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Long-term groundwater variations in Northwest India from satellite gravity measurements

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ABSTRACT

Satellite gravity data from the Gravity Recovery and Climate Experiment (GRACE) provides quantitative measures of terrestrial water storage (TWS) change at large spatial scales. Combining GRACE-observed TWS changes and model estimates of water storage changes in soil and snow at the surface offers a means for measuring groundwater storage change. In this study, we re-assess long-term groundwater storage variation in the Northwest India (NWI) region using an extended record of GRACE time-variable gravity measurements, and a fully unconstrained global forward modeling method. Our new assessments based on the GRACE release-5 (RL05) gravity solutions indicate that during the 10 year period January 2003 to December 2012, the NWI groundwater depletion remains pronounced, especially during the first 5 years (01/2003–12/2007). The newly estimated depletion rates are ~20.4 ± 7.1 Gigatonne (Gt)/yr averaged over the 10 year period, and 29.4 ± 8.4 Gt/yr during the first 5 years. The yearly groundwater storage changes in the NWI region are strongly correlated with yearly precipitation anomalies. In 2009, the driest season of the decade, the groundwater depletion reaches nearly 80 Gt, while in the two relatively wet seasons, 2008 and 2011, the groundwater storages even see net increases of about 24 and 35 Gt, respectively. The estimated mean groundwater depletion rates for the first 5 years are significantly higher than previous assessments. The larger depletion rates may reflect the benefits from improved data quality of GRACE RL05 gravity solutions, and improved data processing method, which can more effectively reduce leakage error in GRACE estimates. Our analysis indicates that the neighboring Punjab Province of Pakistan (especially Northern Punjab) apparently also experiences significant groundwater depletion during the same period, which has partly contributed to the new regional groundwater depletion estimates.

1. Introduction

Groundwater is an important component of the global water cycle, and a vital resource to sustain agricultural, industrial, and domestic activities in many parts of the world, particularly in the most populous countries (e.g., China and India) or arid regions lacking adequate alternative resources of fresh water (e.g., Middle East and North Africa). Excessive groundwater extractions can lead to regional water resource scarcity, and pose significant impacts on the ecosystem and economic and social developments (Foster and Loucks, 2006; Gleeson et al., 2010). During the past few decades, intensive groundwater extractions, especially for agricultural irrigation, have led to dramatic drop of water head in many parts of the world, which in some places can be as much as up to a few hundred meters (Wang et al., 2006; Scanlon et al., 2012a, b). Due to the extremely slow process of groundwater recharging, the excessively depleted groundwater resource in those regions cannot be restored back to normal in foreseeable future. Excessive groundwater depletions not only result in insufficient water resource that is needed to support sustainable local economic development, but also cause higher energy consumption as more energy is needed to pump out groundwater when water head is becoming lower, placing increased pressure on the already constrained energy supply. The excessive groundwater depletions will also lead to significant ground subsidence, which, in extreme cases as in the San Joaquin Valley of California, could reach up to over 16 cm/yr during the middle of last century (Galloway et al., 1999), and greatly increase flood risk in the affected regions, such as Bangkok, Thailand (Giao and Nutalaya, 2006) and Jakarta, Indonesia (Abidin et al., 2008).

A good knowledge of groundwater storage change plays a key role for understanding the global hydrological cycle and its connections with climate change. Monitoring and understanding groundwater storage change, especially its long-term variability, are critical for maintaining sustainable economic development and healthy ecosystems. However, accurate quantifications of groundwater storage and its temporal and spatial variability have been challenging, due to the lack of

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adequate *in situ* observations, complexity of subsurface soil and rock properties, and the complicated nature of groundwater recharging processes (Döll et al., 2012). Limited well water level measurements may serve as a qualitative indicator of local groundwater storage change, but accurate estimation of groundwater storage change in a large region (or river basin) not only requires a dense network of wells covering the entire region, but also relies on good knowledge of subsurface soil and rock properties.

Land surface models (LSMs) have been a useful tool for studying and predicting temporal and spatial variations of terrestrial water storage (TWS) and other hydrologic parameters (e.g., Rodell et al., 2004). However, lack of adequate *in situ* observations as constraints in LSMs has limited the accuracy of TWS change simulations, especially at interannual and longer time-scales (e.g., Chen et al., 2010). Furthermore, the groundwater component is often absent or not separately estimated in LSMs (Rodell et al., 2004). Even in those LSMs that have a groundwater component (Güntner et al., 2007), it is difficult to accurately model and quantify groundwater storage changes, due to reasons noted above (Döll et al., 2012).

Since the Gravity Recovery and Climate Experiment (GRACE) mission was launched in 2002, time-variable gravity measurement from satellite gravimetry has emerged as a successful tool for measuring large-scale TWS changes (Tapley et al., 2004). GRACE has been measuring Earth gravity change on monthly basis for over 11 years, with unprecedented accuracy. The Earth gravity change is introduced by mass redistribution within different components of the Earth system, including the atmosphere, ocean, hydrosphere, cryosphere, and solid Earth. GRACE observed time-variable gravity change can be used to infer surface water mass change, given that other geophysical causes of gravity change can be removed separately (e.g., Wahr et al., 1998; 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, which include contributions from water storage changes in surface snow, subsurface soil, and groundwater reservoirs (and to a lesser extent, surface water reservoirs). Therefore, when surface water storage change (in soil and snow) is known, GRACE gravity measurements can be used to quantify groundwater storage change.

Previous studies (Rodell et al., 2009; 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 significant TWS decrease in the Ganges-Brahmaputra river basins (Northwest and North India) during the period August 2002 to October 2008. In the absence of an apparent precipitation deficit during that period, they attributed GRACE estimates of TWS decrease to anthropogenic effects, mainly agricultural irrigation and domestic consumption. The estimated groundwater depletion rate in Northwest India (NWI) is ~17.7 $\pm$ 4.5 Gt/yr (Rodell et al., 2009). Tiwari et al. (2009) has examined groundwater change for a broader region covering North India (from Northwest to Northeast), and estimated a long-term depletion rate of 54 $\pm$ 9 Gt/yr over roughly the period (April 2002 to June 2008). Using a similar methodology, Famiglietti et al. (2011) reports a large groundwater decrease (up to ~4.8 $\pm$ 0.4 Gt/yr) in California's Central Valley during the period October 2003 to March 2010, attributed to groundwater pumping for irrigation, and similar results are also reported by Scanlon et al. (2012a, 2012b). A more recent study (Feng et al., 2013), based on GRACE gravity data and model predicted surface water storage change, indicates that groundwater storage in North China has also experienced significant decrease (up to ~8.3 $\pm$ 1.1 Gt/yr) during the period 2003 to 2010.

In the present study, we will reassess long-term groundwater variability in the NWI region, using a newer release (i.e., the release-5 or RL05) of GRACE time-variable gravity solutions. The improved data quality and extended record of the GRACE RL05 solutions enable us to better quantify groundwater storage change in the NWI region and understand its long-term variability. In addition, using an improved data processing method, i.e., unconstrained global forward modeling (Chen et al., submitted for publication), we can further improve GRACE estimates by reducing biases that are caused by spatial leakage errors, inherited from the availability of up to limited degree and order of spherical harmonic coefficients in GRACE gravity solutions and spatial filtering or smoothing applied to GRACE data. We will quantify long-term groundwater storage changes in the NWI region using two different approaches: 1) applying the unconstrained forward modeling to GRACE-observed TWS rates (Chen et al., submitted for publication; this has been the concept that forward modeling was originally designed for, i.e. to restore the true mass rate of each given area or grid point from observed apparent mass rate), and 2) applying the unconstrained forward modeling to GRACE monthly TWS estimates. The later is more challenging to implement, but offers a means for evaluating groundwater storage change over a broad spectrum (i.e., in time series domain) at different time scales, as the leakage correction via forward modeling is implemented to each monthly solution, and we can examine groundwater storage change via time series analysis.

2. Long-term NWI groundwater rates

2.1. TWS changes from GRACE gravity measurements

We use GRACE RL05 monthly gravity solutions provided by the Center for Space Research (CSR), University of Texas at Austin. The GRACE gravity solutions used in this study cover a 10 year period from January 2003 to December 2012. Each monthly solution consists of fully normalized spherical harmonic coefficients to degree and order 60. The very low degree spherical harmonic coefficients, especially the degree-2 zonal harmonic coefficients (C_{20}) in GRACE gravity solutions show relatively higher level of uncertainty. Therefore, we have replaced the GRACE C_{20} coefficients by the satellite laser ranging (SLR) estimates provided by CSR (Cheng and Ries, 2012). GRACE gravity solutions do not provide the degree-1 spherical harmonic coefficients (i.e., C_{10}, C_{11}, and S_{11}), which represent the change of the mass center or geocenter of the Earth system. Seasonal variations of geocenter terms are adopted from estimates of Swenson et al. (2008), while long-term geocenter variation is not modeled in this study due to no reliable geodetic estimates of long-term geocenter change are available at the present.

At high degrees and orders, GRACE spherical harmonics are contaminated by noise, including longitudinal stripes, and other errors. Swenson and Wahr (2006) demonstrated that the longitudinal stripes are associated with correlations among certain spherical harmonic coefficients. A decorrelation filtering (Swenson and Wahr, 2006) and 500 km Gaussian smoothing (Jekeli, 1981) are applied to GRACE data, in order to suppress the spatial noise in GRACE high degree and order spherical harmonic coefficients. Effects of long-term solid Earth deformation due to post-glacial rebound (PGR) effect are removed using a PGR model (A et al., 2013). A global gridded ($1° \times 1°$) surface mass change field (in units of equivalent water height) is calculated from each of the GRACE spherical harmonic solutions, following the equations of Wahr et al. (1998), with a truncation up to degree and order 60. At each grid point, GRACE mass rate is estimated using unweighted least squares to fit of a linear trend, plus annual and semiannual sinusoids to GRACE-derived TWS time series (over the 10 year period, 2003 through 2012).

2.2. Ground water storage change from GRACE

GRACE TWS change represents combined effects of surface water (soil moisture, snow water, and surface reservoirs), and groundwater storage change. To separately estimate groundwater storage change, we need to quantify surface water storage change, and remove it from GRACE observations. We use model estimates from GLDAS (Rodell et al., 2004) to do this. GLDAS ingests satellite observations and ground-based measurements, and employs advanced land surface modeling and data assimilation techniques, to estimate land surface states and fluxes (Rodell et al., 2004). Data ingested include precipitation gauge observations, satellite and radar precipitation estimates, and downward radiation flux and analyses from atmospheric general circulation models. GLDAS estimates used here are from the Noah LSM (Ek et al., 2003), with precipitation taken from spatially and temporally downscaled NOAA Climate Prediction Center Merged Analysis of Precipitation. Solar radiation data are from the Air Force Weather Agency's AGRMET system. Monthly averaged soil moisture (2 m column depth) and snow water equivalent were computed from 1979 to present, with TWS at each grid point computed from the sum of soil and snow water. We neglect water storage in surface reservoirs (rivers and lakes), which is not modeled in GLDAS, and is likely a minor component in this region.

To remove GLDAS surface water estimates, we apply the same truncation and spatial filtering used on the GRACE surface mass fields. First, GLDAS surface water gridded fields are represented in a spherical harmonic expansion to degree and order 60 (same as the truncation in GRACE). Then the same 500 km Gaussian smoothing is applied, but the decorrelation filter is not. After these processing steps, the GLDAS long-term surface water storage rate for the 10 year period (January 2003 to December 2012) is estimated using the same least squares fit, and then subtracted from GRACE TWS rate to get groundwater rate. Fig. 1a shows the estimated groundwater rate (in cm/yr of equivalent water height change) in the NWI and surrounding regions. The NWI region (including part of Northeast Pakistan) showing evident TWS decrease is circled by the white contour lines.

2.3. Reducing leakage error in GRACE mass rate estimates

The applied truncation and spatial filtering (or smoothing) are expected to greatly limit spatial resolution of GRACE TWS estimates, and significantly attenuate the amplitudes (up to over 60%) of the true signal (Chen et al., submitted for publication). Based on synthetic data, Chen et al. (submitted for publication) have demonstrated that the global forward modeling is an effective tool for removing the leakage biases (due to truncation and spatial filtering) in GRACE-estimated mass changes, and restoring the true magnitudes of the signal, at least on regional average basis. What GRACE has observed (Fig. 1a) only

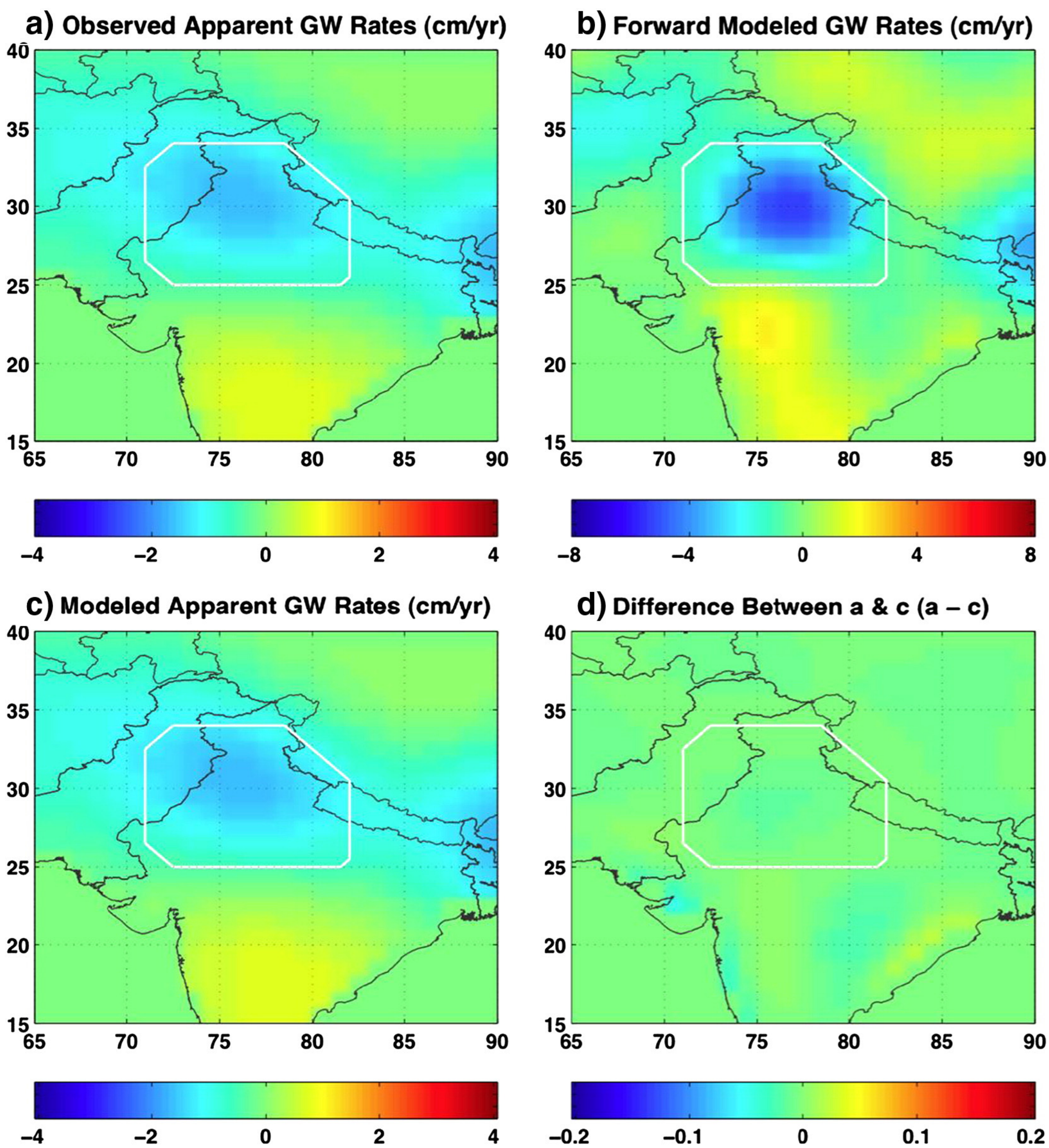

Fig. 1. (a) Apparent long-term groundwater (GW) rates from GRACE-GLDAS (in cm/yr of equivalent water height) in Northwest India (and the neighboring Northeast Pakistan), averaged over the 10 year period 01/2003–12/2012, and after decorrelation filtering and 500 km Gaussian smoothing; (b) Restored "true" long-term GW rates from forward modeling. (c) Forward modeled apparent GW rates; (d) Difference between observed and modeled apparent mass rates (i.e., a–c). Please notice the different color scale used in the 4 panels.

represents the apparent mass rates, after truncation and filtering, and the true amplitude and spatial extent of the signal may be quite different from what have been shown here.

Here, we apply a fully unconstrained global forward modeling [similar to the unconstrained forward modeling discussed in Chen et al. (submitted for publication)] to correct potential leakage errors in GRACE groundwater estimates. While the details of the forward modeling methodology can be found in Chen et al. (submitted for publication), here we provide a brief synopsis of the procedures:

1) At each grid point on a 1° × 1° grid (Fig. 1b), a trial or initial mass rate is assigned equal to the GRACE apparent mass rate (in Fig. 1a).
2) A forward model apparent mass rate map (Fig. 1c) is obtained by representing the 1° × 1° gridded model mass rates from Step 1 (Fig. 1b) into fully normalized spherical harmonics, truncated at degree and order 60. The degree 0 and 1 coefficients are set to zero. Then the 500 km Gaussian smoothing filter is applied and the result is compared with Fig. 1b.
3) At each grid point, the difference between GRACE apparent rate (Fig. 1a) and modeled apparent rate (Fig. 1c) is added to the model rate with a scale factor of 1.2 (which can help speed up the convergence of the iteration; the choice of 1.2 is purely empirical and may not represent the optimal number). The new model rate is filtered as in Step 2, and the process is repeated. Successive iterations produce increasing agreement between modeled and GRACE apparent rate maps (i.e., Fig. 1a vs. Fig. 1c).
4) We stop iterations when residual difference between modeled and GRACE apparent rate maps falls below a specified value, or after a certain number of iterations.

The “true” groundwater rates estimated from the fully unconstrained forward modeling after 60 iterations are shown in Fig. 1b, and the forward modeled apparent rates are shown in Fig. 1c, which resemble the observed apparent rates (Fig. 1a) very well. The differences between observed and modeled apparent groundwater rates are well under 0.05 cm/yr, or less than a few percents of the signals (Fig. 1d). Before the leakage error correction, the total groundwater rate in the NWI region (circled by the white contour line in Fig. 1a–d) is ~ −10.6 Gigatonne (Gt)/yr, while after the leakage correction through unconstrained forward modeling, it reaches ~ −22.8 Gt/yr. The significantly large discrepancy between the two results illustrates the importance of correctly addressing leakage error in GRACE mass change estimations, and is consistent with the conclusions based on simulations using synthetic data (Chen et al., submitted for publication).

The decorrelation filter is not applied the step 2 of the forward modeling process due to two considerations: 1) the decorrelation filter is non-linear and its effect on true signal may not be able to restore through forward modeling; 2) the decorrelation filter is mostly orthogonal and its effect on land water storage changes is minimal in most cases (Swenson and Wahr, 2006).

2.4. Uncertainty assessments

It is challenging to assess uncertainty in GRACE TWS change estimates, mainly due to the lack of adequate *in situ* measurements to validate GRACE observations. An additional complication comes from the removal of surface water storage using GLDAS, whose uncertainty is essentially unknown. One measure of uncertainty comes from variations over the oceans, where long-term mass changes, mainly representing non-steric sea level changes, should be small and typically less than a few mm/yr (Chen et al., 2013). Residual long-term mass changes over the oceans should then reflect uncertainty in GRACE estimates. We can assume that the uncertainty of GRACE mass rates over land is at about the same level as in the ocean area in the same latitudes, and then use the ocean RMS residuals to approximate GRACE uncertainty over land.

We pick up an ocean area in the Pacific ([25 N-35 N, 170E-220E]), which is at about the same latitudes as the NWI region and far enough from land to avoid leakage of variance from land hydrology. The RMS variations within this ocean area are ~0.45 cm/yr for GRACE observed apparent mass rates (Fig. 1a), and 0.48 cm/yr for the forward modeled true mass rates (Fig. 1b), which translate into uncertainties of ~ ±4.4 Gt/yr (before leakage correction) and ±4.6 Gt/yr (after leakage correction) for GRACE-estimated total groundwater depletion rates in the NWI region. Another error source comes from uncertainty in the trend estimates using least squares fit. We estimate that this might result in another uncertainty of ~20% of the signal.

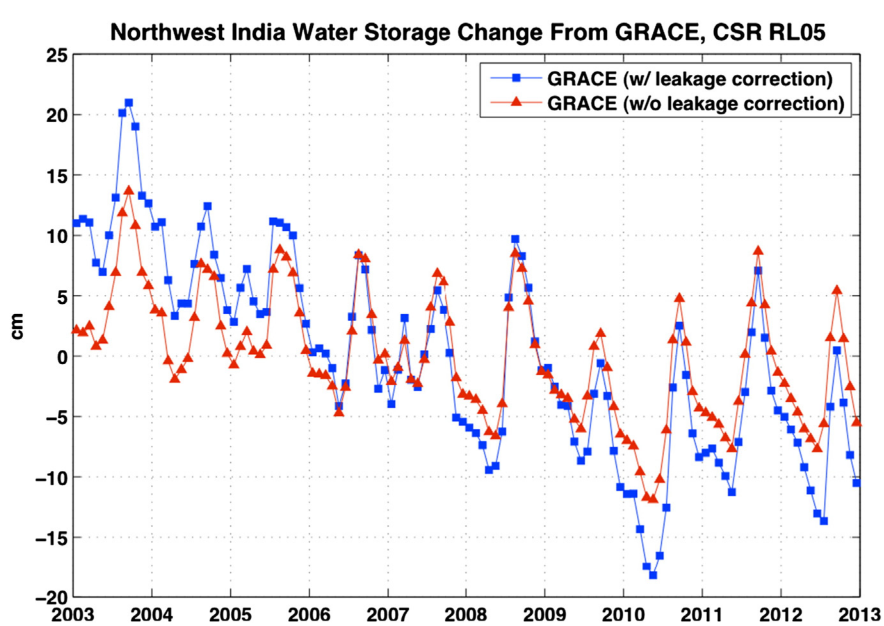

Fig. 2. GRACE-observed mean terrestrial water storage change (in cm of equivalent water height) in Northwest India, within the area circled by the white curves in Fig. 1. The red curve represents GRACE estimates after decorrelation and 500 km Gaussian smoothing, while the blue curve shows the results after leakage correction based on unconstrained forward modeling.

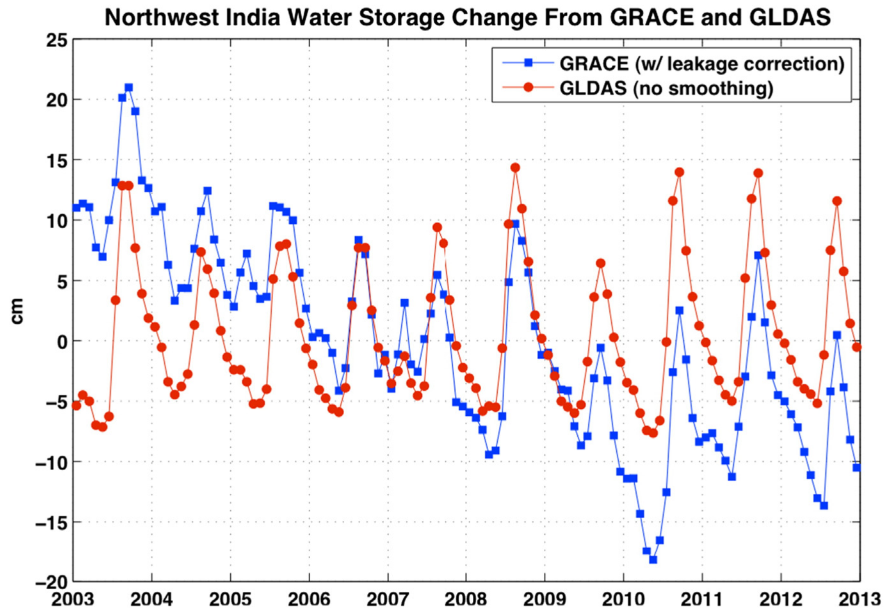

Fig. 3. GRACE-observed mean terrestrial water storage change (in cm of equivalent water height) in Northwest India, within the area circled by the white curves in Fig. 1, superimposed by GLDAS model predicted soil and snow water storage change. GRACE estimates are from forward modeling. No smoothing is applied to GLDAS estimates, but a truncation of spherical harmonics at degree and order 60 is indeed applied to GLDAS data, to be consistent with GRACE results.

In addition, leakage from ice melting of nearby mountain glaciers may also affect GRACE-estimated groundwater change in the NWI region, which is estimated to be around −2.8 Gt/yr (Rodell et al., 2009). We assume that the uncertainty of the glacial melting leakage is about 100% of the estimate. Therefore, after glacial melting leakage is removed and the three discussed uncertainty contributions (GRACE residual error, trend fitting error, and glacial melting leakage error) are considered, GRACE-estimated groundwater depletion rate in the NWI region is 20.0 ± 7.1 Gt/yr during the 10 year period.

In the present study, we neglect long-term geocenter contribution to NWI groundwater rate. Numerical simulations using the long-term geocenter rates provided by Swenson et al. (2008) suggest that long-term geocenter effect on the estimated NWI rate is very small (~0.1 Gt/yr), and is simply negligible.

3. Broad spectrum analysis of NWI groundwater changes

3.1. Reducing leakage error in GRACE monthly mass fields

Spatial leakage error affects not only GRACE-observed mass rates (as in Fig. 1a), but also GRACE monthly mass fields. The earlier versions of the forward modeling method have been mostly applied to correct leakage error in GRACE-observed mass rates, especially in long-term ice mass rates of polar ice sheets and mountain glaciers. This is because in those forward modelings, certain *a priori* information (the so-called constraint) is needed, such as the approximate locations of the signal. It is relatively easy to make this type of assumptions when dealing with long-term ice mass losses of costal glaciers, as at long-term time scales, the locations of the observed ice mass changes are often known

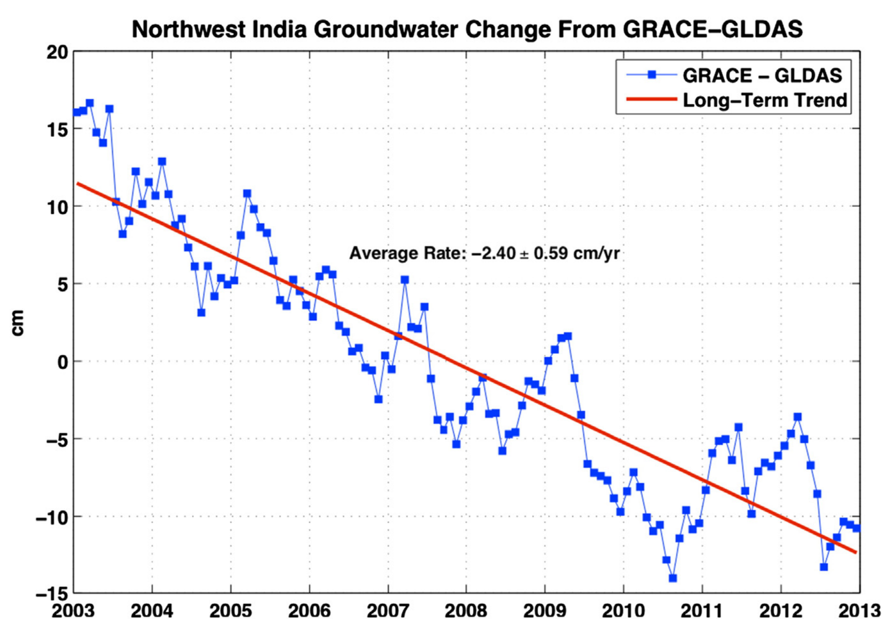

Fig. 4. Mean groundwater storage change (in cm of equivalent water height) in Northwest India, within the area circled by the white curves in Fig. 2, derived by GRACE minus GLDAS (i.e., the difference of the two time series in Fig. 3. Superimposed is the linear trend estimated from least-squares-fit of the time series. The mean groundwater change rate is −2.40 ± 0.59 cm/yr, equivalent to ~−23.6 ± 5.8 Gigatonne (Gt)/yr during the 10 year period (this is before glacial leakage correction).

(i.e., along the coasts), and mass changes in surrounding regions (e.g., over the ocean) can mostly be neglected. However, at monthly time scales or when in inner-land areas, things become more complicated. We cannot simply neglect surrounding mass changes, and the exact location of the signal is often unknown.

The recent development of the fully unconstrained forward modeling technique and improved data quality of the GRACE RL05 gravity solutions make correcting leakage error in GRACE monthly mass fields with fairly good accuracy possible. We apply the same fully unconstrained forward modeling (used to the apparent groundwater rates as described in 2.3) to each of the monthly mass fields derived from GRACE gravity solutions (described in 2.1) to remove the leakage error (due to truncation and spatial filtering applied to GRACE data). GRACE-estimated monthly TWS changes in the NWI region before and after leakage corrections are shown in Fig. 2 in blue and red curves, respectively. It is evident, after the leakage correction, GRACE-estimated TWS change in the region yields a much greater decreasing trend during the 10 year period (i.e. −2.24 cm/yr after leakage correction vs. −0.97 cm/yr before leakage correction).

3.2. Monthly and long-term groundwater storage changes

After leakage correction through forward modeling, at seasonal time scales GRACE-observed TWS changes in the NWI region agree well with GLDAS-estimated water storage changes from surface soil and snow (see Fig. 3; no smoothing is applied to GLDAS estimates in this case). However, during the same period GLDAS-estimated surface water storage changes do not show any decreasing trend, and the last few years (e.g., 2010 to 2012) appear to be even wetter than earlier years, leading to a slight increasing trend in GLDAS surface water storage estimates. This suggests that GRACE-observed TWS decrease is primarily due to groundwater storage change.

After GLDAS surface water storage changes are removed from GRACE estimates, the residuals, presumably representing groundwater

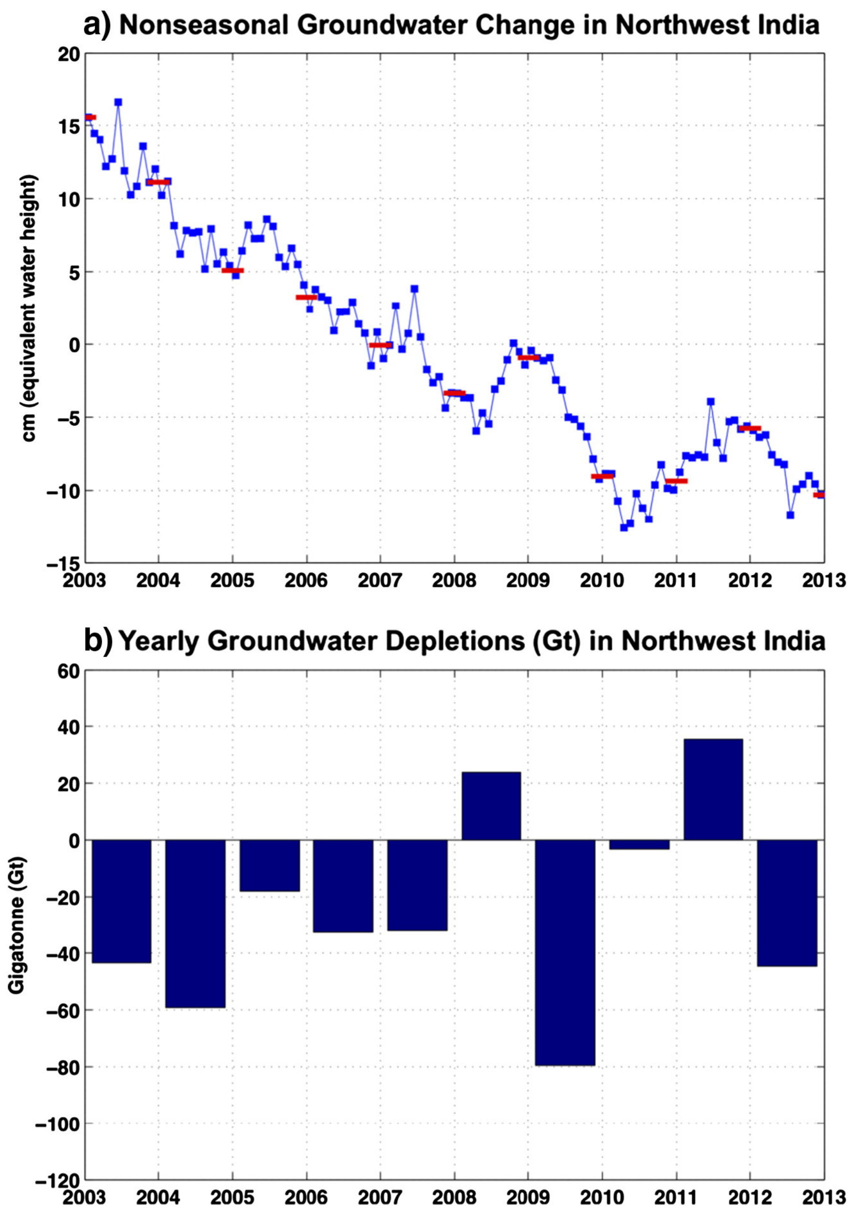

Fig. 5. (a) Nonseasonal mean groundwater storage change (in cm of equivalent water height) in Northwest India, within the area circled by the white curves in Fig. 2, derived by GRACE minus GLDAS (same as the time series in Fig. 4, but with annual and semiannual variations removed using least-squares-fit). The red horizontal bars represent the mean groundwater storage at the beginning (or end) of each year (computed as the mean of previous year's December and current year's January). (b) Yearly groundwater depletions [in Gigatonne (Gt)] computed from the difference of groundwater storages between a given year's end and start, i.e. difference between two consecutive red bars in (a).

storage change in the NWI region, show a steady decreasing trend, especially during the first 5 years (2003–2008). The averaged linear trend over the 10 year period is estimated to be −2.40 ± 0.59 cm/yr based on unweighted least squares fit. The uncertainty represents the formal error with 95% confidence from least squares fit of the groundwater time series (blue curve in Fig. 4) using Monte Carlo tests (Chen et al., 2013). This mean rate (−2.40 ± 0.59 cm/yr) translates into a total groundwater rate of −23.6 ± 5.8 Gt/yr in the NWI region, or −20.8 ± 6.4 Gt/yr after glacial melting leakage correction. However, during the first 5 years (2003–2008), the total groundwater depletion rate is expected to be significantly higher (29.4 ± 8.4 Gt/yr).

3.3. Yearly groundwater storage changes

To better evaluate year-over-year groundwater storage changes in the NWI region, we further remove residual annual and semiannual signals in the GRACE groundwater time series (blue curve in Fig. 4), and show the monthly residuals in Fig. 5a (blue curve). We estimate the mean groundwater storage at the beginning or end of the year (the end of the year is the beginning of the next year) by averaging the groundwater storage changes in January of the current year and December in the previous year (see the red horizontal bar in Fig. 5a). The mean groundwater storages at the two ends of the time series (i.e., 2003.0 and 2013.0) simply adopt estimates in January 2003 and December 2012 instead. Yearly groundwater storage change (in Gt/yr) is computed from the difference between the end and beginning of a given year (Fig. 5b).

It has become rather clear. During the 10 year period, the NWI groundwater storage shows moderate increases in 2008 and 2011, stays in roughly balance in 2010, and experiences significant decreases in other 7 years. The first 5 years show consistent groundwater depletion (averaged at over 30 Gt/yr). However, the largest yearly groundwater depletion occurs in 2009, reaching up to ~80 Gt. The mean of the 10 yearly groundwater storage changes is ~−25.3 Gt/yr, compared to ~−23.6 Gt/yr, the estimate based on unweighted least squares fit to the GRACE groundwater time series (Fig. 4). Please note that the estimated mean rates from least squares fit and averaging the yearly changes' means will not necessarily be the same.

3.4. Groundwater storage change and climate conditions

Long-term groundwater depletions are primarily tied to excessive groundwater pumping for agricultural and domestic uses (e.g., Rodell et al., 2009; Tiwari et al., 2009; Famiglietti et al., 2011). Variations in regional climate condition, especially amount of precipitation received in the regions can also drive decadal, interannual and seasonal groundwater storage changes. To better understand the connections between interannual groundwater storage changes and precipitation variations in the NWI region, we show in Fig. 6 the yearly accumulated total precipitation (in cm), computed from the Global Precipitation Climatology Project (GPCP) monthly precipitation V2.2 datasets (Adler et al., 2003). Consistent with GLDAS model predicted surface soil and snow water storage change, during the 10 year precipitation in the NWI region does not show any long-term decreasing trend, and 2009 appears to be the relatively driest year (with the least amount of precipitation received). The yearly accumulated total precipitations actually show a slight increasing trend.

Yearly precipitation anomalies are computed by removing the mean of the 10 yearly precipitations (from the yearly precipitations), and compared with yearly groundwater storage changes (see Fig. 7). The yearly groundwater storage changes are the same as those shown in Fig. 5b, but presented as regional average (in cm of equivalent water height). The yearly groundwater storage changes and precipitation anomalies are in different scales (the precipitation is amplified by scale factor of 2), marked by the left and right axes, respectively. There is a very good coherence between the two time series, indicating that interannual groundwater storage variability in the NWI region is mostly driven by precipitation change. The driest 2009 season (during the 10 years) experiences the largest amount of groundwater depletion (up to ~8 cm/yr or 80 Gt/yr). The 2003 groundwater depletion rate seems to be greater than it should be when considering the relatively large amount of precipitation received in that year. This is likely related to the fact that 2002 (not shown here due to the unavailability of GRACE RL05 data at the moment) is a very dry season, which receives even less amount of precipitation than the 2009 season. There might be a delayed recovery of groundwater storage from the 2002 drought.

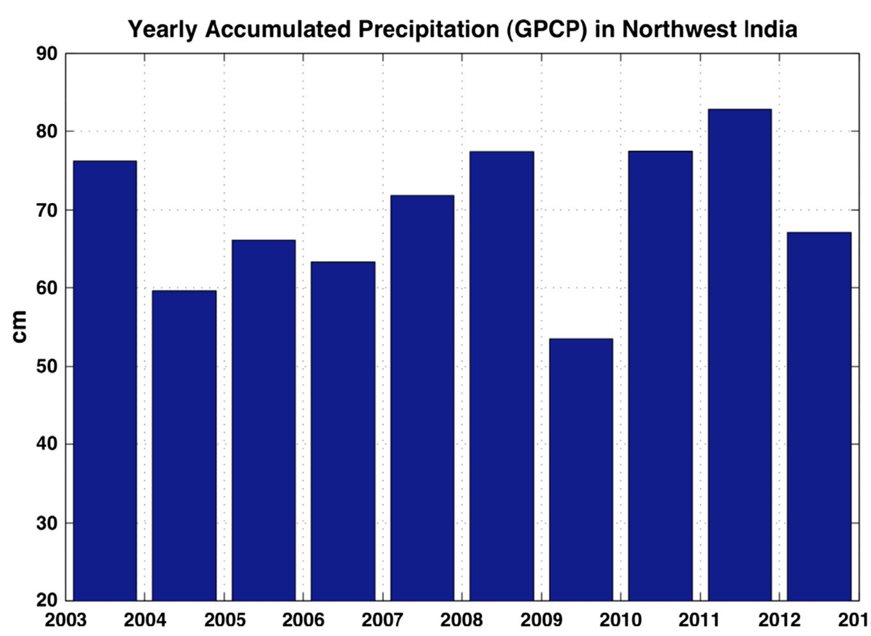

Fig. 6. Yearly accumulated precipitations (in cm) in Northwest India, within the area circled by the white curves in Fig. 1, computed from the Global Precipitation Climatology Project (GPCP) precipitation data.

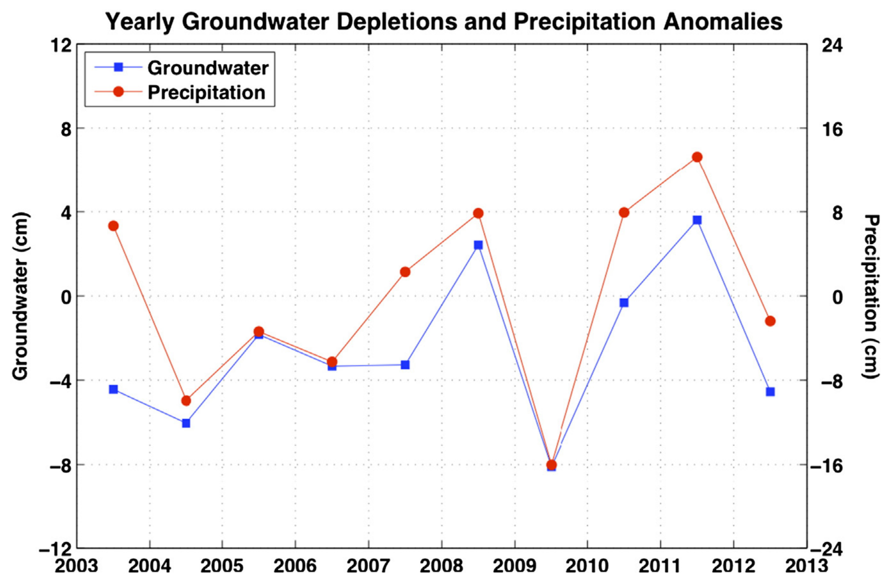

Fig. 7. Comparison between yearly groundwater depletions (in cm of equivalent water height, marked on the left Y axis, same as those illustrated in Fig. 5b, but in different units), and yearly precipitation anomalies (in cm of equivalent water height, marked on the right Y axis, same as those illustrated in Fig. 6, but with the mean over the 10 years removed from each yearly accumulated precipitation).

4. Summary and discussions

Using an extended 10 years record of GRACE RL05 time-variable gravity solutions and estimates from the GLDAS hydrological model, we have re-assessed long-term groundwater depletion rates in the NWI region, and evaluated interannual variability of groundwater storage change in the region and its connection with surface climate conditions. Based on a newly developed unconstrained global forward modeling method (Chen et al., submitted for publication), we are able to successfully remove leakage errors in GRACE estimates that are associated with truncation and spatial filtering applied to GRACE data, and improve the accuracy of GRACE-estimated groundwater storage change. After leakage error correction by applying unconstrained global forward modeling to GRACE-observed apparent mass rate field (Fig. 1a), the total groundwater storage change rate in the NWI region is estimated to be -20.0 ± 7.1 Gt/yr during the 10 year period (January 2003–December 2012), compared to the estimate of -7.8 ± 5.3 Gt/yr before the leakage error correction. Leakage error is apparently the single largest error source to GRACE estimates.

We have also carried out a broad-spectrum analysis of groundwater changes in the NWI region by applying a similar leakage error correction to each of the GRACE monthly mass fields. In this case, the estimated total groundwater storage change rate is -20.8 ± 6.4 Gt/yr during the 10 year period, which agrees very well with the result (-20.0 ± 7.1 Gt/yr) from the mass-rate based forward modeling. We take the average of the two rates (i.e., -20.4 ± 7.1 Gt/yr) as our official estimate of long-term NWI groundwater rate (over the 10 year period) in the present study. The NWI groundwater storage exhibits strong interannual variability as well. During the first 5 years (2002–2008), the NWI groundwater storage experiences more steady and also significant depletion, with an average rate of -29.4 ± 8.4 Gt/yr. During 2009, the driest season in the 10 year period the NWI groundwater depletion rate reaches up to ~80 Gt, while in the two wet seasons, 2008 and 2011 the groundwater storages even see net increases of about 24 and 35 Gt, respectively. At interannual time scales, there is a strong coherence between yearly groundwater change and precipitation anomalies, showing a close connection between groundwater storage and surface climate condition.

The estimated mean groundwater depletion rate for the first 5 years in the present study is significantly higher than previous assessments (e.g., Rodell et al., 2009). The larger depletion rate may reflect the benefit from improved data quality of GRACE RL05 gravity solutions, and improved data processing method, which can more effectively reduce leakage error. Our analysis indicates that the neighboring Punjab Province of Pakistan (especially Northern Punjab) apparently also experiences significant groundwater depletion during the same period, which may have partly contributed to the new estimates. The uncertainty of water storage change in surface soil and snow is not considered in the present study. However, both GLDAS model predictions and GPCP precipitation data indicate not evident long-term decrease in surface water storage in the NWI region, and GRACE-observed TWS decreasing rate should reflect primarily groundwater storage depletion. With the extended record (now exceeding 11 years) of GRACE time series, and improvement of data quality and data processing methods, GRACE time-variable gravity measurements offer a means for studying TWS changes at broader spatial and temporal scales with increased accuracy.

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