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## GRACE satellite monitoring of large depletion in water storage in response to the 2011 drought in Texas

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[1] Texas experienced the most extreme one-year drought on record in 2011 with precipitation at 40% of long-term mean and agricultural losses of ~\$7.6 billion. We assess the value of Gravity Recovery and Climate Experiment (GRACE) satellite-derived total water storage (TWS) change as an alternative remote sensing-based drought indicator, independent of traditional drought indicators based on in situ monitoring. GRACE shows depletion in TWS of  $62.3 \pm 17.7 \text{ km}^3$  during the 2011 drought. Large uncertainties in simulated soil moisture storage depletion ( $14\text{--}83 \text{ km}^3$ ) from six land surface models indicate that GRACE TWS is a more reliable drought indicator than disaggregated soil moisture or groundwater storage. Groundwater use and groundwater level data indicate that depletion is dominated by changes in soil moisture storage, consistent with high correlation between GRACE TWS and the Palmer Drought Severity Index. GRACE provides a valuable tool for monitoring statewide water storage depletion, linking meteorological and hydrological droughts. **Citation:** Long, D., B. R. Scanlon, L. Longuevergne, A.-Y. Sun, D. N. Fernando, and H. Save (2013), GRACE satellites monitor large depletion in water storage in response to the 2011 drought in Texas, *Geophys. Res. Lett.*, 40, 3395–3401, doi:10.1002/grl.50655.

### 1. Introduction

[2] Texas was subjected to the most extreme one-year drought on record in 2011 resulting in agricultural losses totaling \$7.6 billion [Fannin, 2012] related to soil moisture and irrigation deficits, rice irrigators in the Gulf Coast losing interruptible water rights from the Lower Colorado River Authority, 742 public water systems under mandatory water restrictions, one community of ~4000 people running out of water, and shedding of 1500 MW of interruptible electricity

load to avoid blackouts during peak demand in early August 2011. Precipitation for the 2011 water year (October 2010 to September 2011) was 267 mm, representing 40% of mean precipitation (667 mm, 1895–2011). Statewide mean surface runoff was the lowest recorded since 1895 at <1 percentile (WaterWatch.USGS.gov). The drought extended to neighboring states in New Mexico and Oklahoma.

[3] Quantifying the impact of meteorological drought on water storage is critical for water resources management and for assessing hydrological drought persistence and drought recovery [Leblanc *et al.*, 2009; Scanlon *et al.*, 2012b]. It is imperative to understand the impact of droughts to better manage more restricted water resources in the future because of projected increasing frequency of climate extremes and increasing water demand from 80% population growth by 2060 and rapid economic development [Texas Water Development Board (TWDB), 2012].

[4] The magnitude and spatial extent of droughts is monitored in the US using the Drought Monitor (www.droughtmonitor.unl.edu), which is a composite drought index based on the Standardized Precipitation Index, Palmer Drought Severity Index (PDSI), Climate Prediction Center soil moisture model, satellite vegetation health index, USGS weekly streamflow, and subjective information from a panel of experts [Mo, 2008; Svoboda *et al.*, 2002] (Figure 1). The Drought Monitor has become extremely valuable for monitoring drought severity and extent, short- and long-term precipitation deficits, and drought onset and persistence in the US. However, it relies heavily on simulated soil moisture and does not explicitly account for groundwater storage changes. The extent and severity of the 2011 drought in the south central US (extreme, D3 to exceptional, D4, 15% of US) were almost as great as those of the 2012 drought in the central US (D3–D4, 20%, Figures S1 and S2, Supplementary Material 1).

[5] Many studies have evaluated the use of Gravity Recovery and Climate Experiment (GRACE) satellites to monitor the hydrologic impacts of droughts. GRACE consists of two satellites that track each other at a distance of ~200 km and an elevation of ~450 km above the land surface [Tapley *et al.*, 2004]. Monitoring the distances between the satellites provides temporal variation in the Earth's gravity field, which is primarily controlled by changes in total water storage (TWS). Changes in TWS include changes ( $\Delta$ ) in surface water reservoir storage (RESS), soil moisture storage (SMS), and groundwater storage (GWS):

$$\Delta\text{TWS} = \Delta\text{RESS} + \Delta\text{SMS} + \Delta\text{GWS} \quad (1)$$

[6] GRACE satellite data have been applied to monitor TWS depletion in response to droughts over large spatial

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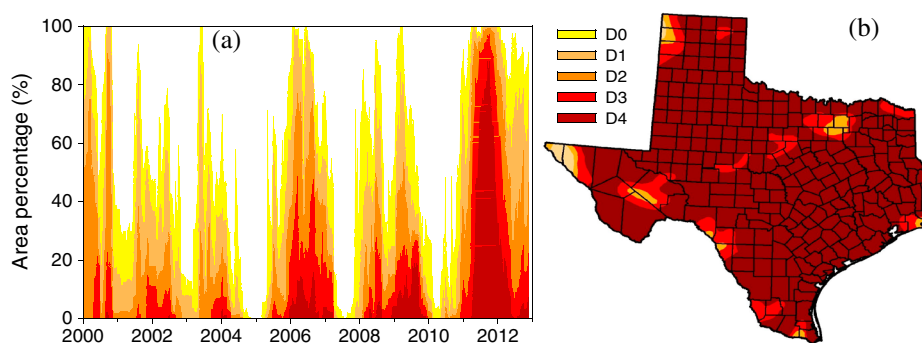
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**Figure 1.** (a) Area percentage of Texas subjected to drought at different severity levels, D0: Abnormally Dry; D1: Moderate Drought; D2: Severe Drought; D3: Extreme Drought; D4: Exceptional Drought from January 2000 to November 2012, and (b) drought severity and extent of Texas on 4 October 2011 (D4: 88%; D3–D4: 97%; D2–D4: 99%; D1–D4: 100%).

scales, e.g., 2002–2003 droughts in the Saskatchewan River basin (406,000 km<sup>2</sup> area; ~37 km<sup>3</sup> depletion) [Yirdaw *et al.*, 2008], 2005 drought in the Amazon basin (6,900,000 km<sup>2</sup> area; ~515 km<sup>3</sup> depletion) [Chen *et al.*, 2009], and 2002–2006 drought in the Murray Darling Basin (~1,000,000 km<sup>2</sup> area; ~140 km<sup>3</sup> depletion) [Leblanc *et al.*, 2009]. The large spatial extent of many of these droughts makes them suitable for monitoring with GRACE.

[7] Motivated by a lack of information on soil moisture in deep layers and groundwater storage in the US Drought Monitor, Houborg *et al.* [2012] recently expanded a data assimilation framework developed by Zaitchik *et al.* [2008] to synthesize GRACE  $\Delta$ TWS data into the US Drought Monitor. Their framework is built upon the Catchment Land Surface Model (CLSM), which simulates SMS and GWS. During data assimilation, an ensemble Kalman smoother algorithm was used to reduce discrepancy between simulated TWS and GRACE observations for the GRACE period (2003–present). A long-term CLSM simulation (1948–2009) was then performed to establish “a reference for creating drought indicator percentiles in a manner consistent with the US Drought Monitor.” The data assimilation approach enables spatial and temporal downscaling of the coarse-resolution GRACE TWS data. However, data assimilation is constrained by (1) assumptions and parameterizations of land surface models (LSMs) (e.g., effects of irrigation and pumping are usually not considered directly), (2) uncertainties in meteorological forcing data and GRACE data, (3) spatial and temporal error models used to “evolve” ensemble statistics, and more fundamentally (4) inherent ill-posedness related to downscaling and disaggregating GRACE TWS into SMS and GWS, especially when in situ data are limited. Drought indicators from this analysis are represented as percentiles of SMS and GWS, rather than TWS. For example, in Texas, only a small number of SMS stations (seven USDA Soil Climate Analysis Network (SCAN) network stations) and groundwater wells (6) were used to compare with simulated SMS and GWS. Houborg *et al.* [2012] showed that assimilation of GRACE data into the CLSM resulted in little skill improvement over Texas.

[8] Many previous studies evaluated relative contributions of different water storage changes to TWS from GRACE. Changes in surface water RESS are negligible in some basins (e.g., the US High Plains and Oklahoma

Mesonet) [Longuevergne *et al.*, 2010; Swenson *et al.*, 2008] and range from 12% in the Murray Darling Basin [Leblanc *et al.*, 2009] to 28% in the California's Central Valley [Famiglietti *et al.*, 2011]. Changes in SMS are generally estimated from LSMs because SMS monitoring is extremely limited (e.g., USDA SCAN, 180 stations in CONUS, 1994–present). The contribution of GWS changes to TWS is generally computed as a residual of changes in TWS, RESS, and SMS (equation 1); therefore, GWS changes accumulate errors in all the other terms. Good correlations between GWS changes from GRACE and from water level monitoring were found in the Murray Darling Basin [Leblanc *et al.*, 2009] and in the High Plains and Central Valley aquifers [Famiglietti *et al.*, 2011; Longuevergne *et al.*, 2010; Scanlon *et al.*, 2012a] (Supplementary Material 2).

[9] The primary objective of this study was to assess the value of TWS changes from GRACE satellites as an integrated estimate of drought impacts on water storage using data from the 2011 drought in Texas as a case study. GRACE TWS was compared with the US Drought Monitor and the PDSI to evaluate droughts based on separate data sets. The 2011 drought covered almost the entire state (~690,000 km<sup>2</sup> in area), with 88% of Texas under exceptional drought (D4) in September/October 2011, making this drought suitable for monitoring with GRACE. Many recent advances have been made in GRACE products [Landerer and Swenson, 2012]. This study uses the latest release of GRACE data from the University of Texas Center for Space Research (CSR), providing an opportunity to evaluate improvements in GRACE products. GRACE data from different processing centers [CSR and the Groupe de Recherche de Géodésie Spatiale (GRGS) RL02] were compared to evaluate reliability of TWS output. Changes in SMS were estimated from several LSMs, i.e., Noah and Mosaic from NLDAS-2 and Noah, Mosaic, VIC, and CLM from GLDAS-1 to evaluate uncertainties in SMS changes. Because Noah and Mosaic from NLDAS-2 and GLDAS-1 reflect different versions and forcings, we refer to them as six separate LSMs. The results of this study should be applicable to many large-scale regions undergoing drought, such as moderate drought over ~65% of the CONUS by the end of September 2012, by providing an integrated estimate of drought impacts on TWS, linking meteorological and hydrological droughts.

## 2. Materials and Methods

### 2.1. Study Region

[10] GRACE analysis was applied to the entire state of Texas (Figure S3). Texas is essentially hydrologically isolated, encompassing 15 major river basins and nine major aquifers, e.g., the High Plains (Ogallala), Edwards, and Gulf Coast aquifers. Climate is highly variable spatially, ranging from semiarid in the west (mean annual precipitation ( $P_a$ )  $\sim 355$  mm) to humid in the east ( $P_a \sim 1187$  mm) for the 1895–2012 climatology from PRISM [PRISM Climate Group, 2004]. Precipitation occurs mostly in the summer in the north and west, in the summer and fall in the south- and north-central regions, and in the spring, summer, and winter in the east. Texas has been subjected to frequent droughts in the past, with the 1950s drought being the longest and considered the drought of record for water resources management ( $PDSI \leq -3$ , 1951–1956). The 2011 drought is the most extreme one-year drought on record in the state. Agriculture is very important in the state, with 20% of the land surface cultivated and  $\sim 20\%$  with herbaceous (grassland) vegetation cover (National Land Cover Database; NLCD 2006). Soil types range from clay to sand and are related to the underlying geology (Figure S4). Soil thickness varies from  $<1$  m ( $\sim 7\%$  of area), 1–1.5 m (21%), 1.5–2.0 m (59%), and  $>2$  m (12%) (Figure S4).

[11] Water storage is monitored daily in 119 major reservoirs with conservation capacities ranging from 0.01 to 5.5 km<sup>3</sup>, totaling 38.7 km<sup>3</sup>. With rising population and economic development, water demand is projected to increase from  $\sim 22$  km<sup>3</sup> in 2010–2019 to  $\sim 27$  km<sup>3</sup> in 2060.

### 2.2. Methods

[12] GRACE satellite data from CSR and GRGS analysis centers were used to derive TWS for Texas. CSR and GRGS represent two end-members for GRACE processing: CSR one of the least constrained solutions and GRGS one of the most constrained solutions, providing valuable information on uncertainty in GRACE TWS changes. The latest release of CSR data (RL05) was used in the analysis, and TWS changes were compared with those from the previous release (CSR RL04) to evaluate improvements in GRACE processing. Details about GRACE processing can be found in Supplementary Material 3. Uncertainties in monthly TWS estimates include: (1) uncertainties in GRACE data and (2) bias and leakage corrections using the additive correction method [Longuevergne *et al.*, 2010] due to uncertainties in SMS changes from LSMs in GLDAS-1. To assess relative contributions of SMS and GWS to TWS, SMS was compared with TWS. SMS was derived from LSMs, i.e., Noah, Mosaic, VIC, and CLM in GLDAS-1 [Rodell *et al.*, 2004; Rui, 2011] and Noah and Mosaic in NLDAS-2 [Xia *et al.*, 2012a; Xia *et al.*, 2012b]. Descriptions of LSMs are provided in Table S1. Uncertainty in SMS was estimated from the standard deviation of SMS from all six LSMs. Note that models in NLDAS-2 or GLDAS-1 use the same forcing; therefore, errors are probably correlated and underestimated. Uncertainty in RESS is not known and a conservative estimate of 10% was prespecified, which has been used in many previous studies [Famiglietti *et al.*, 2011; Scanlon *et al.*, 2012a].

## 3. Results and Discussion

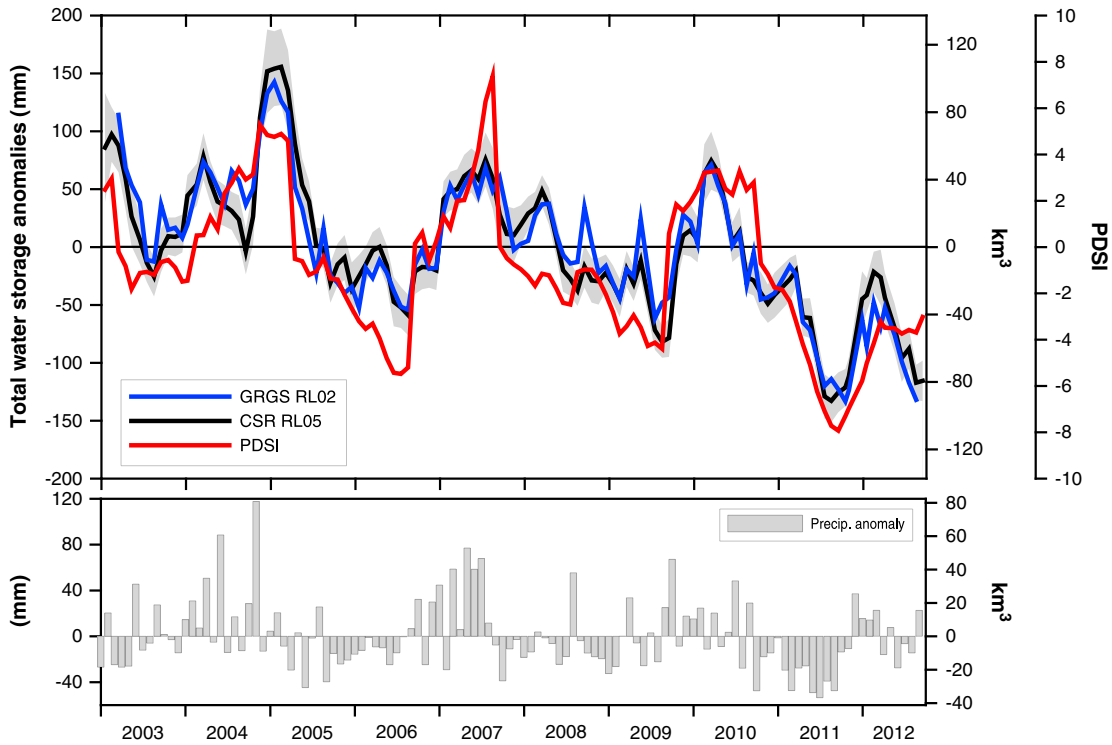
### 3.1. GRACE-Based TWS

[13] TWS anomalies show large interannual variability, ranging from a maximum of  $\sim 107$  km<sup>3</sup> ( $\sim 156$  mm, CSR RL05) in February 2005 to a minimum of  $\sim -91$  km<sup>3</sup> ( $\sim -133$  mm, CSR RL05) in August 2011 (Figure 2). There is no obvious seasonal pattern in TWS, unlike typical TWS seasonal patterns found in many other basins in the US, with winter peaks and summer troughs [Houborg *et al.*, 2012]. The lack of a distinct seasonal pattern in Texas may reflect generally low winter precipitation and mostly lack of snow and peak precipitation in spring and fall (Figure S5). Peak TWS in winter 2004–2005 was preceded by high precipitation in October and November in 2004, peak TWS in summer 2007 preceded by high precipitation from May through August in 2007 with water year (September–October) precipitation of 993 mm being the second wettest year on record, and peak TWS in spring 2010 preceded by high precipitation from January through April in 2010. Monitored changes in RESS are much lower than those of TWS (Figure S6), representing  $\sim 9\%$  of TWS on average from January 2003 through September 2012. This is due to relatively low RESS capacity with respect to total storage of soil moisture and groundwater. RESS peaked in August 2007 at 35.5 km<sup>3</sup> and was lowest in November 2011 at 22.4 km<sup>3</sup>, the latter accounting for  $\sim 58\%$  of reservoir conservation capacity since monitoring began in 1978.

[14] The lowest TWS was recorded in August (CSR RL05)/October (GRGS RL02) 2011, corresponding to the 2011 extreme drought. The magnitude of TWS depletion during drought depends on the times selected for the beginning and end of the drought. Meteorological drought is assumed to begin when the PDSI drops below  $-2$  [Climate Prediction Center, 2011]. The PDSI is a meteorological drought index derived using precipitation, temperature, and soil parameters [Hayes, 2000]. The PDSI was less than  $-2$  from February 2011 through September 2012 in Texas, with a minimum of  $\sim -8$  in September 2011. Therefore, we define the 2011 drought period to span from February through September in 2011. TWS depletion is greatest during the 2011 drought ( $62.3 \pm 17.7$  km<sup>3</sup> for CSR RL05 and  $65.1 \pm 18.6$  km<sup>3</sup> for GRGS RL02, Figure 2). The large recovery in TWS in winter 2011–2012 occurs in response to increased precipitation. Reservoir storage recovered by  $\sim 30$  km<sup>3</sup> from 58% in November 2011 to 78% of their conservation capacity at the end of April 2012. RESS was not fully recovered by September 2012, with a deficit of  $-10\%$  relative to the long-term mean of 30.5 km<sup>3</sup> by the end of September 2012.

### 3.2. Improvements in GRACE Products

[15] CSR RL05 has a 40% lower root mean square (RMS) error (9.8 km<sup>3</sup>, 14.3 mm) than CSR RL04 (16.3 km<sup>3</sup>, 23.7 mm) (Figures S7 and S8), showing notable improvement in CSR RL05. Reduced errors for CSR RL05 are attributed to improvements in the GPS antenna phase center models (IGS08), L1B data, and parameterization of orbit determination, etc. Outliers in RL04 were also edited to improve solutions over several months in RL05. TWS estimates from CSR RL05 are used in the subsequent discussion. The RMS errors in CSR RL05 and GRGS are similar (CSR, 9.8 km<sup>3</sup>;



**Figure 2.** Monthly TWS anomalies from GRACE CSR RL05 and GRGS RL02 and time series of the PDSI, shaded area showing uncertainties in CSR RL05, and monthly precipitation anomaly for Texas from January 2003 to September 2012 (PRISM).

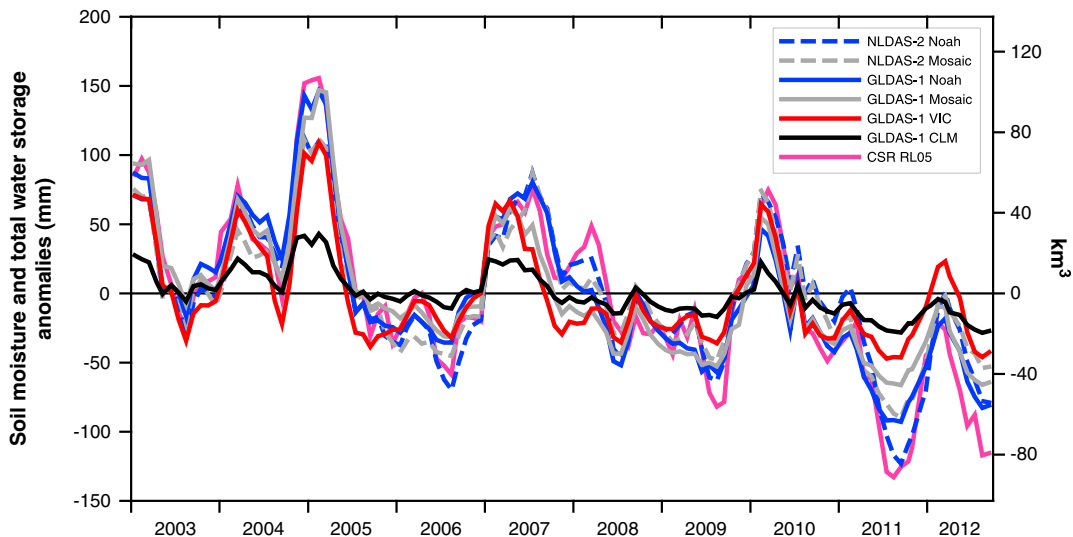
GRGS, 10.9 km<sup>3</sup> (15.9 mm)). The RMS total error (i.e., GRACE error+bias and leakage correction errors) in CSR RL05 TWS is 13.3 km<sup>3</sup> (19.3 mm) and in GRGS RL02 TWS is 13.7 km<sup>3</sup> (20 mm) throughout the study period. GRACE-based TWS estimates from CSR RL05 and GRGS RL02 for Texas are highly correlated ( $r=0.95$ , Figure 2).

**3.3. Comparison of Soil Moisture Storage Changes From Different LSMs (NLDAS-2 and GLDAS-1)**

[16] NLDAS-2 has a higher spatial resolution (0.125°) than that of GLDAS-1 (0.25° or 1°, Table S1). In general, SMS

anomalies from Noah and Mosaic in NLDAS-2 are consistent in terms of timing and magnitude of SMS changes in most months except during extremely dry or wet periods (Figure 3 and Figure S9). SMS from Noah shows greater depletion than Mosaic under extremely dry conditions, e.g., September 2011, SMS from Noah was 37% less than that of Mosaic. The RMS of SMS from Noah and Mosaic in NLDAS-2 are similar (Noah: ~34 km<sup>3</sup> (50 mm); Mosaic: ~30 km<sup>3</sup> (43.5 mm)).

[17] The four GLDAS-1 models tested generally provide consistent timing of SMS changes; however, large differences



**Figure 3.** Monthly total SMS anomalies from Noah, Mosaic, VIC, and CLM in NLDAS-2 and GLDAS-1 and CSR TWS of Texas from January 2003 to September 2012.

**Table 1.** Water Depletion During the 2011 Drought in Texas<sup>a</sup>

Water Storage Components		Drought in 2011 (February–September)
$\Delta$ TWS in km <sup>3</sup> (mm)	CSR RL05	62.3 ± 17.7 (90.8 ± 25.7)
	GRGS RL02	65.1 ± 18.6 (94.8 ± 27.0)
$\Delta$ SMS in km <sup>3</sup> (mm)	GLDAS Noah	41.7 (60.7)
	GLDAS Mosaic	27.3 (39.8)
	GLDAS VIC	18.4 (26.7)
	GLDAS CLM	13.8 (20.1)
	NLDAS Noah	82.7 (120.5)
	NLDAS Mosaic	49.0 (71.3)
	Mean	38.8 (56.5)
Uncertainties	24.8 (36.2)	
$\Delta$ RESS in km <sup>3</sup> (mm)		7.6 ± 0.7 (11.1 ± 1.0)
$\Delta$ GWS using CSR RL05 in km <sup>3</sup> (mm)	GLDAS Noah	13 (18.9)
	GLDAS Mosaic	27.4 (39.9)
	GLDAS VIC	36.3 (52.9)
	GLDAS CLM	40.9 (59.6)
	NLDAS Noah	−28 (−40.8)
	NLDAS Mosaic	5.7 (8.3)
	Mean	15.9 (23.1)
Uncertainties	30.6 (44.6)	
Measured $\Delta$ GWS in km <sup>3</sup> (mm)		5–10 (7.3–14.6)

<sup>a</sup>note that  $\Delta$ TWS,  $\Delta$ SMS, and  $\Delta$ RESS during the 2011 drought (February–September) in column 1 were calculated by the differences in TWS, SMS, and RESS anomalies (January 2003–September 2012) between September and January 2011.  $\Delta$ GWS was subsequently calculated by equation (1). Note that  $\Delta$ GWS calculated using  $\Delta$ SMS estimates from the NLDAS Noah model is minus (increase), which does not mean larger uncertainties in Noah  $\Delta$ SMS estimates but implies problems associated with equation (1) for  $\Delta$ GWS computation during drought.

in magnitude of SMS occur under extremely dry (e.g., summer 2011) and extremely wet (e.g., winter in 2004–2005) conditions. CLM generated the lowest variation (RMS 10.8 km<sup>3</sup>, 15.7 mm), and Noah generated the highest variation (RMS 36.2 km<sup>3</sup>, 52.6 mm) in SMS among the four models across the study period.

[18] Large differences in magnitude of changes in SMS are found between NLDAS-2 and GLDAS-1 LSMs, even for the same LSM. This is attributed to (1) different forcing data, e.g., mean monthly precipitation in NLDAS-2 is ~46% higher than that in GLDAS-1, and monthly downward longwave radiation in NLDAS-2 is generally higher in warm seasons and lower in cold seasons than GLDAS-1 (Figure S10) for Texas during the study period, (2) the same models in NDLAS-2 and GLDAS-1 are based on different versions of LSMs and associated parameters embedded in the codes, and (3) different spatial resolutions between NLDAS-2 and GLDAS-1, e.g., in GLDAS-1 the vegetation tiling approach was employed to represent subgrid heterogeneity because of its relatively coarse spatial resolution. In this case, the GLDAS-1 outputs are average of vegetation tiles within a grid box whereas Noah in NLDAS-2 does not use vegetation tiling.

[19] Though large differences in magnitude of SMS from LSMs were found during drought, the GRACE TWS anomaly is highly correlated with SMS anomalies from individual LSMs, with  $r$  ranging from 0.86 to 0.95 for the entire period (Figure 3 and Table S1). The fraction of TWS anomaly explained by SMS anomalies for the 2011 drought varies markedly, ranging from 25% (GLDAS CLM) to 86% (GLDAS Noah). TWS and SMS show similar trends, declining to a minimum in September 2011 and recovering up until March 2012, then declining again in spring and summer in 2012. Trends in TWS and SMS differ from those in

the PDSI in spring and summer 2012 which levels off at this time. Because of the large variability in estimates of SMS changes among LSMs during drought, they would imply highly unreliable estimates of changes in GWS (Table 1).

[20] The larger magnitude of variation in SMS from Noah than that from Mosaic in NDLAS-2 during extremely dry conditions could be related to different ET parameterization schemes. Note that these LSMs do not computer GWS changes and ET from shallow groundwater. ET from LSMs comes from the vadose zone. Mosaic generates larger ET ( $ET_{\text{Mosaic}}$ ) than Noah ( $ET_{\text{Noah}}$ ) in most of the study period, except the warm seasons in 2006 and 2011 (Figure S11). This is consistent with an overall higher magnitude of ET from Mosaic compared with Noah in most regions in the CONUS [Xia *et al.*, 2012a; Xia *et al.*, 2012b]. Larger magnitudes of  $ET_{\text{Mosaic}}$  than  $ET_{\text{Noah}}$  during normal conditions are caused by greater diffusion of water from deeper soil layers to the shallow root zone [Mitchell *et al.*, 2004] (Table S1). The relatively lower magnitude of  $ET_{\text{Noah}}$  during normal conditions results in higher soil moisture in deep layers and a greater potential to be depleted during drought (e.g., 2011 in Texas) and therefore shows larger SMS depletion under extremely dry conditions.

### 3.4. Monitored Groundwater Storage Changes

[21] Large variability in SMS from LSMs makes it difficult to resolve GWS changes from GRACE TWS and SMS (Table 1). However, groundwater use and groundwater level monitoring data can provide bounding estimates of GWS changes. Estimated groundwater use in 2011 totaled 12.7 km<sup>3</sup> from the TWDB, providing a conservative estimate of groundwater depletion because it assumes that all pumpage is from unconfined aquifers and that there is no return flow or recharge and ET from groundwater. Groundwater depletion from irrigation is focused in the High Plains (Figure S12) and was estimated to be 4.7 km<sup>3</sup> from water-level monitoring by different Groundwater Conservation Districts (GCDs), including 1.8 km<sup>3</sup> for High Plains Underground Water District [Mullican, 2012], 2.5 km<sup>3</sup> for North Plains GCD [Hallmark, 2012], and 0.4 km<sup>3</sup> for Panhandle GCD. Groundwater pumped from other aquifers may have been derived mostly from confined portions of the aquifers with much lower contributions to GRACE GWS changes because storage coefficients in confined aquifers are typically a couple of orders of magnitude less than those in unconfined aquifers [Scanlon *et al.*, 2010a; Scanlon *et al.*, 2010b]. Therefore, estimates of GWS depletion during 2011 range from 5 to ~10 km<sup>3</sup>, representing 8–16% of TWS depletion during the 2011 drought. Considering RESS of 7.6 km<sup>3</sup> and these estimates of GWS changes suggest that SMS changes may range from 70 to 80% of TWS changes.

[22] This study emphasizes the large uncertainties in SMS changes derived from LSMs (24.8 km<sup>3</sup> or 36.2 mm, Table 1) and resultant uncertainties in disaggregated GWS from GRACE TWS (30.6 km<sup>3</sup> or 44.6 mm, Table 1). Therefore, we suggest that the basic TWS may provide a more reliable indicator of drought, rather than disaggregated SMS and GWS. The relatively low contribution of GWS changes to TWS changes in the 2011 drought in Texas differs from those systems where groundwater and soil moisture play comparable roles in TWS changes, such as the High Plains [Strassberg *et al.*, 2007], Illinois [Yeh *et al.*, 2006], and Oklahoma [Swenson *et al.*, 2008], or GWS changes play a

more prominent role in TWS change, e.g., the Murray Darling Basin where groundwater and soil moisture observations accounted for 83% and 14% of the total water lost between 2002 and 2006 [Leblanc *et al.*, 2009].

### 3.5. Comparison of GRACE-Derived TWS With the PDSI and US Drought Monitor

[23] GRACE-derived TWS and PDSI are highly correlated ( $r=0.79$ , Figure 2), providing independent confirmation of PDSI results that primarily reflect SMS in the upper meter of the soil profile [Dai *et al.*, 2004]. The Drought Monitor in the National Integrated Drought Information System (NIDIS) indicates that 88% of Texas in mid Sep 2011 was subjected to exceptional drought (D4) and 99% to severe drought (D2, Figure 1). The severity of the drought is generally consistent with the large magnitude of GRACE-derived TWS depletion. Trends in TWS generally correspond to those of the PDSI until March 2012 when the PDSI levels off but TWS decreases in spring and summer 2012. By the end of September 2012, 5% of the state was subjected to D4 and ~80% to D2; however, TWS declined to values similar to those found in summer 2011. The TWS trends follow those of SMS from LSMs and may provide a more reliable indicator of drought than the PDSI for this time.

## 4. Conclusions

[24] GRACE-derived TWS changes provide a valuable integrated drought indicator for large regions, as shown by results from the 2011 Texas wide drought with TWS depletion of  $62.3 \pm 17.7 \text{ km}^3$ . High correlation ( $r=0.95$ ) between TWS changes from different GRACE processing centers (CSR RL05 and GRGS RL02) provides confidence in the TWS time series. Reduction in RMS errors of ~40% with the latest release of CSR GRACE data (RL05) shows that TWS estimation has markedly improved. Correspondence between GRACE TWS changes and the PDSI provides independent confirmation on PDSI estimates of drought. Large variability in simulated SMS changes from six LSMs, with depletions during the 2011 drought ranging from ~22% (GLDAS-1 CLM) to ~133% (NLDAS-2 Noah) of the TWS change, precludes reliable estimation of GWS depletion by subtracting SMS from GRACE TWS. Differences in simulated SMS among the LSMs are attributed to different precipitation forcings, model versions, and ET parameterization schemes. Estimates of groundwater use in the state totaled  $12.7 \text{ km}^3$  in 2011 dominated by irrigation (78%) and estimates of groundwater depletion in the High Plains, where irrigation is concentrated (~5 km<sup>3</sup>), suggest that GWS changes represent ~8–16% of TWS changes during the 2011 drought. Monitored reservoir storage declines during the 2011 drought were  $7.6 \text{ km}^3$  (12% of TWS changes); therefore, estimated SMS changes represent 70–80% of TWS depletion during the drought. This study suggests that GRACE-derived TWS changes provide a more reliable tool than disaggregated SMS and GWS for monitoring statewide water storage changes in response to drought to improve drought-related water resources management

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