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Dwindling groundwater resources in northern India, from satellite gravity observations

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[1] Northern India and its surroundings, home to roughly 600 million people, is probably the most heavily irrigated region in the world. Temporal changes in Earth's gravity field in this region as recorded by the GRACE satellite mission, reveal a steady, large-scale mass loss that we attribute to excessive extraction of groundwater. Combining the GRACE data with hydrological models to remove natural variability, we conclude the region lost groundwater at a rate of 54 ± 9 km^3/yr between April, 2002 (the start of the GRACE mission) and June, 2008. This is probably the largest rate of groundwater loss in any comparable-sized region on Earth. Its likely contribution to sea level rise is roughly equivalent to that from melting Alaskan glaciers. This trend, if sustained, will lead to a major water crisis in this region when this non-renewable resource is exhausted.
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1. Introduction

[2] Terrestrial water storage is a vital resource for agricultural, industrial, and domestic consumption and for the health of ecosystems. Monitoring total water storage on and beneath Earth's surface is essential for understanding the hydrological cycle in a changing climate, and for achieving sustainable water management for a continually increasing population. Hydrologists and climate scientists construct global land surface models that use meteorological fields (e.g., precipitation, temperature) as boundary conditions, to estimate and predict water storage [*Bonan et al.*, 2002]. However, many models lack groundwater or surface water components (though they do usually include snow) [*Maxwell and Miller*, 2005]. Furthermore, anthropogenic modifications to the hydrologic cycle, such as groundwater pumping, irrigation, and reservoir impoundment, are absent from operational models at these scales [*Sacks et al.*, 2009].

[3] Groundwater extraction across northern India in response to the growing demand for water has recently been exceeding the replenishable groundwater, causing a steady lowering of the water table [*Hoque et al.*, 2007; *Central Ground Water Board of India (CGWB)*, 2006]. The problem of decreasing water availability and how future climate change might impact an already serious situation is well-recognized for northern India [*Barnett et al.*, 2005; *Kumar et al.*, 2005; *Amarasinghe et al.*, 2007]. However, the complexity of water storage modeling and the difficulties of acquiring relevant data pose challenges for estimating the variability of stored water. Here, we describe results from a satellite-based observational technique that allows us to directly monitor regional changes in stored water. It does not require interpolation between local measurements, or extrapolation to unsampled areas, or assumptions about soil characteristics (e.g., porosity). The method, by default, senses all contributions across an entire region. It allows us to produce an up-to-date quantitative estimate of the temporal and spatial variability of groundwater in this region, which is a first step towards management of sustainable water resources for one of most populated places on the globe.

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2. Data and Method of Analysis

[4] The method uses gravity data from the GRACE (Gravity Recovery And Climate Experiment) satellite mission, launched in March 2002 [*Tapley et al.*, 2004]. GRACE provides monthly, global, gravity field solutions at scales of a few hundred km and greater, in the form of spherical harmonic coefficients. Models have been used to remove atmospheric and oceanic contributions. We use coefficients truncated to maximum degree 60, computed by the Center for Space Research at the University of Texas for April 2002 to June 2008 (http://podaac.jpl.nasa.gov/grace) to compute monthly mass changes in southern Asia, which we interpret in terms of changes in continental water storage. The coefficients are filtered to remove correlated errors [*Swenson and Wahr*, 2006], and a Gaussian smoothing factor with a 250-km radius [*Wahr et al.*, 1998] is applied to each coefficient.

[5] The gravity field results are equally sensitive to water at all depths: surface water, soil moisture, and groundwater, and include anthropogenic effects. To isolate the anthropogenic contributions we subtract monthly water storage estimates predicted by land surface models. Residual gravity field coefficients are obtained by transforming the gridded model output into the spherical harmonic domain, applying the GRACE filtering and smoothing procedures, and subtracting those filtered+smoothed coefficients from the GRACE filtered+smoothed coefficients. The residuals thus include anthropogenic effects, GRACE errors, and mismodeled or missing model components.

[6] We use four hydrological models: two versions (NOAH and Mosaic) of NASA's Global Land Data Assimilation System model [*Rodell et al.*, 2004], a model from NOAA's Climate Prediction Center (CPC) [*Fan and van*

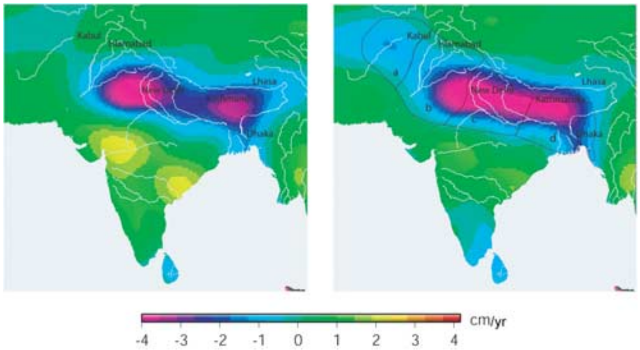

Figure 1. (left) Rate of change of terrestrial water storage, in cm/yr of water thickness, determined from GRACE gravity solutions. White lines show major rivers. (right) Same as Figure 1 (left) but after subtracting the naturally occurring water storage variability predicted by the CLM hydrological model. The results in Figure 1 (right) mostly reflect anthropogenically caused groundwater loss. Outlined are the sub-regions used for computing water loss. (a, mountainous regions of Afghanistan and Pakistan; b, Indus Basin (Pakistan + India); c, Ganga Basin (India-Nepal); d, Ganga-Brahmputra Basin (India-Nepal-Bangladesh etc).

den Dool, 2004], and version 4.0 of the Community Land Model (CLM) maintained by the National Center for Atmospheric Research [*Oleson et al.*, 2008]. None of these models include anthropogenic contributions. CLM includes both a groundwater and a river storage component but the other models do not, and so we use CLM as our default model; though good agreement between CLM and the other models (see below) suggests the absence of groundwater in a model does not notably affect that model's estimate of total naturally varying water storage in this region. None of the models include dynamic lakes or reservoirs. However, since our focus is on long-term trends, and since there is not enough total lake+reservoir volume in this region (~15 km^3 total live reservoir storage; though this number does not include the live volume of natural lakes or wetlands) to accommodate a significant trend in stored water over six years, it is unlikely that contributions from lakes and reservoirs in our residuals will compromise our conclusions. None of these models include mass loss from melting glaciers. Thus, any residual signal in glaciated regions could have contributions from melting ice. Glaciated regions are included separately when recovering groundwater variability.

[7] We use the filtered+smoothed harmonic coefficients to obtain monthly estimates of mass variability on an evenly spaced lat/lon grid [*Wahr et al.*, 1998]. We simultaneously fit a trend and seasonal terms at each grid point. The trends are shown in Figure 1, both before (Figure 1, left) and after (Figure 1, right) removing the CLM model output. The most prominent feature is the large negative trend over northern India. It is the largest broad-scale negative trend evident in the GRACE data anywhere in the world, not due to thinning of ice sheets or glaciers. The trend is largest across a 2,700,000 km^2 region centered on New Delhi, and becomes more prominent after removing the model output. This region is centered well south of the Himalayan glaciers (auxiliary material[1]), in what is probably the most heavily irrigated area in the world (Figure 2; based on data from *Siebert et al.* [2007]). It coincides with a broad region of intensive groundwater extraction and water table decline [*CGWB*, 2006], suggesting it is a result of that extraction. The signal has about the same spatial extent and amplitude (~2 cm/yr) after removing any one of the four land surface models, indicating it is not the result of mis-modeled naturally occurring water storage. Assuming a porosity of 0.2 [*CGWB*, 1997], the ~2 cm/yr decrease in water storage indicates a ~10 cm/yr lowering of the water table, a value consistent with observations in this region [*CGWB*, 2006]. Figure 1 (right) also shows positive trends in southern India. Those trends are considerably smaller than the negative trends in the north, and could be due to a combination of increased reservoir impoundment, mis-modeled naturally varying storage, and (along the southeast coast) tectonic signals related to the Dec 26, 2004 Sumatran earthquake [*Han et al.*, 2006].

[8] We next use the filtered+smoothed residual coefficients to estimate the total groundwater loss averaged over the mass loss region. A regional GRACE water storage estimate is subject to contamination by gravity signals from surrounding areas To minimize that effect we construct sets of filtered+smoothed harmonic coefficients for various sub-regions, and simultaneously least-squares-fit those sets to the residual GRACE harmonics to obtain a mass estimate for each sub-region. This method is tested over several small and large regions on both real and synthetic data.

[9] We separate the region into seven sub-regions: four "primary" sub-regions within the non-glaciated portion of the mass loss region (Figure 1, right); and three secondary sub-regions, two north and one south of the primary sub-regions. Virtually all the glaciers in this area are located within the two northern sub-regions (Figure S3). The primary sub-regions are the focus of this study. The secondary sub-regions are included so that most of the gravity signal from those sub-regions will be absorbed into those solutions instead of leaking into the primary solutions. To

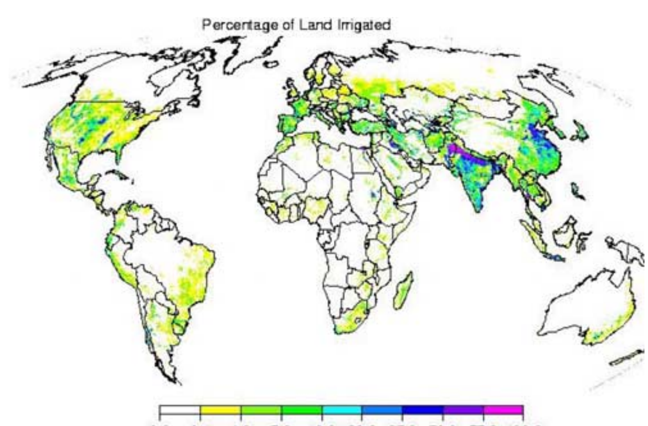

Figure 2. The area equipped for irrigation, given as a percentage of cell area, for 5′ × 5′ cells [*Siebert et al.*, 2007]. For most countries the base year of data is during 1997–2002. The largest-amplitude feature is the narrow east-west band extending across northern India into Pakistan and Bangladesh. This band coincides closely with the GRACE mass loss region.

[1]Auxiliary materials are available in the HTML. doi:10.1029/2009GL039401.

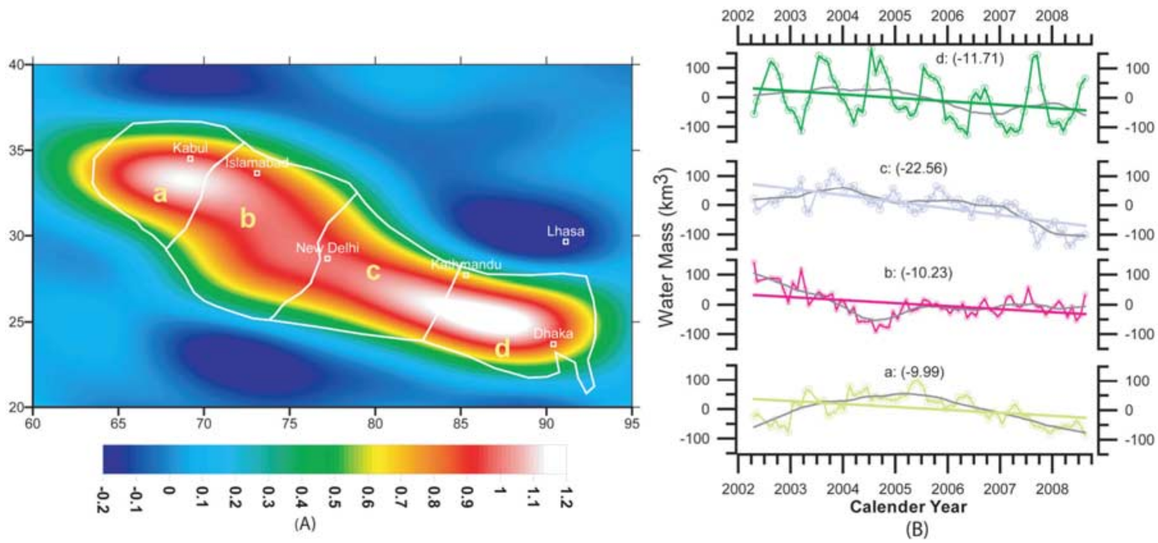

Figure 3. (a) Sum of the sensitivity kernels of the four sub-regions used to compute the northern India water loss. This sum is the effective sensitivity kernel for the entire groundwater region a–d. (b) Monthly time series of water storage change for the regions denoted in Figure 3a. Also shown are the time series after removing the annual and semi-annual components (black), as well as the best fitting straight lines. The numbers in brackets are the estimated water loss in km^3/yr.

understand the way our analysis samples the earth, we determine sensitivity kernels for the sub-regional estimates (auxiliary material). The kernels show that results are more sensitive to mass in the center of a sub-region than along the edges. Figure 3a shows the sum of the sensitivity kernels for the four primary sub-regions, and so represents the sensitivity kernel for the entire non-glaciated portion of the mass loss region.

3. Results and Discussion

[10] Results for the four primary sub-regions are shown in Figure 3b for the GRACE-minus-CLM results, along with their best-fitting trends. Our estimate of the total mass loss rate of the four sub-regions during this period (April, 2002–June, 2008) is 54 km^3/yr. There are three sources of uncertainty in this estimate: GRACE observational errors, CLM model errors, and contamination from mass signals outside the region.

[11] To estimate the effects of measurement errors we smooth the monthly total-mass values using a 13-month moving average, and remove a trend. We interpret the standard deviation of the residuals as the amplitude of the measurement error for each monthly value. We expect this to overestimate the measurement error, since the residuals are certain to also include real geophysical signal. We then perform a Monte Carlo data simulation where we fit trends and seasonal terms to many synthetic monthly data sets, each with values chosen from a population of Gaussian-distributed numbers with that same standard deviation. This assumes the measurement errors are uncorrelated from one month to the next. The standard deviation of the trends is 5 km^3/yr, and is our estimate of the measurement uncertainty.

[12] The effects of CLM model errors are estimated by comparing residuals for the four hydrological models. The standard deviation of the trends for GRACE minus the different models is $\sim$6 km^3/yr (Figure S2), and is our estimated CLM model error.

[13] The uncertainty caused by leakage from outside the region is estimated by applying our solution process to the GRACE signal, but after first removing our best-fitting monthly sub-regional estimates for a-d; and then fitting a trend to the results. The resulting uncertainty estimate is $\sim$4 km^3/yr. Adding these three uncertainties in quadrature gives an overall uncertainty in the total mass loss estimate, of 9 km^3/yr, so that our final total water loss estimate is 54 ± 9 km^3/yr.

[14] We interpret the entire 54 ± 9 km^3/yr water loss estimate for a-d as a groundwater loss. The ± 9 km^3/yr uncertainty estimate does not consider the possibility that some of the 54 km^3/yr water loss might be caused by thinning glaciers. The a-d sensitivity kernels shown in Figure S1, show some overlap with glaciers in the north. Thus, if those glaciers were losing mass they would presumably be contributing something to the 54 km^3/yr total. It is difficult to quantify this contribution, because although there have been published studies of specific glaciers in this region, there is no widely accepted long-term mass balance estimate for the entire glacier system (R. Armstrong, personal communication, 2009). The GRACE results, themselves, offer what is probably the best estimate of mass loss in the region, and it is small. Figure S3 shows that the largest mass loss rates in a-d are concentrated south of the glaciers. The GRACE mass loss time series for sub-region e (not shown), which is dominated by these glaciers (Figure S3), gives a mass loss rate of only 3 km^3/yr. The contribution of those glaciers to the a-d results is probably even smaller than this, given the relatively small values of the a-d sensitivity kernels over the glaciers (Figure S1).

[15] Our final groundwater loss estimate of 54 ± 9 km^3/yr is roughly equivalent to the total mass loss of melting Alaskan glaciers during this same period [*Luthcke et al.*, 2008]. It represents the total volume of water leaving sub-

regions a-d through either evapo-transpiration or runoff. Groundwater that infiltrated back into the soil in those same sub-regions would not contribute to this estimate. The sub-regions are drained by the Ganga-Brahmputra and Indus rivers. Because the sub-regions extend to the mouth of the Ganga-Brahmputra, and because there is no indication of any substantial mass increase along the Indus downstream of the sub-regions (Figure 1, right), it is unlikely that any significant fraction of the groundwater runoff infiltrated back into the ground before reaching the ocean. Assuming all the evaporated water also ended up in the ocean, either as direct oceanic precipitation, or as precipitation over nearby land and subsequent runoff, etc., then the total groundwater loss would have contributed 0.16 mm/yr to global sea level rise.

[16] For individual river basins, our estimates suggest the water loss rate for the Ganga-Brahmputra basin (c + d in Figure 3) was ~34 km^3/year, compared with ~10 km^3/year for the Indus basin (b). The mass loss from western Pakistan and the mountains of Afghanistan (a) was ~10 km^3/year.

[17] The four primary sub-regions lie in an important agricultural area of northern India, Pakistan, and Bangladesh. Excessive extraction of groundwater in this area has been well documented [*CGWB*, 2006; *Hoque et al.*, 2007]. The Indian Central Ground Water Board (CGWB) and ground water departments of other countries estimate the total rate of groundwater extraction in the Indian+Nepal+Bangladesh portion of the Ganga-Brahmputra + Indus basins (b+c+d) was ~172 km^3/yr during the mid-1990's. This is a difficult number to estimate, since much of the extraction is unmonitored. Furthermore, extraction rates have increased dramatically over the last few years and it is likely that more recent rates were much larger [*CGWB*, 2006; *Foster et al.*, 2008]. Groundwater is replenished mainly through infiltration of precipitation and of the extracted water itself. The CGWB estimates that the maximum potential groundwater recharge for these basins is 246 km^3/yr; extraction rates below this value will be offset by recharge during the monsoon season. The net storage loss implied by the GRACE-minus-model results indicates that current rates of groundwater withdrawal have exceeded this value, and the aquifers in these basins are over-exploited.. The GRACE estimate of total water loss in those same basins (Indian portions of b+c+d) between April 2002 and June 2008 is 33 km^3/yr. Thus, the GRACE results suggest the total groundwater extraction rate for this period was 246 + 33 = 279 km^3/yr, about 70% larger than the CGWB estimate for the mid-1990's. This dramatic increase shows the dynamic nature of this increasingly critical situation.

[18] The decrease in total water storage observed by GRACE indicates that aquifers are not being fully recharged. The dewatering of aquifers could lead to quasi-irreversible aquifer degradation due to the intrusion of saline and polluted water [*Foster*, 1992] particularly in the coastal regions of India and Bangladesh. Arsenic pollution caused by groundwater extraction has already been identified in Bangladesh [*Harvey et al.*, 2002]. A general water table decline was observed as early as the mid-1980's in some regions, for example in the capital city of Bangladesh [*Hoque et al.*, 2007], so a sizable portion of the total static water reserve could already have been lost.

[19] The region where GRACE shows decreasing groundwater storage has among the world's highest population densities. The demand for agricultural products is intense. Groundwater demand is expected to grow many fold in coming years, with increasing agricultural growth and industrialization [*Kumar et al.*, 2005; *Amarasinghe et al.*, 2007]. Although future climate change is expected to intensify the precipitation and thus increase water availability in this region [*Bates et al.*, 2008], evaporation will likely also increase due to the warmer climate. It could thus well be that one of the most populated areas on Earth will eventually be struggling for water [*Barnett et al.*, 2005]. It is of immediate concern to recharge the aquifers of north India, Nepal and Bangladesh through suitable management of surface water for the sustainable availability of water and the preservation of ecosystems.

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