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Land water storage variation over Southern India from space gravimetry

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The gravity recovery and climate experiment (GRACE) satellite mission is mapping the earth's gravity field with unprecedented accuracy of a few μGal (10^{-8} m/s^2) every month. This provides a new means of studying hydrological, climatic and tectonic processes that redistribute mass, producing temporal gravity changes. Hydrological changes contribute the strongest signal in the GRACE gravity field on seasonal, annual and inter-annual timescales. This communication presents seasonal and annual hydrological signals over India observed by GRACE and compares them with *in situ* measurements. The spatio-temporal variations of water storage over southern India for 2002–2008 show positive and negative trends, which appear to be related with changes in precipitation patterns. It has also been observed that the negative trend over a large part of south India changed to positive trend after 2005. These observations suggest dominant inter-annual trend of water storage in the southern Indian region. Such observations have also been noticed in the average record of ~ 950 water wells from Andhra Pradesh. We compared GRACE-derived time series with land-based measurements from Andhra Pradesh and found that the GRACE record corroborates with ground data, implying its application in the monitoring of water storage in the region.

Keywords: Hydrological signals, satellite mission, space gravimetry, water storage.

THE increasing demand of water for agricultural, industrial and domestic uses in the climatically changing world requires management of water resources. Planning for sustainable availability of water resources depends on monitoring the spatio-temporal variability of the total water storage, a phenomenal task for a vast country like India, which has a limited network of land observation stations. Recent developments in space technology provide information about total water variations through satellite gravimetry[1,2], and surface-water variation from satellite altimetry (refs 3 and 4 and papers therein). This communication briefly presents the application of the gravity recovery and climate experiment (GRACE) satellite gravity measurements to provide total as well as

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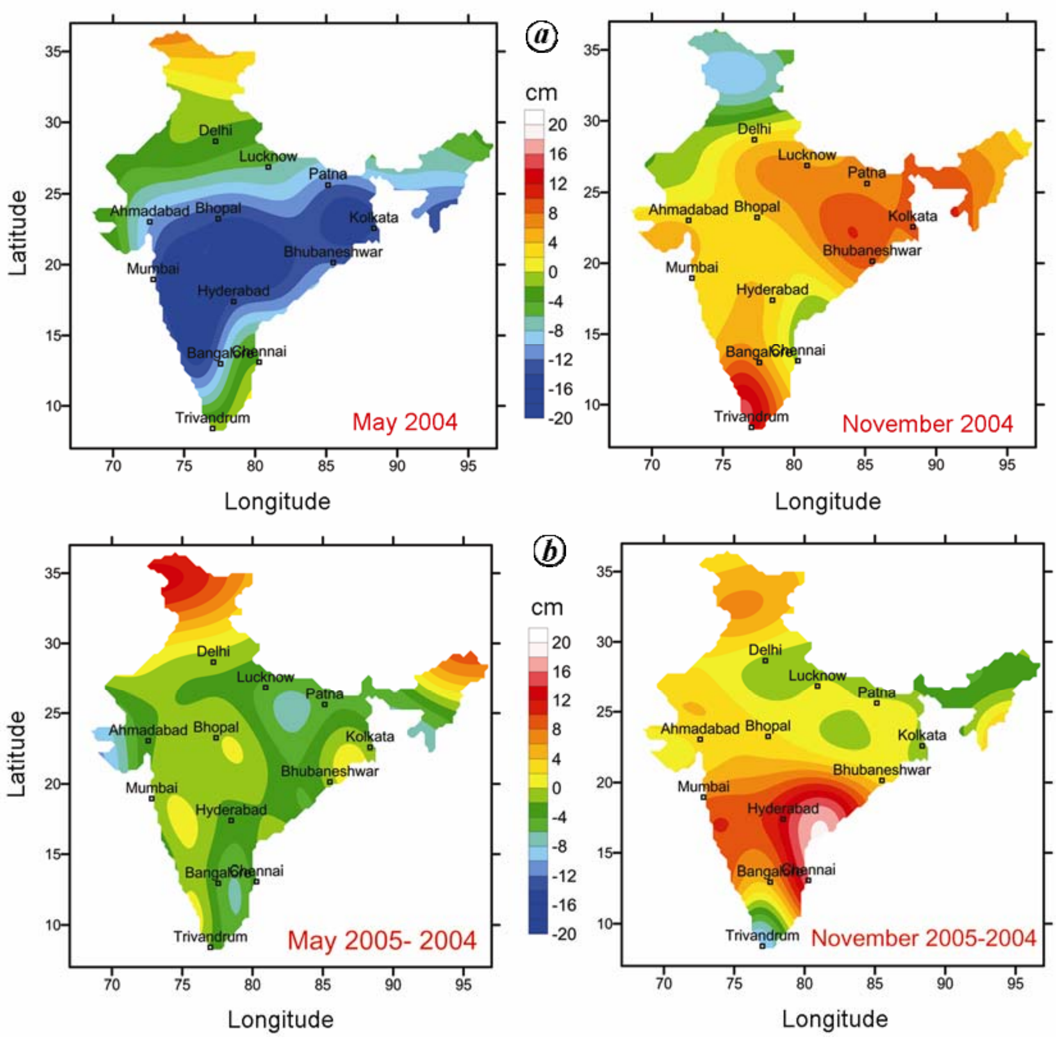

Figure 1. ***a***, GRACE gravity solution for total water storage (after subtracting an average of six years, 2002–2008) for May 2004 and November 2004 showing seasonal changes due to monsoonal rainfall. ***b***, Difference of the total water storage during May and November between 2005 and 2004, showing annual changes.

groundwater storage variability with specific reference to India, and compares GRACE-derived data with *in situ* measurements over Andhra Pradesh, India.

The GRACE satellite mission was launched in 2002 as a collaboration between American and German scientists. The GRACE mission consists of twin satellites placed roughly 200 km apart and track to one another with an accuracy of better than 10 μm. At approximately monthly intervals, global high-resolution models of the earth's gravity field have been provided since 2002 (ref. 5). Global gravity models are typically provided in terms of spherical harmonic coefficients, which can be further processed to derive monthly estimates of mass changes anywhere on the globe[1]. The last six years of GRACE data demonstrate that the largest variations of mass on/or inside the earth's surface are caused mainly by the redistribution of water, ice and snow on land[6–11]. GRACE-derived total mass variations represent the sum of all sources of mass changes on and below the surface. Therefore, it is necessary to have other independent sources of information like soil moisture, groundwater and surface-water storage to separate the GRACE mass estimates into different components. Land surface models based on precipitation data and appropriate forcing predict the contributions of soil moisture to the GRACE signal[9]. Such global hydrological models such as GLDAS/Noah (e.g. Rodell *et al.*[12]), can be used to derive groundwater variations from GRACE data. It has been noted that groundwater variations derived from GRACE data by subtracting the soil moisture contributions using global land hydrological models compare reasonably well with water-level records from bore holes[10].

Monthly solutions of GRACE level-I data are routinely processed at CSR (Centre for Space Research, University of Texas, USA) and GFZ (Potsdam, Germany). The research groups at these two institutes provide spherical harmonic (Stokes) coefficients of the gravity field at monthly intervals (level-II data) to all users. We have

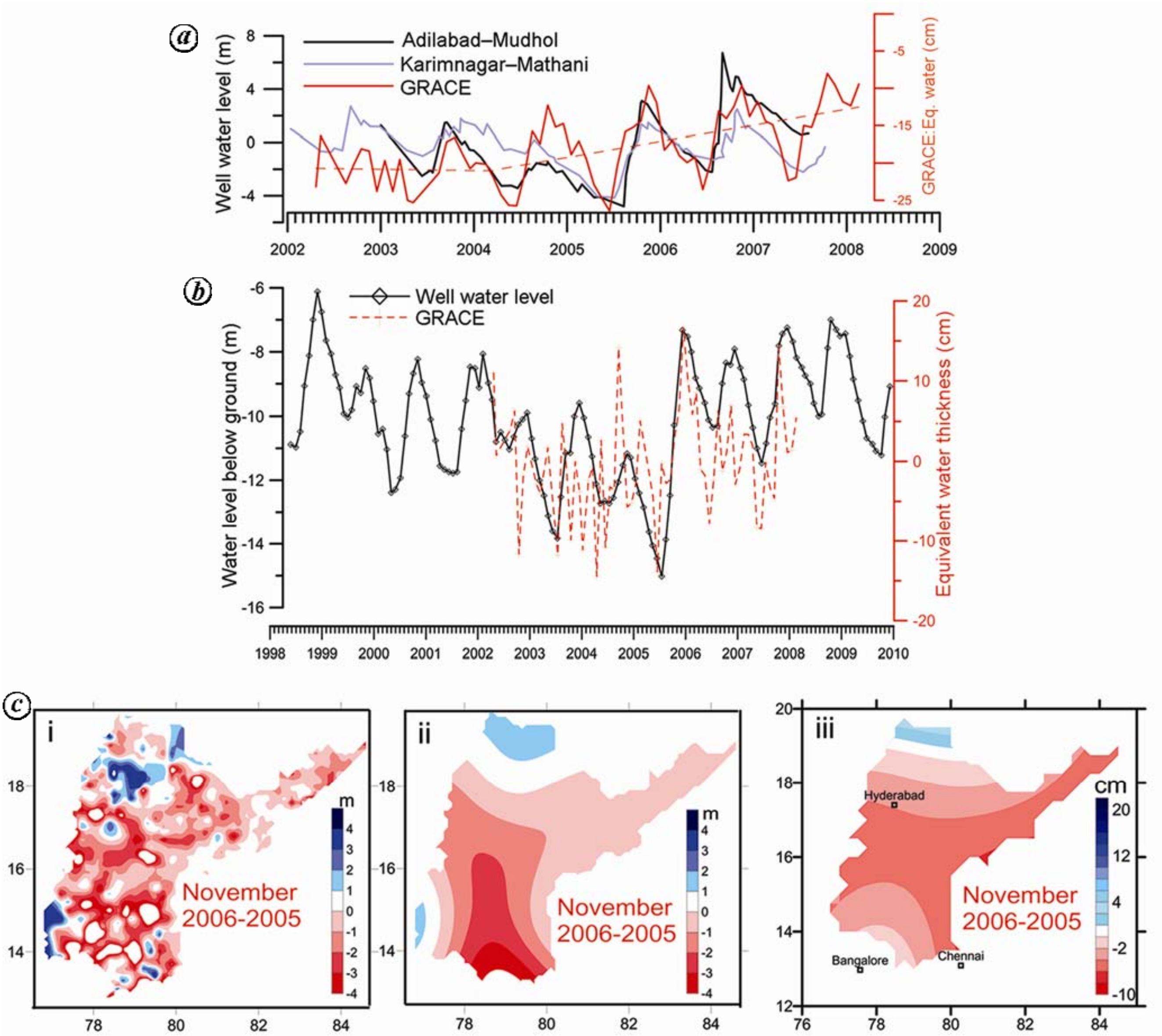

Figure 2. ***a***, Plots of water level recorded at two locations in Andhra Pradesh (AP) (source: CGWB[15]). GRACE-derived time series for the location of Adilabad is also plotted in red for comparison, though groundwater information derived from GRACE data is not point measurements and spatially averaged over a region with 250 km radius. ***b***, Average plot of groundwater level recorded in more than 950 bore wells by the Andhra Pradesh Ground Water Department[16]. A negative water-level trend is evident till 2004, whereas a positive trend is visible after 2005. GRACE-derived time series also averaged for several locations is plotted in red for comparison, exhibiting two trends as noticed in the well records. ***c***, Groundwater variability mapped by GRACE and recorded on ground (after CGWB[15]) over AP. (i) Plot of difference in water level from the bore well in November 2006 and 2005. The colour scale represents differences in water level from the bore well in November 2006 and 2005 (ii) Plot of filtered trend to highlight long wavelength of (i). (iii) GRACE-derived water level for the same period. GRACE results are spatially smoothed with a 250 km smoothing radius.

used level-II data released by CSR (http://podaac.jpl.nasa.gov/grace). Level-II data are corrected for atmospheric, tidal and oceanographic contributions. Post-processing of GRACE level-II data is required due to the correlated errors observed in the GRACE data[8]. We applied a Gaussian smoothing filter of 250 km wavelength[1] and decorrelation filter[13] to the monthly Stokes coefficients. The gravity field coefficients are inverted in terms of equivalent water thickness following Wahr *et al.*[1]. Soil moisture contributions to the total water storage are estimated based GLDAS/Noah. This model predicts all the near-surface water storage, including snow mass, but does not include surface-water components like reservoirs and rivers. Our estimate of groundwater variability is made by removing the soil moisture estimate from the GRACE total water storage estimate.

GRACE-derived mass changes are presented in terms of equivalent water thickness for May 2004 and November 2004 in Figure 1 *a*, after removing the mean over the period 2002–2008. The differences in colour show changes in water mass and thus in total water storage (groundwater, surface water + soil moisture, etc.). These

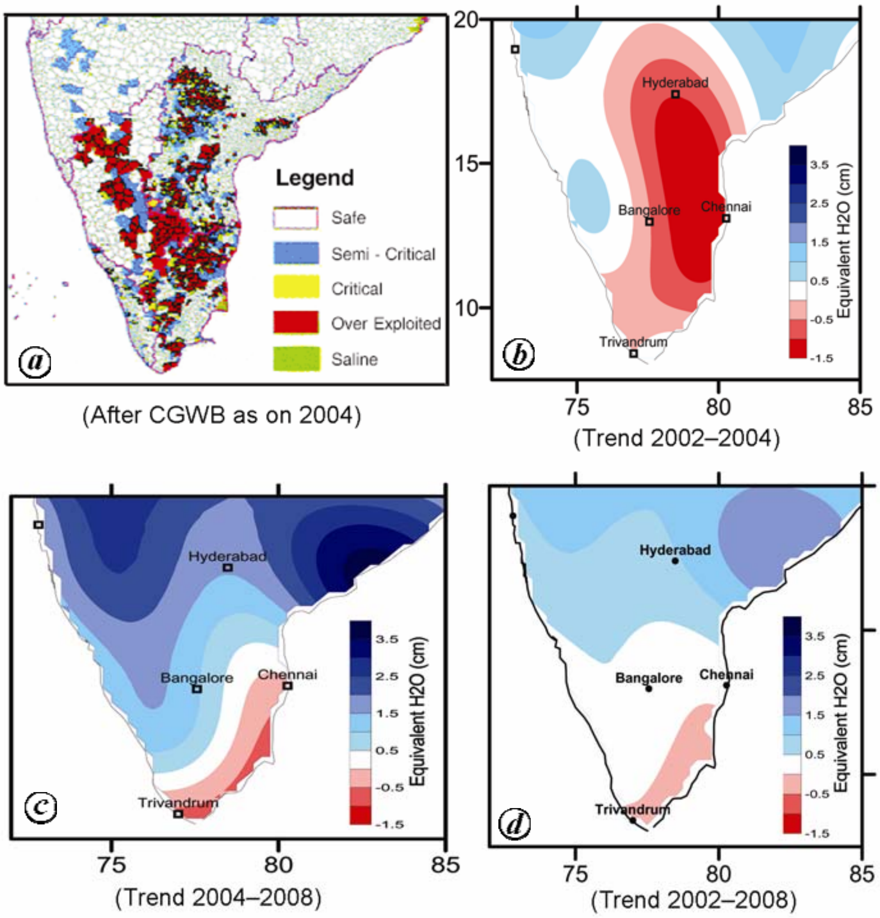

Figure 3. ***a***, Map showing level of exploitation of groundwater (source: CGWB[19]). ***b–d***, GRACE-observed gravity trends, converted to equivalent water thickness and corrected for soil moisture contributions using the GLDAS Noah hydrological model. Red indicates negative trends suggesting decline of groundwater in that region, whereas blue indicates regions of recharged aquifers. The maps show differences due to different periods of observation.

two plots clearly show an increase in total water storage due to seasonal rainfall over India. Such information of total water storage on monthly timescale and over continent-wide coverage was not available before the GRACE era. To see annual differences in water storage, the GRACE signals for the month of November 2004 and November 2005 are plotted in Figure 1 *b*. Significant differences can be seen, suggesting decrease in the total water storage at places such as Delhi, and increase in places such as Central India and parts of southern India.

To illustrate the application of GRACE data to derive groundwater variations and their comparison with *in situ* measurements, we selected Andhra Pradesh (AP), a state of India where the groundwater scenario is changing over years to decades[14]. Much of AP (83%) is underlain by hard-rock terrain, and rainfall in the area is low compared to other parts of India. The occurrence of groundwater in the hard-rock terrain is in the upper few metres of the weathered zone, fracture and cavities[14]. Surface water constitutes a sizeable part of the total water storage in AP. This is not the best region for demonstration of the application of GRACE results for groundwater variability, as the GLDAS/NOAH model, which we are utilizing to derive groundwater variations, does not include the contributions of surface water. Nevertheless, it represents water-storage scenario that is consistent with ground measurements. First, we compare water-levels measured in bore wells at two different locations in AP. Plots of GRACE data and water-level measurements agree well (Figure 2 *a*; CGWB[15]). To elucidate it better, an average time series of water-level variations recorded in more than 950 bore wells by the Andhra Pradesh Ground Water Department (APGWD) for the period of 1998–2010 is also plotted (Figure 2 *b*; APGWD[16]). Figure 2 *b* shows two distinct trends; one from 1998 to 2004 and the other from 2005 onwards in the bore-well data as well in the GRACE-derived groundwater information. It is interesting to note that to further study and compare GRACE-derived data with ground data, we have plotted the spatial variability of water storage in November 2005 and 2006 over AP (i–iii, Figure 2 *c*). These plots are a qualitative comparison of water storage and mainly to demonstrate that positive and negative trends are similar in the GRACE and ground data measurements. Ground measurements plotted in the figure show the water-level variation in metres, whereas GRACE data show water mass variation in centimetres. To convert water-level variation to mass variation (total volume change), aquifer parameters are required, which is complex for a hard-rock terrain. Nevertheless, a visual agreement in the spatial trends of GRACE-derived water mass changes and water-level changes plotted in Figure 2 *c* are notable. The differences in some places (i, Figure 2 *c*) are because GRACE data are smoothed with a 250 km smoothing radius, whereas the contours from ground measurements are from individual point measurements. The short wavelength features of Figure 2 *c* (i) are filtered using digital filter of cut-off wavelength 250 km, just to give an idea that such features would not be possible to detect in the GRACE data.

Time series of GRACE records and water-level measurements in the bore wells show two trends: a diminutive decrease from 2002 to 2004, and an increasing trend from 2005 (Figure 2 *b*). The increasing trend is likely to be caused by more than average precipitation recharging the aquifers considerably. The negative trend before 2004 might be due to less than average rainfall before 2004 (ref. 17). Figure 3 presents plots of the trends and their spatial variation. The spatial distribution of the trend from 2002 to 2004 shows a near-uniform negative trend over almost the whole of South India. Though time-period of two years is small to derive a trend, a similar trend found in water-well records since 1998 is considered to make this assumption. The spatial variability of this trend changes considerably after 2004. The northern part of southern India gained water mass after 2004. Mean annual rainfall was less before 2004 and increased afterwards[17]. Thus it appears that the change in rainfall is profoundly influencing the groundwater trend at inter-annual scales in southern India. Figure 3 also shows that the southeastern region, mainly covering Tamil Nadu has a consistent negative trend, thus indicating that a suitable water management programme is needed to recharge the depleting aquifer in this region.

The above analyses amply demonstrate the usefulness of GRACE satellite gravity data to study hydrological changes over South India. Due to a large seasonal variability of hydrological signals and the vast spatial extent of India, the GRACE data appear useful for studying total water storage variability as well as trends of groundwater variations on regional scales over the Indian subcontinent. This method of groundwater estimation from GRACE has also shown excessive groundwater extraction over northern India[11,18], which is one of the important contributions that GRACE has provided to the policy-makers. The present study suggests that groundwater extraction is greater than recharge mainly over the region encompassing Tamil Nadu and partly over Kerala during 2004–2008. In contrast, the aquifers of south-central India gained water after 2004. It is also likely that the positive trend in water storage raised surface water storage in addition to increasing groundwater-levels in some parts of AP[15].

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