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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 ± 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 ± 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 ± 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 ± 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° × 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