Application of Satellite Gravimetry for Water Resource Vulnerability Assessment

by

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Abstract

The force of Earth's gravity field varies in proportion to the amount of mass near the surface. Spatial and temporal variations in the gravity field can be measured via their effects on the orbits of satellites. The Gravity Recovery and Climate Experiment (GRACE) is the first satellite mission dedicated to monitoring temporal variations in the gravity field. The monthly gravity anomaly maps that have been delivered by GRACE since 2002 are being used to infer changes in terrestrial water storage (the sum of groundwater, soil moisture, surface waters, and snow and ice), which are the primary source of gravity variability on monthly to decadal timescales after atmospheric and oceanic circulation effects have been removed. Other remote sensing techniques are unable to detect water below the first few centimeters of the land surface. Conventional ground based techniques can be used to monitor terrestrial water storage, but groundwater, soil moisture, and snow observation networks are sparse in most of the world, and the countries that do collect such data rarely are willing to share them. Thus GRACE is unique in its ability to provide global data on variations in the availability of fresh water, which is both vital to life on land and vulnerable to climate variability and mismanagement. This chapter describes the unique and challenging aspects of GRACE terrestrial water storage data, examples of how the data have been used for research and applications related to fresh water vulnerability and change, and prospects for continued contributions of satellite gravimetry to water resources science and policy.

1. Introduction

The force of gravity is directly proportional to mass. Although we may think of gravity as being a constant 9.8 m/s^2, mass is not uniformly distributed at Earth's surface and therefore gravity is non-uniform as well. Earth's gravity field can be visualized as a bumpy ellipsoid, having both static and time variable components, the static component being orders of magnitude stronger. Jeffreys (1952) was among the first to report the existence of the time variable component, noting that mass movements such as ocean tides changed the gravity field.

From the perspective of an orbiting satellite, the Rocky Mountains exert more gravitational force than the Great Plains, and eastern Asia exerts more gravitational force during monsoon season, when the ground is wet and therefore more dense, than during the dry season. The orbit of such a satellite is perturbed in a way that can be predicted based on the gravitational potential and thus the surface mass distribution, or vice versa. Realizing this, scientists first began to use the orbits of artificial satellites to identify spatial irregularities in Earth's gravity field in the late 1950s. Satellite tracking via optical and Doppler techniques allowed them to compute departures from predicted orbits, and from those the static gravity field was mapped. In the 1960s, satellite laser ranging enabled more accurate determination of satellite orbits and thus more detailed assessments of the gravity field. Yoder et al. (1983) reported that the orbit of the Lageos satellite was sensitive to temporal variations in the gravity field, which was a first glimpse at the future of time variable gravity field mapping.

For the purpose of mapping Earth's time variable gravity field with enough accuracy to be useful for such applications as ocean, ice sheet, and terrestrial hydrology monitoring, geodesists realized that tracking satellite orbits from the surface was too imprecise. Instead, they concluded that a dedicated, twin satellite gravimetry mission, with each satellite tracking the orbit of the other, was the best strategy (Dickey et al., 1997). Plans for the Gravity Recovery and Climate Experiment (GRACE) satellite mission soon followed.

GRACE launched on 17 March 2002, sponsored jointly by NASA and its German counterpart. In addition to improving the resolution and accuracy of global gravity maps by more than two orders of magnitude, GRACE proved to be immensely valuable for oceanography, cryospheric science, and hydrology. Perhaps the most renowned climate-related application of GRACE is the estimation of mass losses from the Greenland and Antarctic ice sheets and the associated sea level rise (e.g., Velicogna and Wahr, 2006a; 2006b; Luthcke et al., 2006). Similarly, GRACE has measured the ablation of major glacier systems in Alaska (Tamisiea et al., 2005; Luthcke et al., 2008), South America (Chen et al., 2007), central Asia (Matsuo and Heki, 2010), and the Canadian Arctic Archipelago (Gardner et al., 2011). GRACE has also contributed to numerous studies in many areas of hydrology, including river discharge estimation (Syed et al., 2009), regional evapotranspiration (Rodell et al., 2004; Swenson and Wahr, 2006a), hydroclimatic teleconnections (Andersen et al., 2005; Crowley et al., 2006), groundwater variability (Yeh et al., 2006; Rodell et al., 2007), and drought monitoring (Houborg et al., 2012).

Thus satellite gravimetry as demonstrated by GRACE lends itself to the study of climate vulnerability, water resources change in particular. The purpose of this chapter is to provide details of the GRACE mission and the data it provides (section 2), to describe examples of GRACE enabled investigations of hydroclimate and hydro-resources variability including groundwater (section 3), surface waters and glaciers (section 4), integration of GRACE and other data within numerical models (section 5), and drought monitoring, and to report on future prospects for satellite gravimetry.

2. GRACE Data: Unique and Challenging

The GRACE mission consists of two satellites in a near-polar orbit, about 200 km apart, at a starting altitude of about 500 km. The precise distance between the satellites is constantly measured using a K-band microwave ranging system. The range measurements along with positioning data are used to construct a new map of Earth's gravity field each month, represented mathematically by a set of spherical harmonic coefficients describing the shape of the global gravity field (Tapley et al., 2004). From these monthly "gravity field solutions", time series of regional mass anomalies can be derived using specially designed averaging functions (Wahr et al., 1998).

Unlike conventional remote sensing techniques that rely on measurements of various wavelengths of light emitted or reflected from Earth's surface, vegetation, or atmosphere, satellite gravimetry is not blind to subsurface conditions. GRACE senses variations in the total mass from the top of the atmosphere to the center of the Earth. Oceanic and atmospheric circulations and redistribution of terrestrial water via the hydrological cycle are the main sources of gravitational variability on timescales of months to years. Numerical model analyses are used to estimate and remove the oceanic and atmospheric effects, leaving variations in terrestrial water storage (TWS; the sum of groundwater, soil moisture, surface water, snow, ice, and vegetation biomass) as the only major signal over land. Glacial isostatic adjustment also must be taken into account in certain regions such as Hudson's Bay in Canada and the Scandinavian peninsula, and the Sumatra-Andaman earthquake of 2004 and the Japanese Tohoku earthquake of 2011 produced huge, abrupt gravitational anomalies in those regions, but the timescales of most solid earth processes are too long to be relevant.

What has made GRACE uniquely valuable to hydrology is its ability to measure variations in total water availability on and in the land surface, without limitations of depth, visibility, or location on Earth. However, the satellite gravimetry method has its own set of challenges. First, instead of having a remote sensing footprint or pixel resolution, there is a trade-off between resolution and accuracy. The gravity field solutions contain larger errors at higher degrees and orders (smaller length scales). At resolutions finer than about 150,000 km^2, the uncertainty in the estimates overwhelms the retrieved mass variations (Rodell and Famiglietti, 1999; Rowlands et al., 2005; Swenson et al., 2006). Second, measuring changes in all components of TWS at once is a double edged sword. GRACE provides no information on the vertical structure of a TWS change, whether in the saturated zone, shallow subsurface, surface waters, or ice and snow cover. Third, most hydrologists are accustomed to working with instantaneous or daily observations of an absolute quantity, such as rainfall rate or snowpack depth, while GRACE provides monthly mean estimates of TWS anomalies (deviations from the long term average). A related issue is that a monthly observational cycle (for the standard products) ensures that GRACE data will never be available close to real-time. The standard products are typically available a couple of months after the fact. Development of an expedited product is being studied by the GRACE science team, but that still would not meet the needs of most operational water resources and weather related applications.

3. Groundwater Depletion Assessment

Clearly, real-time data are not required for all applied or scientific hydrology applications. Quality and duration of observations are more important for assessing groundwater variability and depletion. In order to employ GRACE data for this purpose, groundwater storage must be isolated from the other components of TWS. A simple approach is to use auxiliary data to estimate variations in soil moisture and snow water equivalent, and to subtract these from TWS variations, leaving variations in groundwater storage as a residual. The assumption here is that temporal variability of vegetation biomass and surface water storage is negligible relative to that of groundwater, soil moisture, and, depending on the region, snow mass. Rodell et al. (2005) demonstrated that seasonal and interannual changes in biomass are at or below the limits of detection by GRACE. Outside of humid tropical regions such as the Amazon (Han et al., 2009) and Bangladesh (Shamsudduha et al., 2012), surface water storage mass variations are also typically insignificant relative to soil moisture, groundwater, and snow mass variations (Rodell and Famiglietti, 2001; Rodell et al., 2009). However, rare are networks of soil moisture (and snow) measurement sites that are dense enough to construct reliable time series of regional mean water storage variability (e.g., Yeh et al., 2006). Rodell et al. (2007) demonstrated that soil moisture and snow time series from numerical land surface models were a reasonable alternative, deriving a time series of groundwater storage in the Mississippi River basin that compared favorably with a time series based on groundwater well observations.

The High Plains aquifer of the central United States, whose groundwater depletion is well documented (e.g., Luckey et al., 1981), provides a useful case study for evaluating the ability of GRACE to monitor interannual variations in groundwater storage. As in many other agricultural regions where rainfall is frequently insufficient to support crop production demands, groundwater withdrawals for irrigation exceed recharge over the long term. This has caused the water table to decline at an average rate of about 7.2 cm per year since 1950, which is equivalent to a reduction in water storage of 337 km^3 between 1950 and 2009 (McGuire et al., 2011). The rates of water table decline are greater in the central and southern parts of the aquifer, reaching more than 80 cm per year in some areas of the Texas panhandle.

Strassberg et al. (2007) combined GRACE TWS observations with soil moisture output from the Global Land Data Assimilation System (GLDAS; Rodell et al., 2004) to compute groundwater variations in the High Plains aquifer during 2003-05. The correlation coefficient between observed and GRACE derived monthly groundwater storage was determined to be 0.58, though the time period was too short to assess the efficacy of the GRACE technique for monitoring interannual variability. A subsequent analysis by Strassberg et al. (2009) improved upon those results in a study covering the period 2003-07 with a more optimally derived GRACE terrestrial water storage time series and both observational and model based soil moisture data, achieving correlation coefficients of 0.73 and 0.72, respectively, between observed and GRACE based monthly groundwater storage time series.

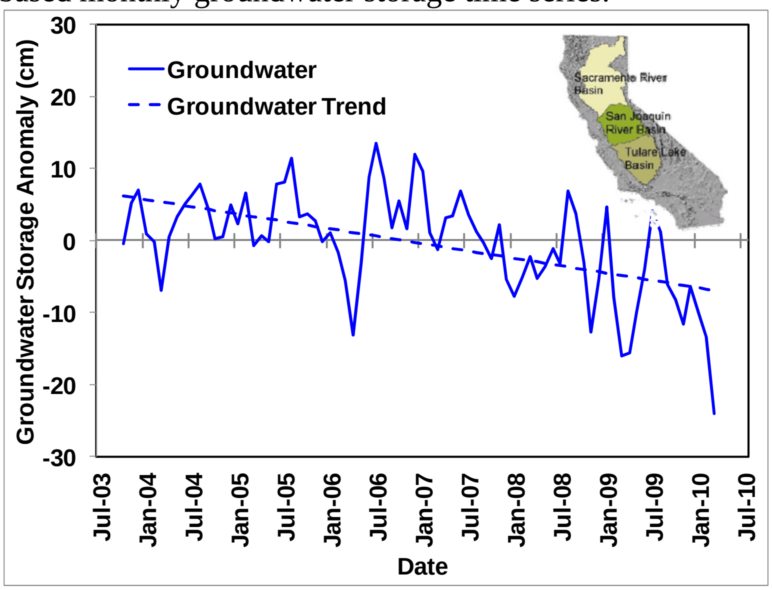

Figure 1. Time series of GRACE-estimated groundwater anomalies (with linear trend) as an equivalent height of water in centimeters, averaged over California's Sacramento, San Joaquin, and Tulare Lake basins (inset). Modified from Famiglietti et al. (2011).

Another area of the United States that may be overly dependent on groundwater is California's Central Valley. Thanks to its favorable climate and good soil, the Central Valley supports a wide variety of crops and is considered one of the most productive agricultural regions in the world. However, sustaining this productivity requires a rate of rainfall that is not consistently available and may be well short during dry years. The proximal solution is irrigation fed by water from the aquifer beneath the Sacramento and San Joaquin River basins, which are mainly recharged by melting snow from the Sierra Nevada mountains (Faunt, 2009). Famiglietti et al. (2011) used GRACE data spanning October 2003 to March 2010 to estimate that the Sacramento and San Joaquin River basins (154,000 km^2) lost water at an average rate of 4.8 km^3/yr (Figure 1), about two thirds of which was groundwater pumped from the Central Valley. They concluded that groundwater depletion at this rate was unsustainable and would have serious consequences if unabated. Fortunately for California, exceptionally wet weather during the winter of 2010-2011 helped the Central Valley aquifer to recuperate to some extent, delaying those consequences for the time being.

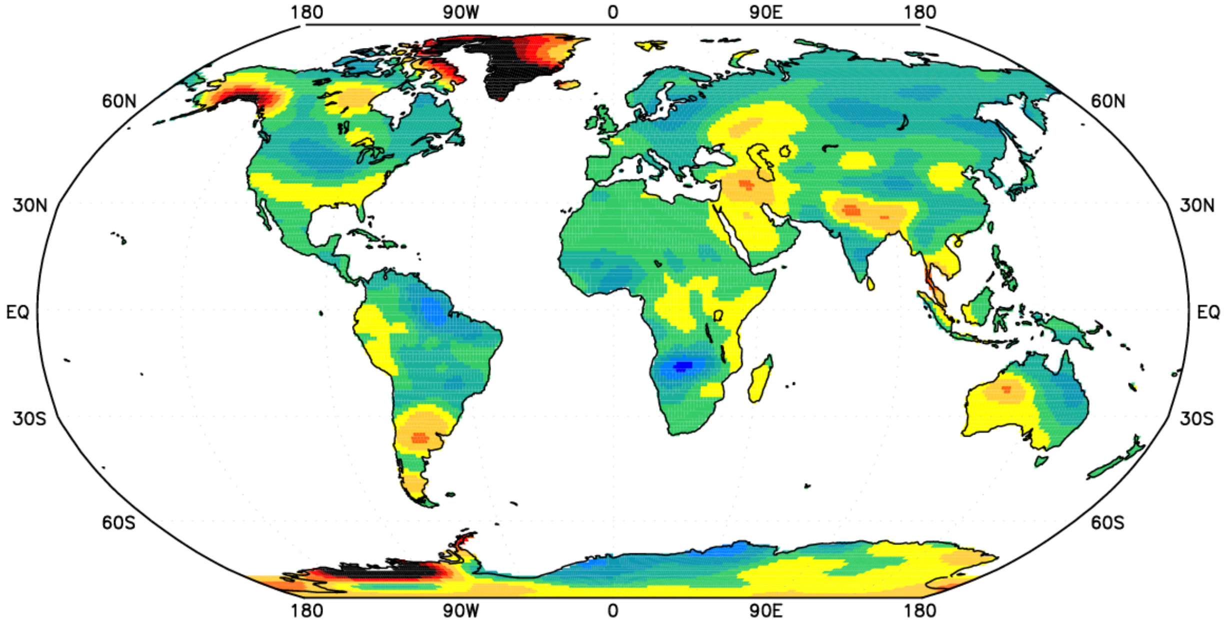

Figure 2. Mean rates of change ("trends") of terrestrial water storage (cm/yr) based on GRACE data from August 2002 to August 2011. The effects of post glacial rebound have been removed from the GRACE data using the model of Paulson et al. (2007), but the gravitational effects of major earthquakes in Sumatra (2004) and Japan (2009) distort the estimated trends near those locations.

The starkest example of groundwater mining over a large area is in northern India. Such a massive quantity of water is being removed from this region that it stands out like a bull's eye on a global map of trends in the gravity field derived from GRACE data (Figure 2). Although officials in India have long been aware that groundwater withdrawals exceed recharge on annual average across the Indian states of Rajasthan, Punjab, and Haryana (including Delhi), an integrative assessment of the rate of depletion had not been performed prior to the onset of GRACE. Rodell et al. (2009) used GRACE TWS data and simulated soil moisture from the Global Land Data Assimilation System (GLDAS) to determine that groundwater was depleted at a mean rate of 17.7 ±4.5 km^3/yr between August 2002 and October 2008 over the 438,000 km^2 region (Figure 3). That equates to 4.0 ±1.0 cm/yr equivalent layer of water (about 33 cm of water table decline per year) and a total of 109 km^3 of groundwater during the study period, which is triple the capacity of Lake Mead, America's largest man-made reservoir. Annual rainfall was close to normal throughout the period, which rules out the possibility of drought related TWS diminishment, and it was determined that surface water and other TWS components did not contribute significantly to the observed trend. Analyzing a 2,700,000 km^2 surrounding area of northern India in a similar GRACE based study, Tiwari et al. (2009) estimated a groundwater depletion rate of 54 ±9 km^3/yr. Currently, farmers are given free electricity for groundwater pumping, so there is no incentive for conservation, yet there is great resistance to changing this policy. The desire for water intensive crops, rice in particular, exacerbates the problem. A sustainable solution to avert hydrological and agricultural catastrophe for the 600 million residents of the broader region will require creativity, political will, and, above all, acceptance of the need for change.

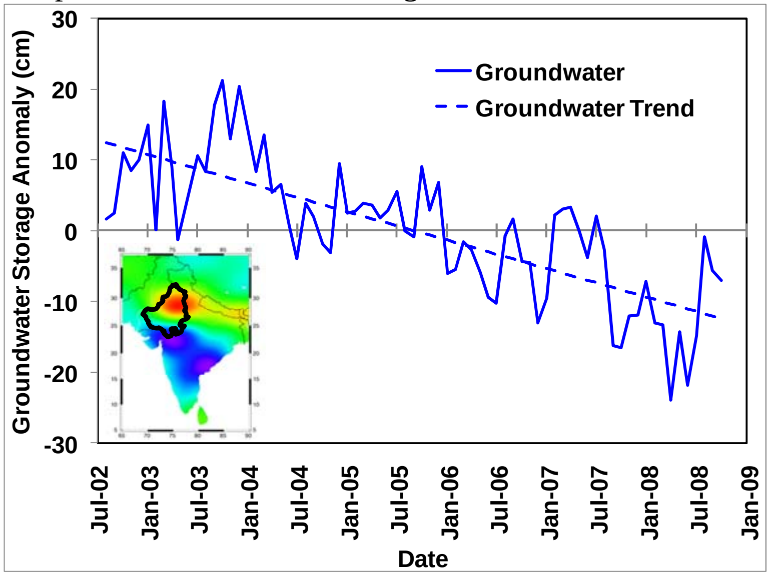

Figure 3. Time series of GRACE-estimated groundwater anomalies (with linear trend) as an equivalent height of water in centimeters, averaged over the Indian states of Rajasthan, Punjab, and Haryana. The inset outlines the region in black on a map of groundwater trends, with depletion in warmer shades. Modified from Rodell et al. (2009).

A similar situation exists just to the east in the Bengal basin of Bangladesh. Groundwater abstraction for irrigating dry-season rice crops along with reduced recharge due to urbanization has depleted the aquifers over the past 40 years. Groundwater abstraction is believed to mobilize arsenic, putting further pressure on this vital yet vulnerable resource (Ahmed et al., 2004). It is unclear how future climate change (for example, if the south Asian monsoon shifts in location or intensity) would affect groundwater storage dynamics. Shamsudduha et al. (2012) compared ground based observations with GRACE terrestrial water storage data and confirmed that GRACE captures both the seasonality and trend of groundwater storage in the Bengal basin, making it valuable for water resources assessment in the region. They found that groundwater storage accounted for the greatest proportion of total variability in terrestrial water storage in the basin, at 44%, with soil moisture and surface water storage accounting for 33% and 22% of variability respectively. The rate of groundwater depletion based on GRACE observations during 2003 to 2007 was estimated to be 0.5 ±0.3 km^3/yr.

4. Lakes and Glaciers

Inland surface waters are another resource that are vulnerable to over-exploitation and drought, which effects can be detected by GRACE if the mass changes are large enough. Seasonal water storage changes in the Amazon River system are the largest in the world, and interannual variability, mainly due to El Nino Southern Oscillation cycles, is similarly immense. Because Amazon surface waters are often dispersed across the landscape rather than concentrated in distinct river channels, ground based quantification of total storage and flow volumes is imprecise. Thus several studies have applied GRACE observations to refine understanding of water cycle variability and surface water dynamics in the Amazon River basin (e.g., Han et al., 2009; Alsdorf et al., 2010). Awange et al. (2008), Swenson and Wahr (2009), and Becker et al. (2010) used GRACE to study water level changes in east African lakes, which are affected by both climatic variability and water resources management, both poorly documented. Swenson and Wahr (2009) used GRACE data together with satellite altimetry based lake levels to infer the water balance of Lake Victoria and the surrounding region. Results were compared with reservoir management data as available and results from previous studies. They concluded that at least half of the observed lake level declines during 2002-06 were caused by releases from Lake Victoria's dams in excess of amounts approved via international treaty (lake discharge being used for hydroelectric power generation). Other surface water bodies whose water storage variability has been elucidated by GRACE include the Caspian Sea (Swenson and Wahr, 2007), Lakes Baikal and Balkhash (Hwang et al., 2011), and the Three Gorges Reservoir (Wang et al., 2011).

Glaciers store fresh water and release it gradually in warm seasons, making them an important resource which happens to be very susceptible to climate variability and longer term change. Over the past decade or more, several of the world's major glacier systems have been melting fast enough that the associated mass change signals are observable by GRACE. While thinning of Greenland's ice sheet has attracted most of the attention in the arctic region (e.g., Velicogna and Wahr, 2006a; 2006b; Luthcke et al., 2006), Gardner et al. (2011) recently made use of GRACE to determine that the melt rate from ice caps and glaciers of the Canadian Arctic Archipelago is equivalent to about 61 km^3/yr of water, or 0.17 mm/yr sea level rise. For comparison, Greenland loses about 219 km^3/yr, or 0.61 mm/yr sea level rise (Chen et al., 2011). Tamisiea et al. (2005) and Luthcke et al. (2008) showed that glaciers along the southern coast of Alaska are melting at a rate of about 84 km^3/yr (0.23 mm/yr sea level rise). Chen et al. (2007) calculated that Patagonian glaciers in southern South America are losing 28 km^3/yr (0.08 mm/yr sea level rise). Matsuo and Heki determined using GRACE that ice water storage losses from the Tibetan Plateau were at least 47 km^3/yr (0.13 mm/yr sea level rise) during 2003-09, which is double the estimated rate of the preceding 40 years, and that the rate could be as high as 61 km^3/yr depending on glacial isostatic adjustment beneath the plateau.

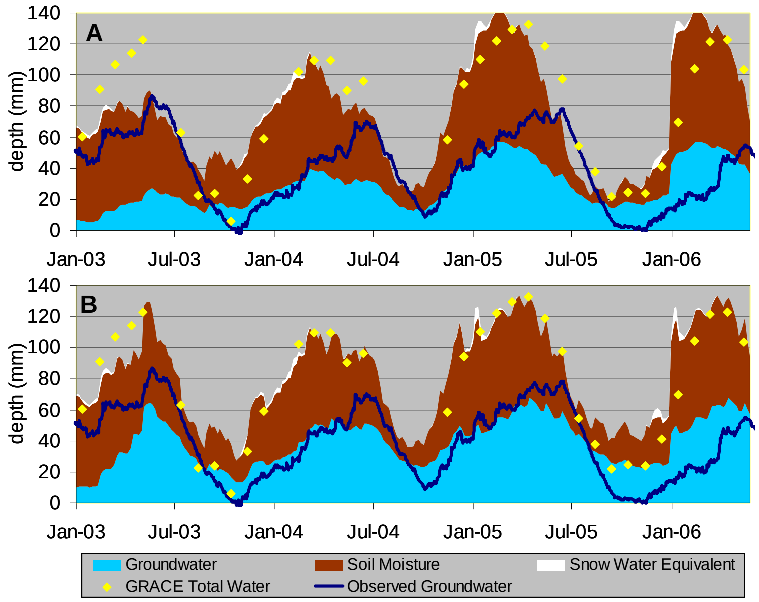

Figure 4. Groundwater, soil moisture, and snow water equivalent averaged over the Mississippi river basin from (A) open loop Catchment land surface model and (B) GRACE data assimilation. Also shown are daily, observation-based groundwater and monthly GRACE-derived TWS anomalies. GRACE and modeled TWS were adjusted to a common mean, as were observed and modeled groundwater. The correlation coefficient between simulated and observed groundwater improved from 0.59 (open loop) to 0.69 (GRACE-DAS). Unlike GRACE alone, the assimilated product is 3-hourly and vertically distributed. Modified from Zaitchik et al. (2008).

5. GRACE data assimilation

While the previous sections clearly demonstrate that GRACE observations have been valuable for a range of hydrological studies, decision support and most other applied disciplines require data that are higher resolution and available closer to real time. With this as motivation, Zaitchik et al. (2008) introduced a more sophisticated approach for spatially, temporally, and vertically disaggregating GRACE derived terrestrial water storage, while simultaneously allowing the information to be extended to near real time. The approach employs an ensemble Kalman smoother to assimilate GRACE data into a numerical land surface model. This has several advantages. First, physical equations of hydrologic and energetic processes, integrated within the model, provide a basis for synthesizing GRACE and other relevant observations (e.g., precipitation, solar radiation, land cover) in a physically consistent manner. Second, the model fills spatial and temporal data gaps, while observations anchor the results in reality. Third, in addition to separating groundwater, soil moisture, and snow, the assimilated output has much higher spatial and temporal resolutions than the original GRACE data. Zaitchik et al. (2008) selected the Catchment land surface model for this purpose, in large part because it simulates groundwater storage variations, a prerequisite that most models do not satisfy. They chose to use an ensemble Kalman smoother rather than the more common Kalman filter because the latter assimilates observations as they become available and updates only the most recent model states, whereas smoothers use information from a series of observations to update model states over a window of time (Dunne and Entekhabi, 2005; Evensen and van Leeuwen, 2000). Smoothers are therefore well suited for GRACE observations, which are non-instantaneous. Prior to assimilation, GRACE TWS anomalies are converted to absolute TWS values by adding the corresponding regional, time-mean water storage from the open loop (no data assimilation) portion of the Catchment model simulation. Zaitchik et al. (2008) validated the technique in the Mississippi River basin using groundwater data from a network of wells, and showed significant improvement in both the timing and amplitude of modeled groundwater variations (Figure 4). The correlation coefficient between the simulated and observed groundwater storage time series improved from 0.59 to 0.69 due to GRACE data assimilation. Further, it was shown that GRACE data assimilation impacts modeled evapotranspiration and runoff fluxes. In addition to drought monitoring (described in the next section) GRACE data assimilation has now been applied for snowpack quantification in the Mackenzie River basin (Forman et al., 2012), water cycle characterization in western Europe (Li et al., 2012), and water resources assessment in the Middle East North Africa region (Bolten et al., 2010).

6. Drought monitoring

Drought has devastating impacts on society and costs the U.S. economy 6 to 8 billion dollars per year on average (WGA, 2004). Drought affects the availability of water for irrigation, industry, and municipal usage, it can ravage crops, forests, and other vegetation, and, where rivers support hydropower and power plant cooling, it affects electricity generation. Most current drought products rely heavily on precipitation indices and are limited by the scarcity of reliable, objective information on subsurface water stores. Groundwater levels, which integrate meteorological conditions over timescales of weeks to years, would be particularly well suited to drought monitoring, if only such data were available with some semblance of spatial and temporal continuity and a reasonably long background climatology (Rodell, 2010).

Droughts cause declines in all types of terrestrial water storage, and as a result they stand out in the GRACE data. For example, drought in the southeastern U.S. (2007-08) imparted a negative trend in that area in Figure 2. GRACE has been applied directly to investigate a decade long drought in southeastern Australia (Awange et al., 2009; LeBlanc et al., 2009). Yirdaw et al. (2008) characterized terrestrial water storage changes associated with a recent drought in the Canadian prairie. Chen et al. (2009) used GRACE to study a major drought event in the Amazon that occurred in 2005, and Chen et al. (2010) examined a recent drought in the La Plata basin.

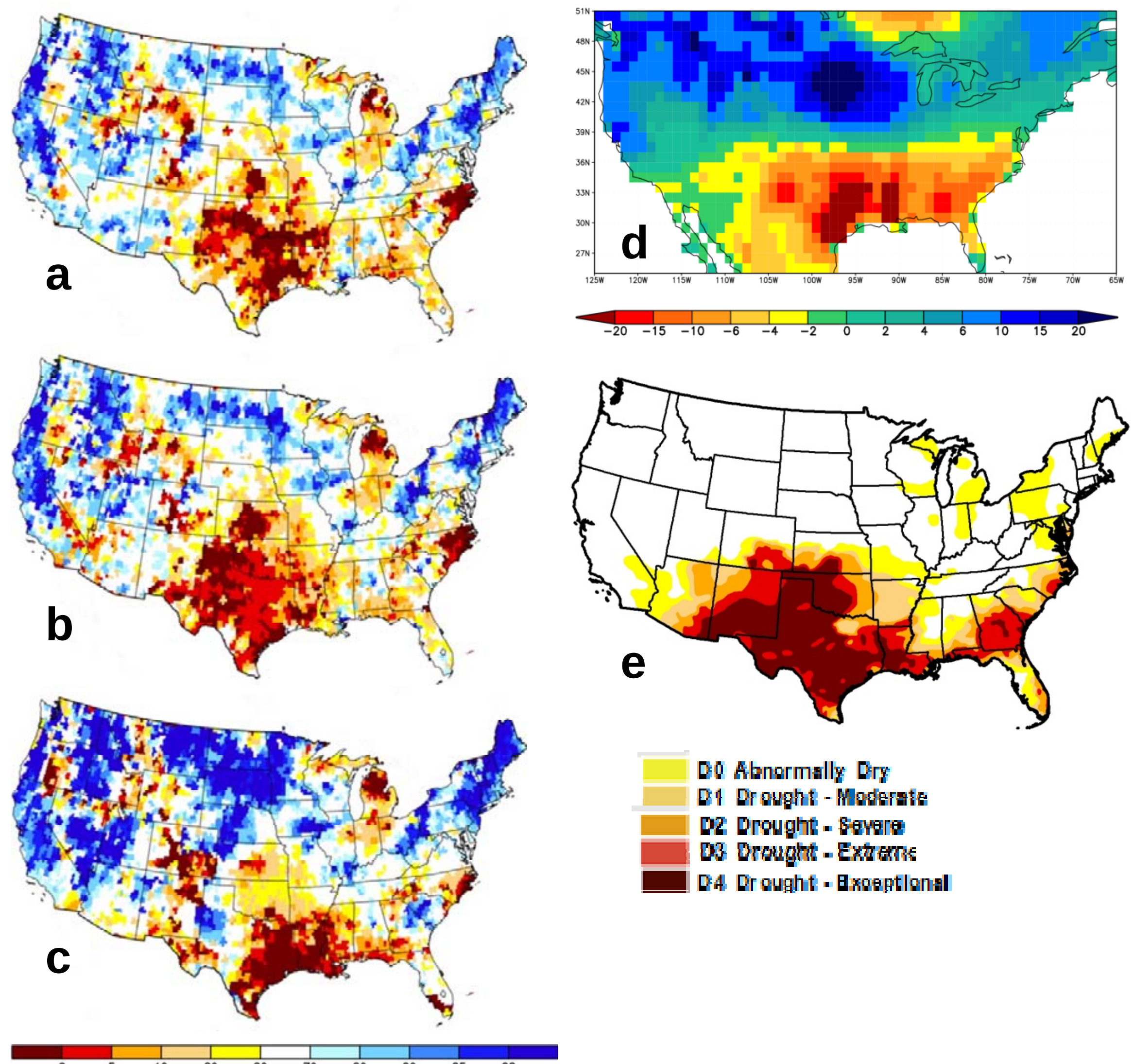

Figure 5. GRACE based drought indicators (wetness percentiles) of surface soil moisture (a), root zone soil moisture (b), and groundwater (c) for 27 July 2011, compared with the GRACE terrestrial water storage anomalies (cm equivalent height of water) for July 2011 (d) and the U.S. Drought Monitor product for 26 July 2011 (e).

Houborg et al. (2012) applied the GRACE data assimilation approach to enhance the value of GRACE for drought monitoring, developing surface and root zone soil moisture and groundwater drought indicators for the continental U.S. Because a long term record is needed as background to quantify drought severity, while GRACE data are only available from mid-2002, it was necessary to rely on the Catchment land surface model alone for most of the record. Therefore, Houborg et al. (2012) executed an open loop model simulation for the period 1948 to near present using for input a meteorological forcing dataset developed at Princeton University (Sheffield et al., 2006). Monthly GRACE TWS anomaly fields (Swenson and Wahr, 2006b) were converted to absolute TWS fields by adding the time-mean total water storage field from the open loop Catchment model simulation. This assured that the assimilated TWS output would be nearly identical to that of the open loop, which is to say that there was no discontinuity between the open loop and assimilation portions of the run. However, the GRACE data, and therefore the assimilation results, could still have a larger or smaller range of variability than the open loop LSM results at any given location. This is significant because drought monitoring concerns the extremes. Therefore, to correct for differences in the range of variability between the assimilation and open loop model output, Houborg et al. (2012) computed and mapped between the cumulative distribution functions of wetness at each model pixel for the open loop and assimilation results during the overlapping period (2002 forward). Drought indicator fields for surface (top several centimeters) soil moisture, root zone soil moisture, and groundwater were then generated based on probability of occurrence in the output record since 1948. To mimic other drought indicators that contribute to the U.S. Drought Monitor product, dry conditions were characterized from D0 (abnormally dry) to D4 (exceptional), corresponding to decreasing cumulative probability percentiles of 20-30%, 10-20%, 5-10%, 2-5%, and 0-2%. Following this process, new GRACE data assimilation based drought indicators (Figure 5) are now being produced on a weekly basis by NASA and disseminated from the University of Nebraska's National Drought Mitigation Center web portal. They are also being delivered to the principals of the U.S. Drought Monitor, who are currently assessing them as new inputs. The U.S. Drought Monitor is the premier decision support tool for drought in the United States, however, it lacked spatially continuous groundwater and soil moisture inputs prior to the development of the new GRACE based drought indicators. Currently, there are very few drought assessment products available that have global coverage, and those that do exist lack the sort of information on subsurface water stores that GRACE provides. It is likely that the GRACE based drought indicators just described will be extended to the global scale in the near future to help alleviate this knowledge gap.

7. Future Prospects

Satellite gravimetry is the only remote sensing technology currently available for measuring water stored below the first few centimeters of the soil column or total liquid and frozen water storage. In addition to GRACE, two other advanced gravity monitoring satellites have been launched: Germany's Challenging Minisatellite Payload (CHAMP) in 2000, and the European Space Agency's Gravity Field and Steady-State Ocean Circulation Explorer (GOCE), in 2009. CHAMP and GOCE each significantly advanced the capability to map the static gravity field at their times of launch, GOCE with significantly higher spatial resolution than GRACE, but neither was suitable for monitoring the time variable gravity field and inferring changes in terrestrial water storage (Han and Ditmar, 2008).

GRACE has endured well beyond its designed 5-year mission lifetime, and there is no set end date. Depending on battery and instrument health and fuel consumption for orbital adjustments, the mission might continue into the middle of the 2010s. NASA, Germany's space agency, the European Space Agency, and various other organizations have begun discussions of a next-generation satellite gravimetry mission, which would improve upon GRACE's horizontal resolution by up to an order of magnitude. This could be achieved by replacing the microwave ranging system with a laser interferometer, flying at a lower altitude in atmospheric-drag-free spacecraft (NRC, 2007), and possibly maintaining multiple satellite pairs in orbit simultaneously (Wiese and Nerem, 2011). While the improved resolution would be valuable, the need for further downscaling via data assimilation would remain. In the meantime, NASA has begun development of a follow-on to GRACE with a nearly identical mission design, which would provide continuity in the data record while affording some improvement in resolution due to basic technological advancements of the past ten years (Watkins et al., 2011). That mission could launch as soon as 2016 and enable gravimetry-based water availability monitoring into the next decade.

Water is essential to life and vulnerable, for example, to overexploitation, pollution, and redistribution associated with any changes in precipitation and temperature. The information provided by GRACE and future satellite gravimetry missions has great potential to improve monitoring and understanding of freshwater availability, thereby helping to reduce environmental and social consequences. The hydrology and other climate communities have been somewhat slow to embrace GRACE as a tool of the trade because of the unique and challenging aspects of the observations. However, success stories such as those described here are increasing awareness and building momentum for GRACE enabled research and applications. Extending the data record by maintaining GRACE and launching the GRACE follow-on mission will also reduce uncertainty in and improve understanding of climatic and anthropogenic impacts on the water cycle that have begun to be revealed. Hopefully, as these impacts become less equivocal, stakeholders and policymakers will make better decisions and reduce threats to our precious freshwater resources.

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