to find a “true” mass change field that best matches the GRACE-observed mass change, after repeating the same data processing procedures as applied to GRACE data, which include truncation of spherical harmonics, treatment of low-degree terms, and spatial filtering. The major advantage of forward modeling is that it is solely dependent on GRACE data and is unaffected by model uncertainty as in the scale factor approach. The details of the forward modeling algorithm and procedures with and without constraint are available in a recent article (Chen et al. 2015b).

Leakage error in GRACE estimates can also be reduced by using high-resolution mascon solutions that are derived either directly from GRACE satellite range and range rate measurements (Rowlands et al. 2005; Luthcke et al. 2013) or from GRACE spherical harmonic solutions (Jacob et al. 2012; Schrama et al. 2014). Please note that forward modeling can be regarded as a mascon approach using GRACE spherical harmonic solutions and is solved in the spatial domain, as compared to the spherical harmonic domain (e.g., Jacob et al. 2012).

In addition to the leakage and attenuation effects discussed previously, other error sources also affect GRACE-observed TWS and groundwater storage change. Some low-degree spherical harmonics of GRACE gravity solutions, especially the zonal term C20, are not well determined and are recommended to be replaced by independent measurements from satellite laser ranging (Cheng and Ries 2012). The degree-1 terms (C_{10}, C_{11}, S_{11}), representing geocenter motion (mass center of the Earth system with respect to the origin of the reference frame) are not available in GRACE solutions. The uncertainty (or absence) of these low-degree terms on TWS and groundwater estimates may not be negligible, depending on spatial scales of the studied regions (e.g., Chen et al. 2005).

However, because groundwater depletion often occurs in relatively small confined regions (such as NWI, HPA, Central Valley, and NCP), the effects from uncertainties of those lowest degree terms (longest wavelength mass change) are expected to be small.

It is worthy of note that groundwater storage change estimates derived from GRACE observations likely have larger uncertainty in humid regions (e.g., Bangladesh) due to large seasonal water storage changes (Shamsudduha et al. 2012). This is because the uncertainty of model-estimated seasonal TWS changes in these humid regions can be translated into relatively large uncertainty of interannual or long-term TWS changes and therefore affect the estimates of long-term TWS and groundwater change. When time series are relatively short (e.g., a few to several years), the uncertainty of GRACE-estimated long-term groundwater change can be large due to strong seasonal and interannual variability. With longer records (over 13-years so far) of GRACE gravity solutions available, the associated uncertainty will become less of a concern.

4 Summary

The 13-year record of GRACE time-variable gravity solutions provides a revolutionary means for measuring water mass movement and redistribution in the global water cycle and offers a unique tool for monitoring long-term groundwater storage change at continental to global scales (Famiglietti 2014). GRACE measurements have captured significant groundwater depletion in many aquifers or regions globally, including NWI (and neighboring eastern Punjab Province in Pakistan), HPA, and Central Valley in the USA, the NCP in China, the Middle East, and the southern MDB in Australia. Among those, the NWI and Middle East regions show the most significant and persistent groundwater depletion over the past decade, with rates as large as 20.4 ± 7.1 km^3/year and 25 ± 3 km^3/year, respectively, for the period 2003–2012 (Chen et al. 2014; Joodaki et al. 2014). The Central Valley is also losing a large amount of groundwater with estimated depletion rates range from 4.8 ± 0.4 to 7.7 ± 0.7 km^3/year, depending on the time span of the studies, and GRACE estimates agree well with in situ well data (Famiglietti et al. 2011; Scanlon et al. 2012). Even though the estimated Central Valley groundwater depletion rates appear not so significant compared with those for NWI and the Middle East, the current record-breaking severe chronic drought in California is only expected to worsen the already dismal situation there.

A summary of GRACE-estimated groundwater depletion rates for regions or aquifers discussed in the present study plus some other regions compiled by Famiglietti (2014) is listed in Table 1. The definitions of aquifers or regions may be somewhat different in different studies and some of them may be overlapped. It is difficult to get an accurate estimate of the total groundwater depletion rate over the world based on these estimates due to the different time spans covered by different studies and the omission of many other aquifers or regions. However, given the significant and persistent groundwater depletions in some of the regions, the total groundwater depletion rate over the past decade in these studied regions can be easily over 100 km^3/year. Excessive groundwater depletions not only pose as a great threat to the sustainability of regional water resource supply and ecosystem, but also contribute to global sea level rise. The 100 km^3/year groundwater loss over land will contribute $\sim$0.27 mm/year to the global sea level rise. The actual total groundwater depletion rate over the world could be significantly higher than the above

Table 1 Summary of GRACE-estimated groundwater depletion rates (in units of km^3/year) for selected aquifers or regions over the world discussed in the present study, plus some compiled by Famiglietti (2014)

Aquifer or region (References)	Depletion rate (km^3/year)	Time period (year.month)
Northwestern India, Rodell et al. (2009)	17.7 ± 4.5	2002.08–2008.10
Northwestern India, Chen et al. (2014)	29.4 ± 8.4	2003.01–2007.12
Northwestern India, Chen et al. (2014)	20.4 ± 7.1	2003.01–2012.12
Northern India (NW + NE India), Tiwari et al. (2009)	54 ± 9	2002.04–2008.06
Middle East, Iran, Joodaki et al. (2014)	25 ± 3	2003.01–2012.12
Middle East, North-Central, Voss et al. (2013)	13 ± 1.5	2003.01–2009.12
Southern MDB Australia, Leblanc et al. (2012)	18 ± 1.3	2002.08–2010.12
Southern MDB Australia, Chen et al. (2015a, b)	17.2 ± 4.7	2003.01–2010.01
Central Valley USA, Famiglietti et al. (2011)	4.8 ± 0.4	2003.10–2010.03
Central Valley USA, Scanlon et al. (2012a, b)	7.7 ± 0.7	2006.04–2009.09
High Plains Aquifer, Breña-Naranjo et al. (2014)	12.5 ± 0.4	2003.01–2012.12
North China Plain, Feng et al. (2013)	8.3 ± 1.1	2003.01–2010.12
Arabian Middle East, Richey (2014)	15.5	2003.01–2013.01
Canning Basin Australia, Richey (2014)	3.6	2003.01–2013.01
Guarani South America, Richey (2014)	1.0	2003.01–2013.01
Northwest Sahara, Richey (2014)	2.7	2003.01–2013.01
Arabian Richey (2014)	2.7	2003.01–2013.01

Please note that definitions of aquifers or regions may be different in different studies and some of them may be overlapped

estimate, as many other aquifers or regions with relatively small magnitudes of groundwater depletions are not included.

Due primarily to the sparseness of soil moisture observations, quantifying groundwater change using GRACE time-variable gravity measurements often depends on accurate removal of SSS water storage changes by subtracting modeled estimates (Rodell et al. 2007) or by assimilating GRACE TWS data into a land surface model (Zaitchik et al. 2008). This is one of the major challenges limiting effective application of GRACE data to study GWS changes. Any uncertainty in model-estimated SSS water storage changes will be reflected in the residual groundwater storage changes. Further, modeled interannual SSS trends are with significant uncertainty (as shown in Fig. 5c). GRACE-observed TWS changes are subject to large "leakage" of signals from adjacent regions, due to the truncation of GRACE gravity spherical harmonic coefficients and the spatial filtering required to suppress the dominant spatial noise in GRACE data. How to reduce leakage bias in GRACE TWS and groundwater estimates is another major challenge to overcome. The effect of uncertainty in GRACE low-degree spherical harmonic coefficients on GRACE groundwater estimates is expected to be small, due to the scales of groundwater depletion in most cases being significantly smaller than the length scales of those harmonics.

The GRACE mission is entering its 14th year, and the GRACE follow-on mission is scheduled to be launched in 2017. With the long record (now 13 years) of GRACE time series, and improvement of data quality and data processing methods, GRACE time-variable gravity measurements will continue offering great potential to improve understanding of the global water cycle and for monitoring and quantifying long-term variability in groundwater resources globally.

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