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Key Points:

- Spatiotemporal changes in water storage of India are characterized
- GRACE records are validated using in situ groundwater levels from observation wells
- Significant water storage loss from the indirect effect of climate variability

Supporting Information:

- Supporting Information S1

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Spatiotemporal evolution of water storage changes in India from the updated GRACE-derived gravity records

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Abstract Investigating changes in terrestrial water storage (TWS) is important for understanding response of the hydrological cycle to recent climate variability worldwide. This is particularly critical in India where the current economic development and food security greatly depend on its water resources. We use 129 monthly gravity solutions from NASA's Gravity Recovery and Climate Experiment (GRACE) satellites for the period of January 2003 to May 2014 to characterize spatiotemporal variations of TWS and groundwater storage (GWS). The spatiotemporal evolution of GRACE data reflects consistent patterns with that of several hydroclimatic variables and also shows that most of the water loss has occurred in the northern parts of India. Substantial GWS depletion at the rate of 1.25 and 2.1 cm yr^{-1} has taken place, respectively in the Ganges Basin and Punjab state, which are known as the India's grain bowl. Of particular concern is the Ganges Basin's storage loss in drought years, primarily due to anthropogenic groundwater withdrawals that sustain rice and wheat cultivation. We estimate these losses to be approximately 41, 44, and 42 km^3 in 2004, 2009, and 2012, respectively. The GWS depletions that constitute about 90% of the observed TWS loss are also influenced by a marked rise in temperatures since 2008. A high degree of correspondence between GRACE-derived GWS and in situ groundwater levels from observation well validates the results. This validation increases confidence level in the application of GRACE observations in monitoring large-scale storage changes in intensely irrigated areas in India and other regions around the world.

1. Introduction

Water scarcity has posed serious challenges to food security, ecosystem sustenance, and economic prosperity in many parts of the world today, particularly triggered by population growth and climate variability [*Schewe et al.*, 2013]. Recognized as one of the future global hot spots of food and water scarcity [*UNESCO-WWAP*, 2009; *Wheeler and von Braun*, 2013], the Indian subcontinent has become a water-stressed region with a sharp drop in per capita water availability, from a surplus level of 5410 m^3 in 1951 to 1614 m^3 in 2011 for its population of 1.2 billion [*Jain*, 2011; *UNICEF et al.*, 2013]. In general, the increasing water demands for agriculture, economic activities, power generation, and drinking water has led to interbasin conflicts within the country and also to transboundary water disputes because of similar level of demand from the densely populated neighboring countries [*UNESCO-WWAP*, 2009; *Wirsing et al.*, 2013]. In particular, Indian agriculture, leading the world in total irrigated land by consuming ~85% of the utilizable water resources of 1123 billion m^3 (i.e., ~28% of 4000 billion m^3 total fresh water availability) [*Douglas et al.*, 2006], is the backbone of the country's socioeconomic developments in term of its contribution to the GDP (gross domestic product) and its involvement of a large section of the population. The water requirement for a projected food production of 250 million metric ton by 2050 and the rising demands for recent economic development underscore the need for sustainable management of its water resources.

Terrestrial water storage (TWS), an important component of the hydrological cycle that integrates both the surface and subsurface water (i.e., sum of surface water in lakes and reservoirs, groundwater storage (GWS), soil moisture (SM), snow and ice, and water in biomass), reflects natural and anthropogenic changes of the terrestrial component of the Earth's water cycle [*Syed et al.*, 2008; *Yeh and Famiglietti*, 2008]. Moreover, TWS influences the climate system through the exchange of water and energy at the land surface. Although TWS can be derived from water balance models using runoff, evapotranspiration, and precipitation data sets, this variable was not often used in the literature until the launch of the Gravity Recovery and Climate

Experiment (GRACE), a satellite mission administered jointly by the U.S. and Germany. Since its launch in 2002, GRACE has provided temporal variations in the Earth's gravity field with unprecedented accuracy [*Tapley et al*., 2004; *Wahr et al*., 2004]. Changes in the gravity field are caused by changes in the Earth's mass distribution, and, at the time scales of the GRACE observations, those are mostly controlled by changes in TWS, after accounting for atmospheric effects. The vertically integrated water storage signals from GRACE on monthly time scales can be disaggregated using either in situ observations, or by land surface model output such as those provided by the Global Land Data Assimilation System (GLDAS) [*Rodell et al*., 2004], in order to estimate any particular water storage component (e.g., GWS), as GRACE itself cannot vertically differentiate the individual TWS components.

Many studies, ranging from large river basins to continental scales, have shown the value of GRACE records for assessing hydrological mass variations, including their use as a reliable indicator of the impact of recent extreme hydroclimatic events [e.g., *Chen et al*., 2010; *Frappart et al*., 2013; *Houborg et al*., 2012; *Long et al*., 2013; *Reager and Famiglietti*, 2013; *Scanlon et al*., 2012a; *Voss et al*., 2013]. The primary reason for the growing scientific interest in GRACE as a hydrological tool is the lack of adequate monitoring of terrestrial hydrological components, as well as restrictions on sharing the available information for political, socioeconomic, and defense purposes in many parts of the world [*Alsdorf et al*., 2007; *Famiglietti and Rodell*, 2013]. For the Indian subcontinent, as highlighted in a recent special Intergovernmental Panel on Climate Change report [*IPCC*, 2012], that data unavailability has led to limited understanding about recent climatic events. Using 73 monthly GRACE records during August 2002 to October 2008, *Rodell et al*. [2009] and *Tiwari et al*. [2009] have provided unprecedented information regarding large-scale groundwater depletion in the north and northwestern parts of India. They attributed these negative anomalies in GWS to the unsustainable consumption of groundwater for irrigation, as the annual rainfall during that period was normal and there was little change in other components of terrestrial water storage.

The hydroclimatology of the Indian subcontinent is characterized by a strong annual cycle forced by the South Asian summer monsoon during June–September, which contributes ~80% of the annual rainfall [*Webster et al*., 1998]. Small changes in the magnitude and timing of monsoonal rainfall have led to severe droughts, with socioeconomic cost amounting to billions of dollars, as occurred during the century-scale droughts of 2002 and 2009 [*Gadgil and Gadgil*, 2006; *Hazra et al*., 2013]. In the adjacent regions of western Nepal and southwestern China, signatures of the recent droughts have been observed as negative anomalies in GRACE-derived TWS [*Tang et al*., 2014; *Wang et al*., 2013]. Although adverse impacts of droughts on the subsurface hydrological component have been studied at local scales [*Panda et al*., 2007, 2011], nationwide or basin-scale characterization of the response to recent climatic variability would be of immense scientific and socioeconomic interest.

The primary objective of this study is to investigate the spatiotemporal evolution and trends in water storage changes in India using 129 months of GRACE records over the period of January 2003 to May 2014. Moreover, to evaluate the reliability of GRACE records in depicting the propagation of hydroclimatic variables into the terrestrial branch of the water cycle, we compare the GRACE results with a suite of variables, including rainfall, soil moisture (SM), maximum temperature (T_{max}), minimum temperature (T_{min}), the Palmer Drought Severity Index (PDSI), and the Normalized Difference Vegetation Index (NDVI). In the absence of in situ soil moisture data at large scales in India, we use the modeled SM of the CLM4.5 land surface model. As an integrated measure of rainfall, temperature, and evapotranspiration, PDSI is likely to provide an independent measure of the impact of meteorological drought on GRACE-derived water storage changes [*Dai*, 2011; *Frappart et al*., 2013]. In monsoon regions of the world, since meteorological data would yield a biased trend estimate due to the strong seasonality driven by the monsoon climate [*Dorigo et al*., 2012; *Shamsudduha et al*., 2012], the premonsoon (JFMAM), summer monsoon (JJAS), and postmonsoon (OND) season storage changes are presented separately.

At a large spatial scale, the application of GRACE records to assess groundwater storage changes is validated using in situ groundwater level data from ~2800 observation wells in one of the global hot spots of groundwater depletion, i.e., the Ganges River Basin in India [*Wada et al*., 2010]. In the published literature, only a few studies have investigated the reliability of GRACE-derived GWS by comparing with water table data from more than 100 observation wells [e.g., *Joodaki et al*., 2014; *Scanlon et al*., 2012a; *Shamsudduha et al*., 2012; *Swenson et al*., 2006, 2008]. The regional-scale analysis in India shows significant relationship between groundwater levels and GRACE-derived GWS [*Dasgupta et al*., 2014; *Tiwari et al*., 2011], suggesting the scope of utilization of both in situ and satellite data sets for solving the basin-scale water management problems. Although GRACE satellite records capture large-scale depletions, in situ water table data are crucial for aquifer management, considering the large spatial and temporal variability in depletion [*Scanlon et al.*, 2012b]. The intensely irrigated transboundary Ganges Basin, encompassing the maximum 861,452 km^2 drainage area in India (i.e., ~26% of the geographical area of India and 79% of the entire Ganges Basin), contributes about half of India's total food grain production and is home to about 42% of the population. The reported hydroclimatic sensitivity and consequent crop vulnerability issues of the Ganges River Basin [*Bollasina et al.*, 2011; *Lobell et al.*, 2012] underscore the need of investigating water storage changes to assist policy makers in adopting sustainable water management strategies.

2. Data and Methods

2.1. Hydroclimatic Data

The GRACE satellite, launched in March 2002 by NASA and the Deutsches Zentrum fur Luft- und Raumfahrt (DLR), provides monthly gravity field solutions in the form of spherical harmonic coefficients down to scales of a few hundred kilometers, which can be used to make global estimates of vertically integrated terrestrial water storage [*Tapley et al.*, 2004; *Wahr et al.*, 2004]. This study uses 129 monthly gravity fields, from January 2003 to May 2014, of the GRACE Release-5 (RL05) Stokes coefficients, processed by the Center for Space Research (CSR) at the University of Texas, Austin. Since the degree-two zonal harmonic coefficients (C20) in GRACE gravity solutions show relatively higher levels of uncertainty, we have replaced the GRACE C20 coefficients with those determined from Satellite Laser Ranging [*Chen et al.*, 2014]. Moreover, we have included degree-one coefficients, computed as described by *Swenson et al.* [2008] and provided by S. Swenson (personal communication, 2015). The results have been spatially smoothed with a 350 km Gaussian smoothing function [*Wahr et al.*, 1998]. This latest release of CSR GRACE RL05 time-variable gravity solutions, which includes improved background processing methods to reduce leakage error, leads to further improvements in estimates of water storage changes [*Chen et al.*, 2014; *Long et al.*, 2013].

For consistency with previous studies [*Chen et al.*, 2014; *Tiwari et al.*, 2011], groundwater storage (GWS) is estimated in this study by removing the modeled soil moisture (SM) of GLDAS/Noah, which is a land surface modeling system integrating satellite and ground-based data products to drive advanced simulations for climate and hydrologic investigations [*Rodell et al.*, 2004], from the GRACE gravity field solutions. When we use the GRACE spherical harmonic coefficients to generate total water storage signals in the spatial domain, it introduces distortions, though those distortions, incidentally, are no more serious than the distortions present in the mascon solutions. But by transforming the GLDAS fields into the spherical harmonic domain, and using the same analysis methods on those GLDAS harmonics as we used on the GRACE harmonics, we distorted the GLDAS fields in exactly the same way as we did for the GRACE fields. This helped to remove the problem of introducing spurious signals into the GRACE GWS solutions.

For hydroclimatic comparisons, we use the modeled SM from version 4.5 of the Community Land Model (CLM4.5) [*Oleson et al.*, 2013], the terrestrial component of the Community Earth System Model (CESM1) [*Gent et al.*, 2011]. This version of SM includes a modified soil evaporative resistance parameterization, employing the atmospheric inputs from the CRUNCEP data set [*Swenson and Lawrence*, 2014]. Moreover, the modeled groundwater component of CLM4.5 is used for understanding the naturally occurring groundwater variation. As a surrogate for soil moisture, we also use the self-calibrated PDSI data on 2.5° grids during January 2003 to December 2012 to assess drought severity [*Dai et al.*, 2004; available at http://www.esrl.noaa.gov/psd/data/gridded/data.pdsi.html]. The recently updated gridded data set by the Indian Meteorological Department (IMD) for daily rainfall at a spatial resolution of $0.25° \times 0.25°$ and minimum (T_{min}) and maximum (T_{max}) temperatures at a spatial resolution of $1° \times 1°$ [*Srivastava et al.*, 2009] are used to assess meteorological linkages. Finally, the surface greenness indicator (i.e., Normalized Difference Vegetation Index, NDVI) used in this study at a spatial resolution of $0.5° \times 0.5°$ is derived from the MODIS 16 day composite vegetation index, recorded by the NASA's Terra platforms (MOD13Q1).

2.2. Groundwater Level Data

In India, groundwater levels (in meters below ground level, m.b.g.l.) are recorded 4 times a year, during January, May, August, and November, from more than 15,000 observation wells, by the *Central Ground Water Board* (*CGWB*) [2011]. However, only limited groundwater level data are available in the public domain. We obtain groundwater level data, with the mean water table up to 20 m below ground level, from about 2800 observation wells for the period of 2003–2013 within the Ganges River Basin in India (21.6°–31.21°N, 73.2°–89.5°E) from CGWB, for the first time, to validate the GRACE-based groundwater storage estimates. Moreover, for the state of Punjab that is recognized as the most overexploited region of India, about 250 observation wells, with the water table up to 40 m below ground level, are used to compare with the GRACE data. This is because the mean water table of Punjab varies from 3 to 34 m below ground level [*CGWB*, 2011]. While the premonsoon and postmonsoon water table reflects stable states of natural and anthropogenic stresses of groundwater recharge and discharge, the August water table values are biased due to the direct effect of monsoon rainfall, and have also been less frequently monitored. A subset of 374 and 521 observation wells in May (i.e., premonsoon), and November (postmonsoon season), respectively, without having a single missing observation during the study period, are used for trend assessment over the Ganges River Basin.

2.3. Nonparametric Trend Analysis

The availability of a decade-long GRACE record prompts us to use the nonparametric Mann-Kendall test, which does not require distributional assumptions about the time series, is robust against outliers that generally occur in hydroclimatic data due to extreme events, and is also a powerful trend detection technique for nonnormally distributed data even for a time series as short as 10 years [*Hirsch et al*., 1982; *Yu and Wang*, 2002]. In recent years, this test has been extensively used in hydroclimatic research [e.g., *Dorigo et al*., 2012; *Gan et al*., 2013]. As the Mann-Kendall test requires serially independent data [*Hirsch and Slack*, 1984], we assess the trends for the premonsoon (JFMAM), monsoon (JJAS), and postmonsoon (OND) seasons separately, using the seasonal average of GRACE and other meteorological data to handle the serial dependence from the strong seasonality of monsoon climate and also from the lag response of groundwater recharge [*Lettenmaier et al*., 1994]. Although high interannual variability ensures data independence for most of the time series, the prewhitening approach [*Zhang et al*., 2001] is also employed to remove the serial correlation from the data. The discussion of the results is based on the statistical significance of the trends evaluated using a two-sided 5% level significance (i.e., $p < 0.05$). To assess the magnitude of the trends, we use the Theil-Sen approach, which estimates the slope by calculating the median of the slopes between all combinations of two observations of the data [*Lettenmaier et al*., 1994; *Zhang et al*., 2001].

Initially, to better understand the linkages among climatic and water storage variables, the Spearman's linear correlation (r) analysis is performed using their nationally and regionally averaged anomalies. For the monsoon rainfall, the time series are standardized by subtracting the mean and then dividing by the standard deviation at each grid before spatially averaging, since the severity of droughts is better reflected through the standardized anomaly in the spatially diverse rainfall distribution of India. The null hypothesis of no correlation ($r = 0$), against the alternative hypothesis that there is a significant correlation, is evaluated at the significance level $p < 0.05$, unless the exact significance level (p) is mentioned. Moreover, in order to understand the spatial evolution, the spatial anomalies of hydroclimatic variables are mapped using the inverse distance weighting method.

3. Results and Discussion

3.1. Seasonal and Spatiotemporal Changes in Hydroclimatic Variables

To examine the temporal evolution at seasonal scales, we plot the nationally averaged changes of the GRACE-derived water storage anomalies and other variables in the premonsoon (JFMAM), summer monsoon (JJAS), and postmonsoon (OND) seasons (Figure 1). For these and all other variables, an "anomaly" refers to the value after the 2003–2013 average has been removed. In general, the amplitude and sign of the anomalies suggest that the premonsoon (JFMAM) season water storage losses, represented by the water equivalent thickness (cm), are replenished in the following seasons, particularly due to the contribution of the summer monsoon season (JJAS) rainfall, which modulates the interannual variability of the surface and subsurface components of the hydrological cycle by contributing about 80% of the long-term annual rainfall total of 1083 mm. The JJAS rainfall correlates significantly ($p < 0.05$) with CLM4.5 SM ($r = 0.74$), TWS (0.68), and the NDVI greenness index (0.81). In the premonsoon and postmonsoon seasons, however, the hydroclimatic variables are least influenced by the rainfall changes in those seasons, with no apparent linear relationship. Marginally, larger positive TWS and GWS anomalies in the postmonsoon

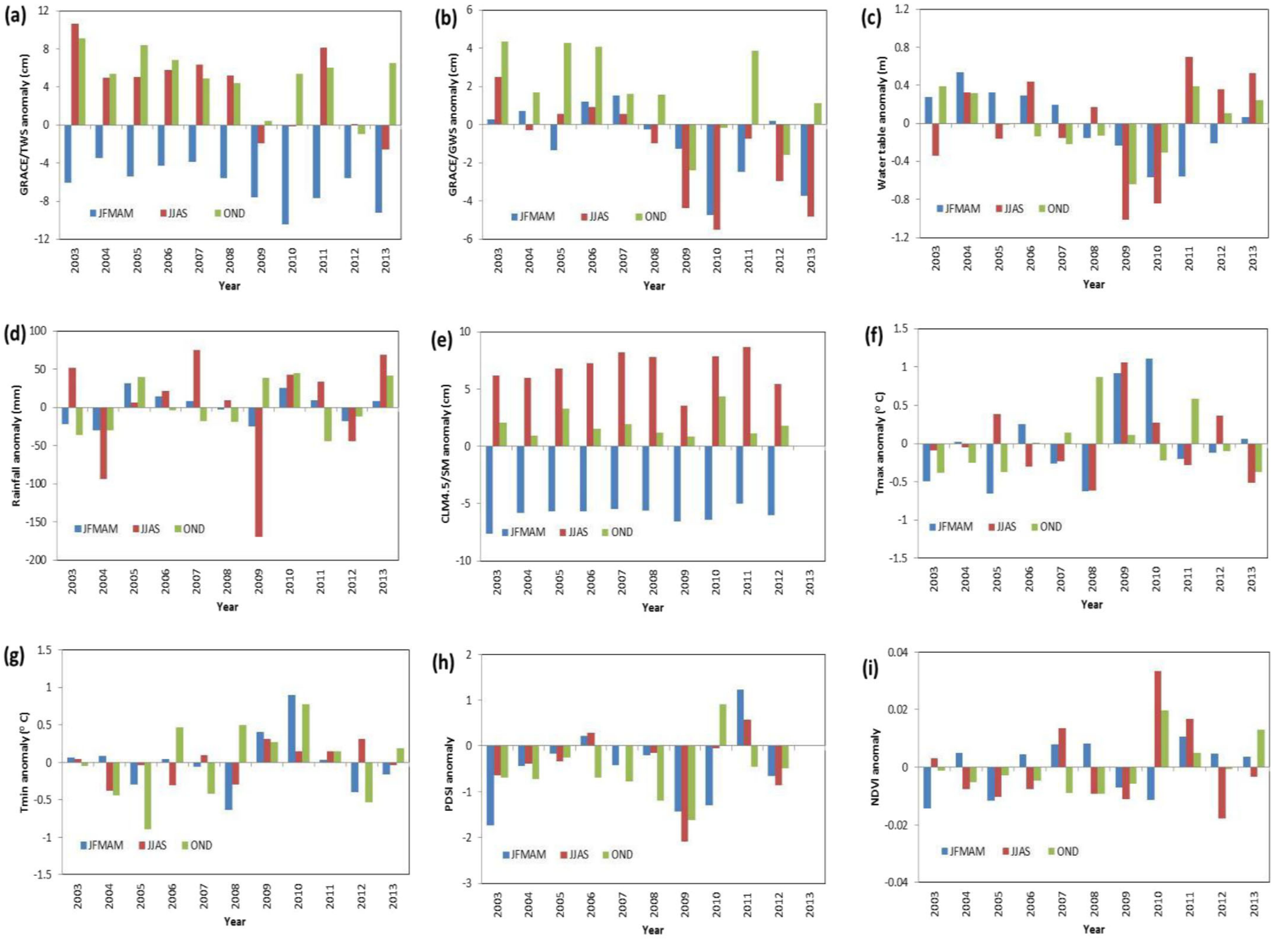

Figure 1. The premonsoon (JFMAM), monsoon (JJAS), and postmonsoon (OND) seasonal average anomalies in (a) GRACE-derived terrestrial water storage (TWS) and (b) groundwater storage (GWS) denoted by water equivalent thickness (cm), (c) in situ groundwater levels (m), (d) rainfall (mm), (e) CLM4.5 soil moisture (SM, cm), (f) maximum temperature (Tmax, °C), (g) minimum temperature (Tmin, °C), (h) Palmer Drought Severity Index (PDSI), and (i) Normalized Difference Vegetation Index (NDVI).

season (OND) over that of the monsoon season, even if there are little contributions from the postmonsoon rainfall and soil moisture (SM) (Figures 1d and 1e), are indicative of the inherent time-lag propagation of the monsoon rainfall through recharge processes into the subsurface soil.

In a particular year, the premonsoon season (JFMAM) changes in most of the hydrologic variables are a reflection of the combined influence of evapotranspiration losses due to rise in temperatures of the dry premonsoon environment, and of the monsoon season rainfall during the previous year. However, occurrence of drought years and their associated anthropogenic influence appears to have led to a reversal of the sign of the anomalies, specifically in the GWS and in the water table anomalies inferred from of observation wells (Figures 1a–1c), thus disturbing the expected year-to-year linear correspondence with rainfall. In these cases, it is the groundwater storage that mostly determines the interannual variability of TWS ($r = 0.95$), possibly due to its heavy use in meeting ~80% of drinking water and 61% of irrigation requirements, with a total annual use of 230 km^3 [*Shah*, 2009; *Siebert et al.*, 2010]. Therefore, water storage loss in a drought year is primarily due to the extra groundwater withdrawal to balance the moisture deficit and the increased drinking water demand, as evident from the drawdowns of in situ groundwater tables during the 2002 drought year, a century-scale dry year with a monsoon season rainfall deficit of ~21% [*Panda et al.*, 2007; *Samra*, 2004]. Although both the drought (PDSI) and vegetation (NDVI) indices show a dominance of negative anomalies, a prominent dry phase can be noticed during the 2008–2010 period, centering the worst

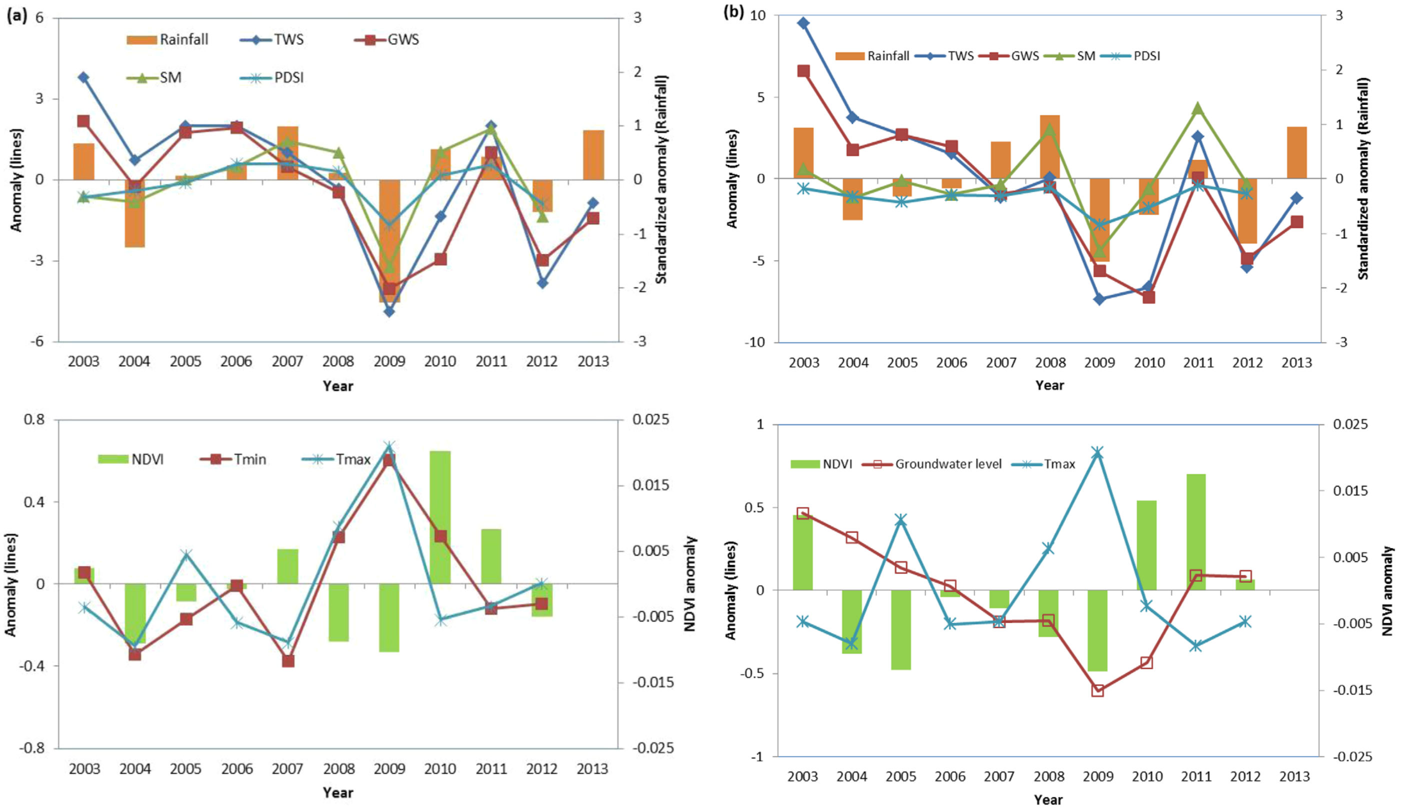

Figure 2. Temporal evolution of anomalies based on the water year (i.e., start of the current year monsoon season in June through the succeeding year May before the monsoon onset) averaged (a) over the whole country and (b) over the Ganges River basin in India. The anomalies in the water year 2003, for example, represent the spatial averages during June 2003 through May 2004. However, the in situ groundwater table anomaly in the Ganges River basin (Figure 2b) denotes the average level (m) of the postmonsoon (November of the current year) and the premonsoon (May of the succeeding year) seasons, from about 2800 observation wells. In these plots, the numbers along the left-hand axes refer to the quantities plotted as lines; while the numbers along the right-hand axes refer to the quantities plotted as bars.

drought year 2009 (Figures 1h and 1i), along with a string of high temperature anomalies (Figures 1f and 1g). The monthly time series of the above discussed variables (see supporting information Figures S1 and S2) also reflect the signal of water storage loss, consistent with the dry and warm phases during the study period.

Therefore, to capture the lag response of the hydroclimatic and ecological variables, particularly in the context of several extreme climatic years during the study period, we compare anomalies on a water year basis, which starts with the onset of the monsoon rainfall in June and extends through May in the succeeding year (Figure 2). The corresponding spatially interpolated anomalies are presented to better understand whether the subregional influence of rainfall variability is reflected in the water storage changes (Figure 3 and supporting information Figure S3). Moreover, the nationally and regionally (i.e., the Ganges River Basin) averaged time series (Figure 2) have a tendency to underestimate the actual storage changes because there can be considerable differences, even in the sign of the anomalies, between neighboring regions. These tend to cancel out when constructing national averages and so those averages have a tendency to underestimate the actual temporal variability in those anomalies. Although the interannual variability of most of the hydroclimatic time series (water year based) is correlated with one another (Figure 2a), it is worth mentioning that a part of the lag response of GWS to rainfall variability is captured, as their correlation coefficient has improved to 0. 6 ($p < 0.06$) compared to the monsoon season r of 0.43 (Figures 1b and 1d).

During the study period, the amplitudes of rainfall anomalies and their spatial extent (Figures 2a and 3a) suggest that India experienced major droughts in 2004 and 2009 with rainfall anomalies larger than one standard deviation, while regional rainfall deficits appear to be more recurrent than rainfall surpluses in every year [*Mujumdar et al.*, 2012; *Rao et al.*, 2010].

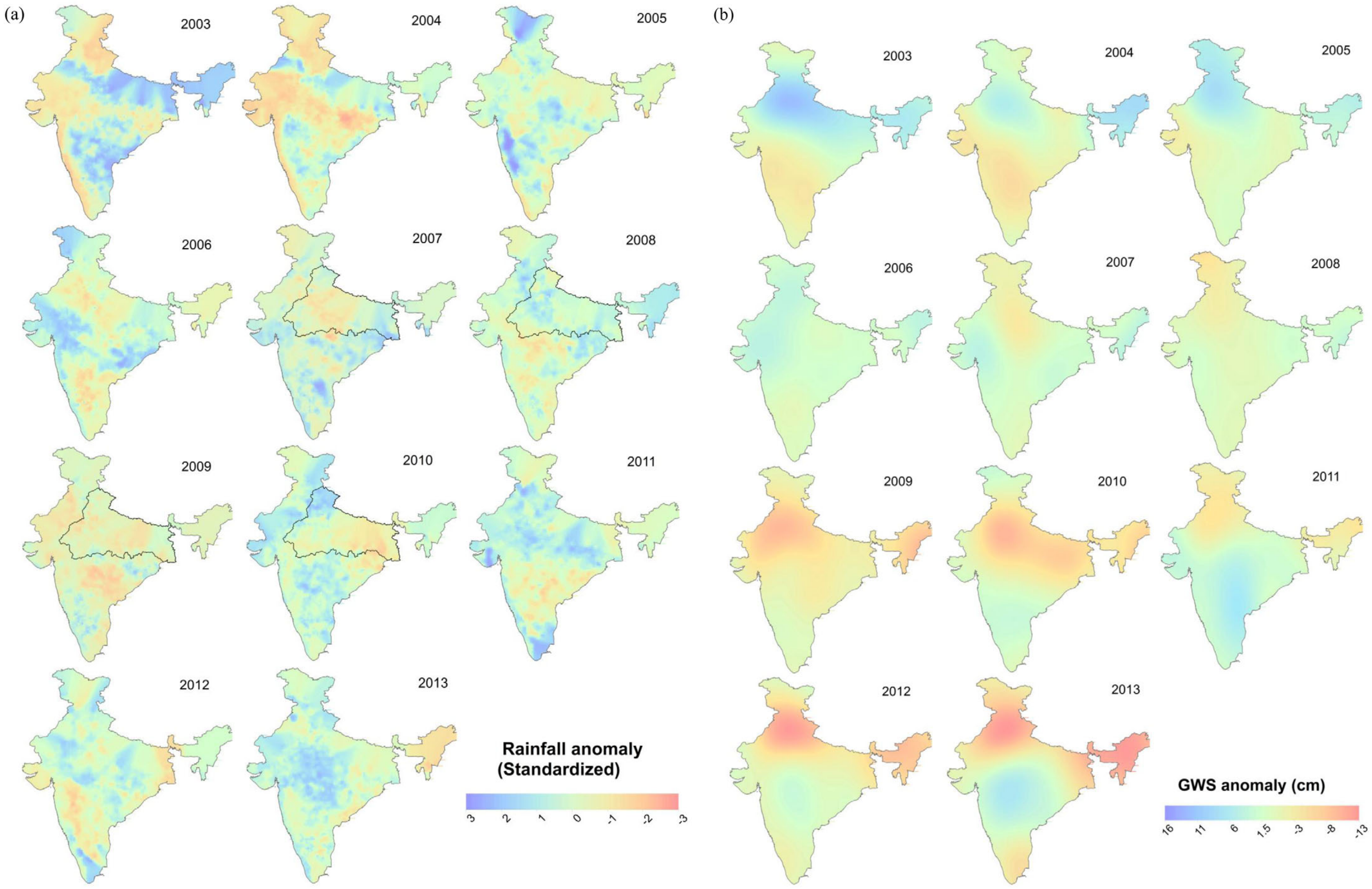

Figure 3. Spatial evolution of anomalies based on the water year (current year June through next year May) for (a) standardized rainfall and (b) GRACE-derived GWS (cm of water equivalent thickness). The Ganges River basin location in India is embedded in the rainfall map (Figure 3a). The maps for GRACE-derived TWS (cm), CLM4.5 soil moisture (cm), and Normalized Difference Vegetation Index (NDVI) are presented in the supporting information.

It is interesting to note that the corresponding spatial changes in TWS and GWS (supporting information Figure S3a and Figure 3b) are reasonably consistent, even though anthropogenic influences might have factored into (discussed later) the storage anomalies. In absence of a systematic soil moisture data set in India, the modeled soil moisture anomalies of the CLM4.5 land surface model seem to have depicted the rainfall anomalies reasonably well, as is evident from their spatial similarity (compare Figure 3a with supporting information Figure S3b) and a high degree of temporal correspondence ($r = 0.85$).

In particular, the 2009 drought year (June 2009 to May 2010), which is the third largest dry monsoon season since 1901 with a rainfall deficit of about 23% from the long-term average [*Hazra et al*., 2013; *Ratnam et al*., 2010], cooccurs with the warmest year since 1901, with a rise of more than 0.6°C in daytime (T_{max}) and nighttime (T_{min}) temperature during the study period. This year exhibits the largest GRACE TWS and GWS drop of up to -4.88 and -4.03 cm, respectively (Figure 2a). This warm-dry year is clearly captured in the spatially interpolated anomalies of the climate-driven PDSI drought index (not shown), which is also reasonably correlated with rainfall ($r = 0.79$, $p < 0.05$), but weakly correlated with TWS ($r = 0.60$, $p < 0.\ 06$) and GWS ($r = 0.57$, $p < 0.08$). This week correlation with water storage variables is consistent with the findings of *Dai* [2011], who observed a weak relationship between the PDSI and GRACE-derived water storage changes in regions where anthropogenic withdrawal influences groundwater resources throughout the world, including in north India. This could also be the reason for the observed weak correspondence between the water storage anomalies and the vegetation changes, because groundwater irrigation sustains crop growth in most of the deficit rainfall years. Although the governing factors for vegetation changes are many, including technological factors, the rainfall variability has been a major one ($r = 0.68$, $p < 0.05$) (Figure 2a and supporting information Figure S3c). In general, we note that the most pronounced change in water storage has occurred in the heavily groundwater irrigated Gangetic north India, which not only determines the nationally averaged time series but also seems to be better accounted for by climatic and anthropogenic factors.

Preceding the 2009 worst drought, the spatiotemporal evolution of groundwater declines in the Ganges Basin shows that the water year 2007 (i.e., June 2007 through May 2008) marks the transition from a positive mean GWS anomaly to a negative anomaly (Figure 2b), possibly because of declines over a region comprised of the states of Punjab, Haryana, and western Uttar Pradesh (Figure 3b), where the rainfall was also $\sim$15% below the long-term average (Figure 3a). In 2008, it seems that the water storage estimates responded to the central India drought, associated with the tropical Indian Ocean warming [*Rao et al*., 2010], with a spatially extended water storage loss. The 2009 rainfall deficit over northern India, which is about 2.5 times larger than the national average, shows consistent depletion of TWS and GWS of up to -7.35 and -5.63 cm, respectively. In the following year 2010, contrary to the countrywide TWS and GWS recovery, the groundwater storage became further depleted in the Gangetic and adjacent regions. Although the northwestern parts of India and Pakistan witnessed an excess rainfall in 2010, it is below the long-term normal value in the eastern and central parts [*Mujumdar et al*., 2012; *Webster et al*., 2011]. It can be inferred that the recharge in 2010 was not sufficient enough to recover the previous year's drawdown and the current year's water requirements for irrigation and drinking water purposes in the Ganges Basin. Moreover, the reported time-lagged persistence and desaturation of conductive channels and alteration of transmissivity following a worst drought [*Eltahir and Yeh*, 1999; *Laroque et al*., 1998] are likely to have factored into the 2010 drawdown. The spatially averaged CLM4.5 groundwater anomaly (see supporting information Figure S1), simulating the nonanthropogenic (i.e., natural) variations only, also clearly reflected the influence of water stress years, for example 2004 and 2009.

It should be pointed out the 2009 drought that propagated from a meteorological drought to a hydrological drought, also coincided with an agricultural drought as indicated by a marked drop in the vegetation index (NDVI), though this is not the case in 2010. It is evident from the 2010 NDVI anomaly ($\sim$25 million t more food grain production over that in 2009) that human-driven groundwater irrigation compensated the moisture stress over a large part of the Ganges Basin (Figure 3a). In drought years, in general, reduction in the food grain production (i.e., about 7%) of the country, such as in 2004 and 2009, is mainly due to a drop in the area under cultivation, particularly in the monsoon-rain dependent regions. The Ganges Basin aquifer represents more than 50% of the groundwater irrigated area of India with an annual withdrawal of 104 km^3. In a normal rainfall year, a volume of $\sim$202 km^3 groundwater gets replenished (i.e., 46.8% of all India volume) [*Government of India*, 2014]. But, in rainfall deficit years, with little replenishment and nonsignificant contribution from the surface water sources, extraction of nonrenewable groundwater meets most of the irrigation requirements, which has been estimated to be $\sim$68 km^3 yr^{-1} for the entire country, the largest in the world [*Wada et al*., 2012]. During the study period, the Ganges Basin experienced an estimated groundwater storage loss of $\sim$41, 44, and 42 km^3 in 2004, 2009, and 2012, respectively, while a recovery of $\sim$63 km^3 is estimated in the 2011 water year (i.e., June 2011 through May 2012). The positive rainfall anomalies in large parts of the Ganges Basin in 2011 (Figure 3a), with a long-term mean monsoon rainfall of 898 mm and coefficient variation of 13%, support this groundwater recovery.

It is interesting to note a consistent temporal behavior of the groundwater level anomaly, represented by the postmonsoon (November) and premonsoon (May) mean level from about 2800 observation wells in the Ganges Basin aquifer (Figure 2b). Similar to the GRACE-based groundwater storage anomalies, a transition in the in situ groundwater level observation from a mean positive anomaly to a negative one can be noticed in 2007, with the largest decline and recovery in 2009 and 2011, respectively. However, the rise in the groundwater table in 2010, and the fact that the water table remained relatively constant from 2011 through 2012, in contrast to the GWS declines, could be due to the sensitivity of open wells to local flood effects that are witnessed in the basin along with the rainfall deficits (Figure 3a and supporting information Figure S2). The other reason could be that the water loss from deep aquifers (i.e., nonrenewable) is not reflected in the shallow groundwater table observations. Overall, a high agreement ($r = 0.\ 82$, $p < 0.\ 05$) in this largest aquifer basin of India provides confidence regarding the utility of GRACE GWS to track the climatic and anthropogenic influence on groundwater storage. A high correlation of 0.92 is noted between the groundwater table and GWS anomalies in May, that contains the cumulated signals of the abovementioned stresses in a water year, and it is 0.84 for the month of November.

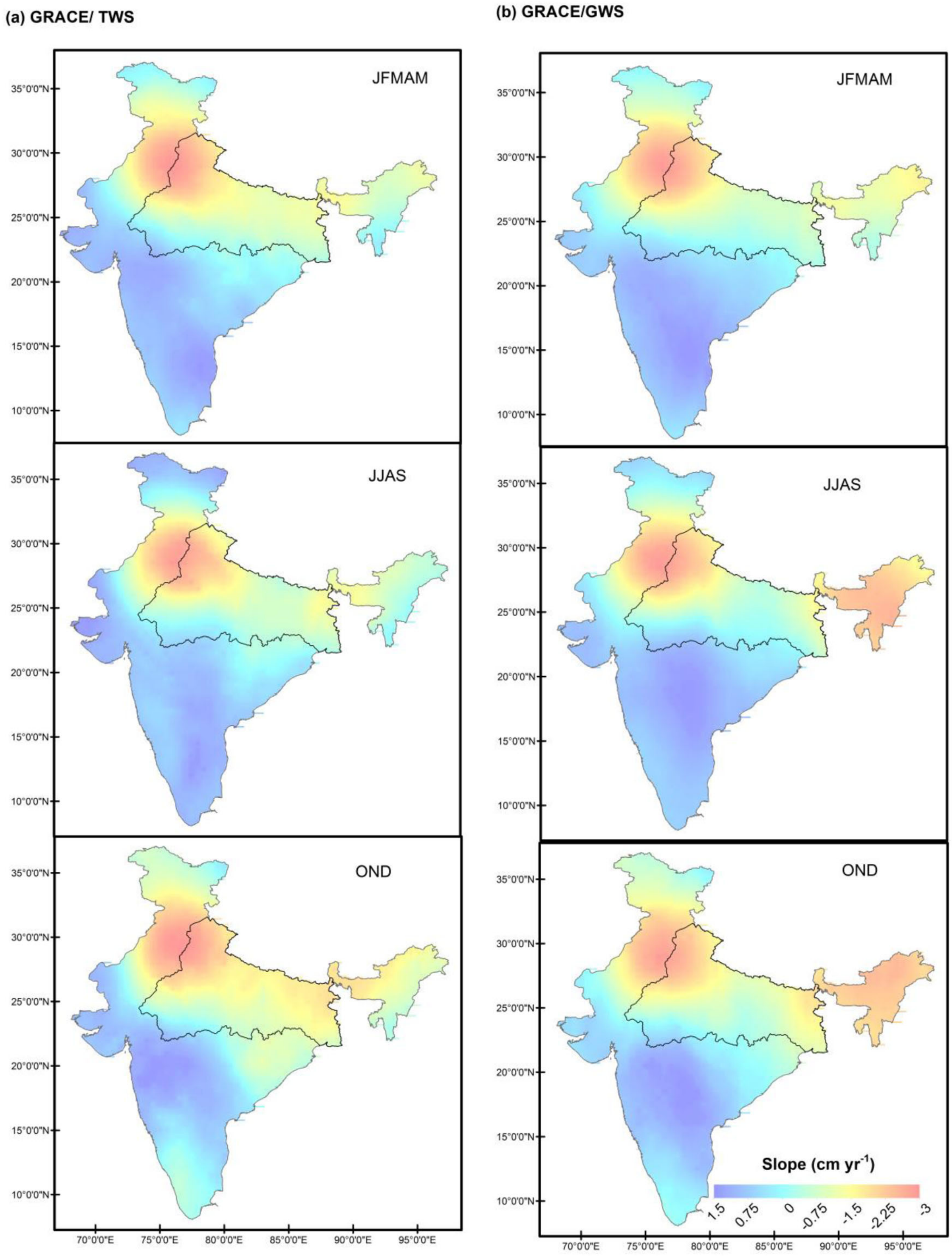

Figure 4. Spatial distribution of the Theil-Sen trend magnitudes (equivalent water thickness, cm yr^{-1}) of the GRACE-derived (a) TWS and (b) GWS anomalies in the premonsoon (JFMAM), monsoon (JJAS), and postmonsoon (OND) seasons during 2003–2013. Inset map focuses the changes over the Ganges River basin.

3.2. Spatial Changes in GRACE-Derived Water Storage Trends

Figure 4 depicts the Theil-Sen trend magnitudes of the seasonal GRACE-derived TWS and GWS anomalies during 2003–2013, indicating clear spatial distinctions, while a comparison between TWS and GWS suggests that the groundwater storage changes drive the freshwater or terrestrial water storage changes in both the

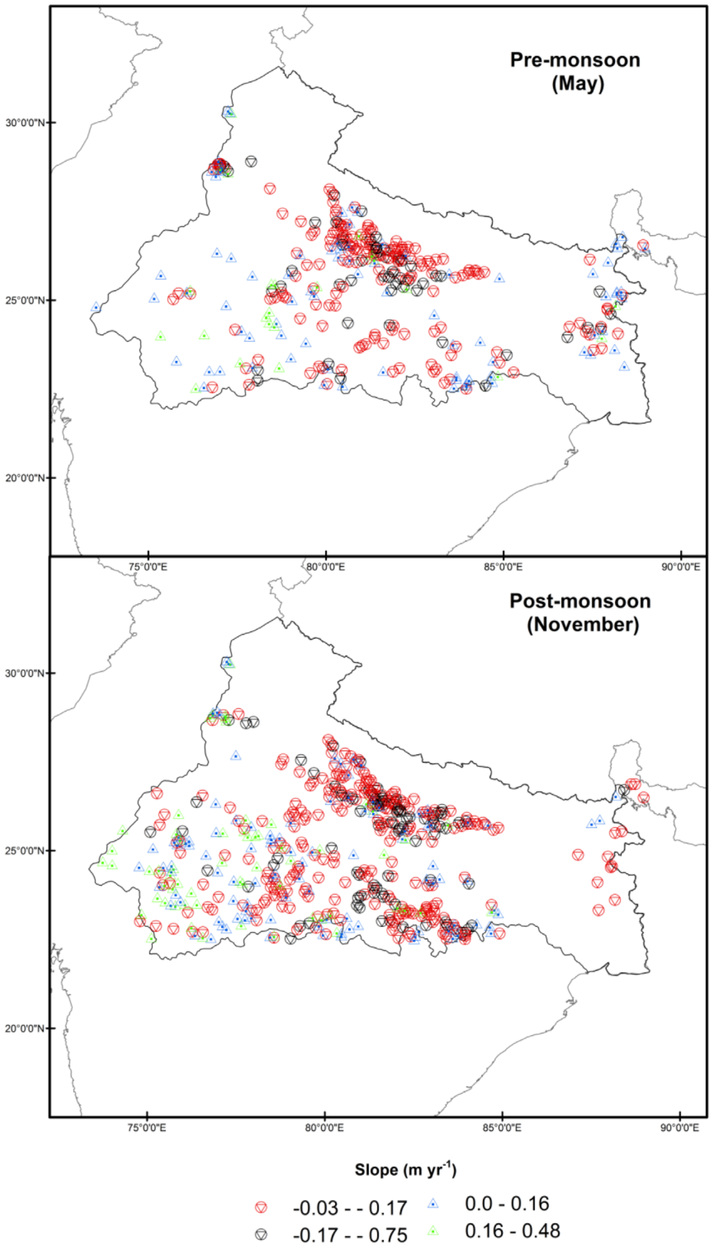

Figure 5. Spatial distribution of the in situ groundwater level trends over the Ganges River basin from 374 and 521 observation wells in the premonsoon (May) and postmonsoon (November) seasons, respectively. The triangles and inverted triangles illustrate the trend magnitudes (m yr^{-1}) of the rising and declining groundwater levels, respectively.

spatial and seasonal contexts. In general, negative water storage trends are concentrated in the northern and northeastern parts of the country, with the hot spot centered in the intensely groundwater irrigated and densely populated states of Punjab and Haryana. Similar to our results, assessment of the dynamic groundwater resources during 2006–2008 by the Indian Central Ground Water Board [*CGWB*, 2011] showed groundwater table declines in the northwest and north, in contrast to rises in the peninsular south India. Particularly, *Tiwari et al.* [2011] noted rises in GWS over a large part of south India after 2005. Seasonal comparisons indicate that in the months following the monsoon season (i.e., the postmonsoon and premonsoon seasons), water storage loss is more widespread in north and central India. This is due to the predominant rice-wheat cropping system, where groundwater is a source of life-saving irrigation for the rice crop in case of a failure and/or erratic distribution of monsoon rainfall, while groundwater is the only source of irrigation for the wheat crop during December–April.

To compare with the in situ groundwater table from observation wells, Figure 5 illustrates the spatial distribution of the rising (triangle symbols) and declining (inverted triangles) trends of groundwater levels in the Ganges Basin, with their sizes being proportional to the rate of change in meters per year. In the premonsoon month of May, about two third of the 374 observation wells show groundwater level declines at an average rate of 0.13 m yr^{-1}, of which 27% of the wells have significant ($p < 0.05$) declines of 0.22 m yr^{-1}. In contrast, ~17% of the rising trends (124 wells) are statistically significant ($p < 0.05$). However, in the postmonsoon month of November, 58% and 34% of 514 observation wells show declining and rising trends, respectively, of which 16% and 12% of wells are significant ($p < 0.05$).

Although the observation wells are not uniformly distributed over the Ganges Basin, it is important to note a distinct spatial congregation of trends in general (Figure 5). It should be pointed out that most of the declines with stronger trends are concentrated in the northern parts of the region, with clear distinctions in

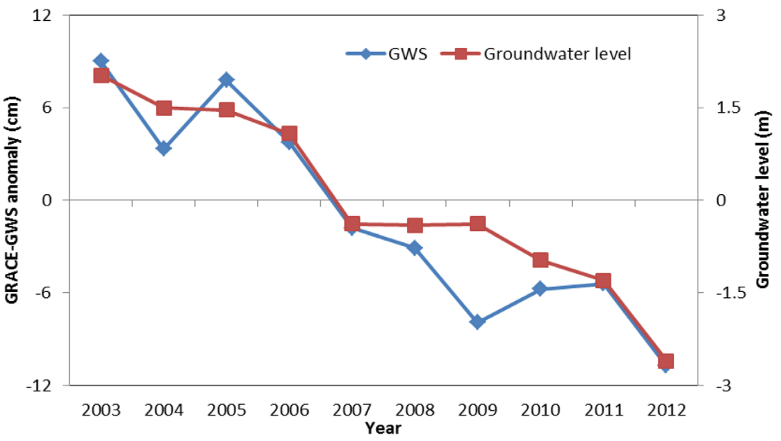

Figure 6. Comparison of the GRACE-derived GWS anomalies and in situ groundwater level anomalies averaged from about 250 observation wells in Punjab (i.e., the highest overdraft state) during the water years 2003–2012.

the premonsoon and postmonsoon seasons; however, the southwest parts encompassing central India show a dominance of contrasting patterns. While in situ groundwater levels in this study simultaneously capture local changes, the low-resolution GRACE records are capable of assessing large-scale changes only, similar to the observations of *Scanlon et al*. [2012a]. However, a high degree of temporal correspondence (evident from the significant correlations discussed in the previous section) and the spatial similarity in the trend distribution suggests that there is a general agreement between the response of the observation wells and the GRACE-derived GWS anomalies, pointing to a large-scale groundwater depletion in the Ganges Basin (Figures 4b and 5).

The Ganges Basin-aggregated trend estimate on a water year basis (i.e., start of the current year monsoon season in June, through May the next year before the monsoon onset) presented in Figure 2b also indicates a significant ($p < 0.05$) GWS depletion of 1.25 cm yr^{-1} equivalent water thickness, which sums to a total volume of 118 km^3 during 2003–2012 (i.e., June 2003 through May 2013). Accounting for $\sim$92% of the total fresh water (TWS) loss of the basin, this volume of groundwater has primarily contributed to the observed significant nationwide decreasing GWS trend (Figure 2a). Using a specific yield of 0.12, as has been used by *Rodell et al*. [2009] and also a representative value for the northern parts of the country [*Central Ground Water Board*, 2012; *Richey et al*., 2015], the equivalent water table decline corresponding to the above mentioned storage loss of the basin would be 10.4 cm yr^{-1}. Consistently, the corresponding in situ groundwater table trend (Figure 2b) has declined at a rate of 0.11 m yr^{-1}, significant at the 7% level (i.e., $p < 0.07$). This provides additional evidence of the reliability of the GRACE-based GWS anomalies in capturing the trends and variability of the subsurface groundwater hydrology.

Recently, *Chen et al*. [2014] has highlighted the benefits of improved data quality of GRACE RL05 gravity solutions and improved processing method in reducing the leakage error in GRACE estimates of northwest India. Similarly, our estimates are also likely to have minimal effect of the possible sources of uncertainty. As noted earlier by *Chen et al*. [2014] and *Tiwari et al*. [2009], water storage in surface reservoirs (rivers, canals, and lakes) is not a major component and groundwater irrigation meets most of the water requirement of agriculture (supporting information Figure S4). Long-term irrigation pattern indicates that while groundwater irrigated area has been increasing at the rate of about 70 km^2 $decade^{-1}$ since 1961, there is no perceptible change in surface water irrigated area, but shows clear decreases during the recent drought years (supporting information Figure S5). Moreover, choice of the GLDAS/Noah from the four available SLM to disaggregate GWS may not have been a major source of uncertainty as indicated by *Tiwari et al*. [2009].

It is worth pointing out that the state of Punjab, that represents India's highest nonrenewable groundwater withdrawal region with an annual utilization of 34.66 km^3 (33.97 km^3 for irrigation only, i.e., twice that of the High Plain aquifer of the U.S.) compared to a renewable volume of 20.35 km^3 [*Central Ground Water Board*, 2013], is also part of the identified hot spot region adjacent to the northwest Ganges Basin in this study (Figure 4). Comparison of the GRACE-derived GWS anomalies and in situ groundwater level anomalies from about 250 observation wells of Punjab during the water years 2003–2012 (Figure 6) reveals a high degree of correspondence, with a correlation coefficient of 0.94. GRACE data indicate a significant rate of groundwater decline of 2.1 cm yr^{-1}, which would be equivalent to a mean water table decline of 17.6 mm, assuming the same specific yield of 0.12. In contrast, the estimated trend in the groundwater level from observation wells is declining at a rate of 0.46 m yr^{-1} ($p < 0.05$), more than twice the rate inferred from the GRACE results. This discrepancy could be due to the use of a uniform value of specific yield, which generally relates to an unconfined aquifer. But, most of the nonrenewable groundwater is pumped from the deep confined aquifer, with the mean water table depth from observation wells ranging up to 40 m compared to that of 20 m in the Ganges Basin aquifer. Since the storage coefficients of confined aquifer are orders of magnitude less than that of the unconfined aquifer [*Scanlon et al*., 2012a], the above estimated water table decline from the GWS changes could well be underestimated. Thus, use of specific yields of the confined aquifer is likely to decrease the observed difference from the groundwater level trend.

Nevertheless, our results lend support to the pronounced groundwater depletion of Punjab, with reported water table declines of up to 1 m yr^{-1} in some locations and consequent rises in energy requirements [*Fishman et al*., 2011; *Perveen et al*., 2012]. While a normal rainfall year does not meet the groundwater-fed irrigation requirement of the rice-wheat cropping system of Punjab, four dry years, such as 2004, 2007, 2009, and 2012, with rainfall deficits more than 100 mm appear to have further impacted the nonrenewable groundwater resource. Still, from only 1.53% of the geographical area of the country (i.e., 50,362 km^2), this deep alluvial aquifer has ensured food security of the country by producing 11.37 million t of rice and 16.11 million t of wheat in 2012 (water year), that constitutes 10.89% and 17.42% of the entire Indian production [*Government of India*, 2013].

4. Summary and Conclusions

Interestingly, none of the national or Ganges Basin climatic and ecological (i.e., NDVI) variables (Figure 2) show a statistically significant trend, for the obvious reason that the interannual variability is high, characterized by contrasting climatic extremes during the study period. It is logical to infer that the indirect effects of intermittent drought and dry spells, which can be greater than the direct effects in term of recharge [*Taylor et al*., 2013], have resulted in overwithdrawal of groundwater. However, the influence of a steady rise in temperature, with daytime (T_{max}) and nighttime (T_{min}) temperatures increasing by 0.05°C yr^{-1}and 0.03°C yr^{-1} during the study period, cannot be underestimated. Because, according to the *India Meteorological Department* [2012], this study period also includes most of the high temperature years since 1901, with the warmest year in 2010 (i.e., 0.93°C over the 1961–1990 average), and followed by 2009 (0.92°C), 2006 (0.60°C), 2003 (0.56°C), 2007 (0.55°C), 2004 and 2012 (0.49°C), and 2011(0.46°C). And the warmest month of the year, May, on which these warmest years are based on, has registered a shift toward a warmer climate since 2008 (Post-2008) compared to the 2003–2007 period (Pre-2008) as evident from the changes in the T_{max} and T_{min} probability density function (PDF) (supporting information Figure S6a). In the Ganges Basin, specifically, this warming is more pronounced with a clear change in the tails of the PDFs (supporting information Figure S6b). Since most of the hot extremes have cooccurred with the droughts (in 2008 and 2009 water years), which has increased globally due to anthropogenic warming [*Diffenbaugh et al*., 2015], it is difficult to segregate their individual influence on the estimated water storage losses from the current data set, given the nonlinear response of the subsurface hydrology to climatic stresses.

Internationally, consistent with our results, several studies have reported sharp reduction in water storage, for example, in the hot spot aquifers of the California Central Valley and High Plains of the U.S. [*Famiglietti et al*., 2011; *Long et al*., 2013; *Scanlon et al*., 2012a], southeast Australia [*Leblanc et al*., 2009], and northcentral Middle East [*Joodaki et al*., 2014; *Voss et al*., 2013], primarily because of drought-induced groundwater withdrawal (i.e., indirect effects) during 2007–2013. The extent and impact (i.e., intensity) of these droughts have shown spatiotemporal differences in storage losses. Before the century-scale 2009 drought in India, the groundwater storage loss during 2002–2008 was estimated to be 4 cm yr^{-1} over the region of the semiarid northwest India and Pakistan [*Rodell et al*., 2009] and 2.5 cm yr^{-1} over parts of Bangladesh, Nepal, and West Bengal (India) (i.e., zone D of *Tiwari et al*. [2009]). Reassessing the depletion in the northwest India and Pakistan using the GRACE RL05 gravity solutions, *Chen et al*. [2014] observed a GWS decline of 2.4 cm yr^{-1} during January 2003 to December 2012, with storage gains in the wet years 2008 and 2011, although the first 5 years (2003–2008) had a higher depletion rate of about 25%. Consistently, with a further recovery from the relatively wet year 2013 (Figures 2 and 3b), our study shows a groundwater depletion range from 1.75 to 3 cm yr^{-1} over the states of Haryana, Punjab, and western Uttar Pradesh in different seasons during January 2003 to December 2013 (Figure 4). While the Bengal Basin of Bangladesh exhibited a GWS decline ranging between 0.34 and 1.14 cm yr^{-1} during 2003–2007 [*Shamsudduha et al*., 2012], it was 1.25 cm yr^{-1} in the adjacent Ganges Basin in this study.

Nevertheless, application of the GRACE-derived GWS anomalies to estimate large-scale groundwater storage changes in India is validated as evident from a high degree of linear correspondence with the in situ groundwater level results as determined from observation wells, and also through a reasonable spatiotemporal consistency with the climatic variables (rainfall, CLM4.5 soil moisture, PDSI), particularly in drought years (Figures 2 and 3). But the uncertainty associated with using a fixed specific yield of 0.12, leading an underestimation of the GWS trend compared to the in situ groundwater level trend in Punjab, remains to be explored. Given the highly variable nature of aquifer characteristics and the observation well water table trends (Figure 5), with specific yields ranging from 0.04 to 0.22 in the alluvial Ganges Basin aquifer [*CGWB*, 2011], the use of distributed specific yields is likely to improve the agreement, as highlighted by *Shamsudduha et al*. [2012]. Future study will focus on these issues, after compiling the distributed specific yield data set from the pumping tests conducted by the regional centers of CGWB. Finally, since northern India and the adjacent regions of Pakistan, Nepal, China, and Bangladesh represent the most intensively irrigated and densely populated domain in the world, with annual nonrenewable groundwater-fed irrigation alone that accounts for nearly half of the world's total withdrawal [*Siebert et al*., 2010; *Wada et al*., 2012], a transboundary aquifer management, with international agreement for sharing classified hydroclimatic data and policy implementation, is needed.

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