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Key Point:
- GRACE-based drought severity using water storage rather than just precipitation explicitly quantifies the volume of water needed to return to normal conditions and identifies hydrological drought onset, peak magnitude, duration, and severity

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A GRACE-based water storage deficit approach for hydrological drought characterization

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Abstract We present a quantitative approach for measuring hydrological drought occurrence and severity based on terrestrial water storage observations from NASA's Gravity Recovery and Climate Experiment (GRACE) satellite mission. GRACE measurements are applied by calculating the magnitude of the deviation of regional, monthly terrestrial water storage anomalies from the time series' monthly climatology, where negative deviations represent storage deficits. Monthly deficits explicitly quantify the volume of water required to return to normal water storage conditions. We combine storage deficits with event duration to calculate drought severity. Drought databases are referenced to identify meteorological drought events in the Amazon and Zambezi River basins and the southeastern United States and Texas regions. This storage deficit method clearly identifies hydrological drought onset, end, and duration; quantifies instantaneous severity and peak drought magnitude; and compares well with the meteorological drought databases. It also reveals information about the hydrological effects of meteorological drought on regional water storage.

1. Introduction

The elements of drought characterization typically include drought type, frequency, duration, magnitude (including peak magnitude), severity, and areal extent of drought occurrence. Prevailing methodologies include a variety of objective (e.g., meteorological and hydrological data) and subjective (e.g., drought-related articles and impact reports) information to assess drought severity. Determining one definition of drought that can be considered comprehensive is complex, due to a lack of a universal definition [*Wilhite et al*., 2007]. Still, investigating the prevailing characteristics of drought for various climatic regimes and impact sectors contributes to the development of more accurate identification methods that are able to describe the evolution of drought conditions in space and time. For hydrological drought, observing all of the relevant hydrological variables (i.e., snow, surface water, soil moisture, and groundwater) necessary for characterization, across the appropriate temporal and spatial scales, remains challenging.

Satellite remote sensing has emerged as a valuable tool for characterization, because it offers regional-to-global coverage [*Mu et al*., 2013]; yet because many characterization techniques do not incorporate observations of water storage variability in all hydrological components, they cannot provide an integrated measure of the amount of water "missing" from a region during a drought episode.

NASA's Gravity Recovery and Climate Experiment (GRACE) mission [*Tapley et al*., 2004] provides monthly, integrated information about water storage variations throughout all components of the surface and subsurface water balance that was unavailable prior to its launch in 2002 [*Wahr et al*., 2004]. GRACE terrestrial water storage anomaly (TWSA) data have been used in a range of hydrologic studies to estimate fluxes and water storage variations from large river basins to global scales [e.g., *Seo et al*., 2006], groundwater storage changes [e.g., *Rodell et al*., 2009; *Tiwari et al*., 2009], freshwater discharge [e.g., *Syed et al*., 2007], ice mass loss [e.g., *Velicogna*, 2009], and regional flood potential [*Reager and Famiglietti*, 2009]. *Famiglietti and Rodell* [2013] also report on the potential of the GRACE mission for further contributions to regional water management, including drought.

Currently, GRACE observations are being assimilated into land surface models [*Zaitchik et al*., 2008] and subsequently incorporated into the U.S. Drought Monitor [*Houborg et al*., 2012]. While these models enable downscaling and decomposition of GRACE data into water storage components, simulation of the severity of drought events is limited by the model physics, model structure, and the accuracy of additional model parameters and meteorological forcing data [*Long et al*., 2013]. An independent, observation-based water storage deficit is desirable for drought characterization because it is not limited by model assumptions or access to auxiliary data sets. In addition to the potential for advancing drought characterization, it also creates the opportunity for improving models and for new applications including forecasting drought initiation and recovery.

Previous work from *Yirdaw et al*. [2008], *Chen et al*. [2009], *Leblanc et al*. [2009], *Frappart et al*. [2012], and *Long et al*. [2013] examined individual, regional-scale droughts using gravity-based measures of water storage variations from the GRACE mission; however, these studies did not place GRACE observations into a consistent, globally applicable drought characterization framework for quantifying drought severity in terms of the water absent from a region.

We demonstrate that GRACE can contribute to regional drought characterization by measuring water storage deficits in previously identified, drought-stricken areas and that the duration and magnitude of the deficits can serve as new metrics to help quantify hydrological drought severity. We present gravity-based measurements of water storage anomalies during recent, well-documented meteorological droughts (defined as extended periods of precipitation deficits). We use GRACE to further characterize the effects of meteorological drought within the hydrological system to explore how hydrological drought (generally defined as extended periods of water storage deficits) may be better characterized and to estimate the associated regional water storage deficit. We expect that these results can ultimately contribute to a comprehensive framework for hydrological drought monitoring [*Famiglietti and Rodell*, 2013].

2. Data

GRACE observes monthly changes in Earth's gravity field caused by mass redistribution, which, over land and after removal of the atmospheric contributions, are attributed primarily to the movement of water in various surface and subsurface hydrologic reservoirs [*Wahr et al*., 2004]. Here we use the University of Texas Center for Space Research Release 5.0 (RL05) monthly, global, 1° gridded and scaled GRACE land water storage data, which are expressed in centimeters of equivalent water thickness [*Landerer and Swenson*, 2012]. Data are available at http://grace.jpl.nasa.gov (refer to *Swenson and Wahr* [2006] for postprocessing details). GRACE data require scaling to restore true signal amplitude attenuated by data processing [*Velicogna and Wahr*, 2006]; therefore, scaling factors based on the Community Land Model v4.0 [*Oleson et al*., 2008] are provided and multiplied by the unscaled GRACE data following *Landerer and Swenson* [2012]. A 3 month, low-pass filter is also applied to reduce noise before converting storage anomalies from centimeters of water-equivalent height to cubic kilometers of water volume.

Prior work by *Long et al*. [2013] showed GRACE to be a valuable tool to link meteorological drought to hydrological drought. Accordingly, we use two drought databases to identify the presence of meteorological drought in each region and to border our two U.S. study regions. First, maps of drought conditions from the United States Drought Monitor [*U.S. Drought Monitor*, 2013] were used to define the boundaries of regions subjected to major meteorological drought during the GRACE mission lifetime. The maximum areal extent of *severe* to *exceptional* drought severity classes was used to delineate boundaries for the 2007–2009 southeastern United States and 2010–2013 Texas region droughts (see Figure 1). Second, we selected watersheds based on drought information from the Office of U.S. Foreign Disaster Assistance (OFDA)/Centre for Research on the Epidemiology of Disasters (CRED) International Emergency Events Database [*EM-DAT*: *The OFDA/CRED International Disaster Database*, 2013]. This archive identified major meteorological droughts that occurred within the world's large river basins during the GRACE period of record. The Amazon and Zambezi River basins were subsequently selected for analysis (Figure 1).

Study area masks were used to calculate monthly regional average water storage volume anomalies (in cubic kilometers) by multiplying GRACE storage anomalies with the regional mask area (see Table 1a for mask areas). Gridded, time-invariant measurement and leakage errors were provided with the GRACE data set and applied for the calculation of the following total monthly regional average errors based on methodology from *Landerer and Swenson* [2012]: ±11.25 mm/69.12 km^3 (Amazon), ±19.06 mm/25.55 km^3 (Zambezi), ±14.55 mm/11.33 km^3 (Texas), and ±16.02 mm/11.75 km^3 (southeastern United States). These errors offer a measure of the relative GRACE sensitivity to water storage variations in different regions. Larger areas have smaller relative error (per signal), directly related to the effective spatial resolution of GRACE satellites.

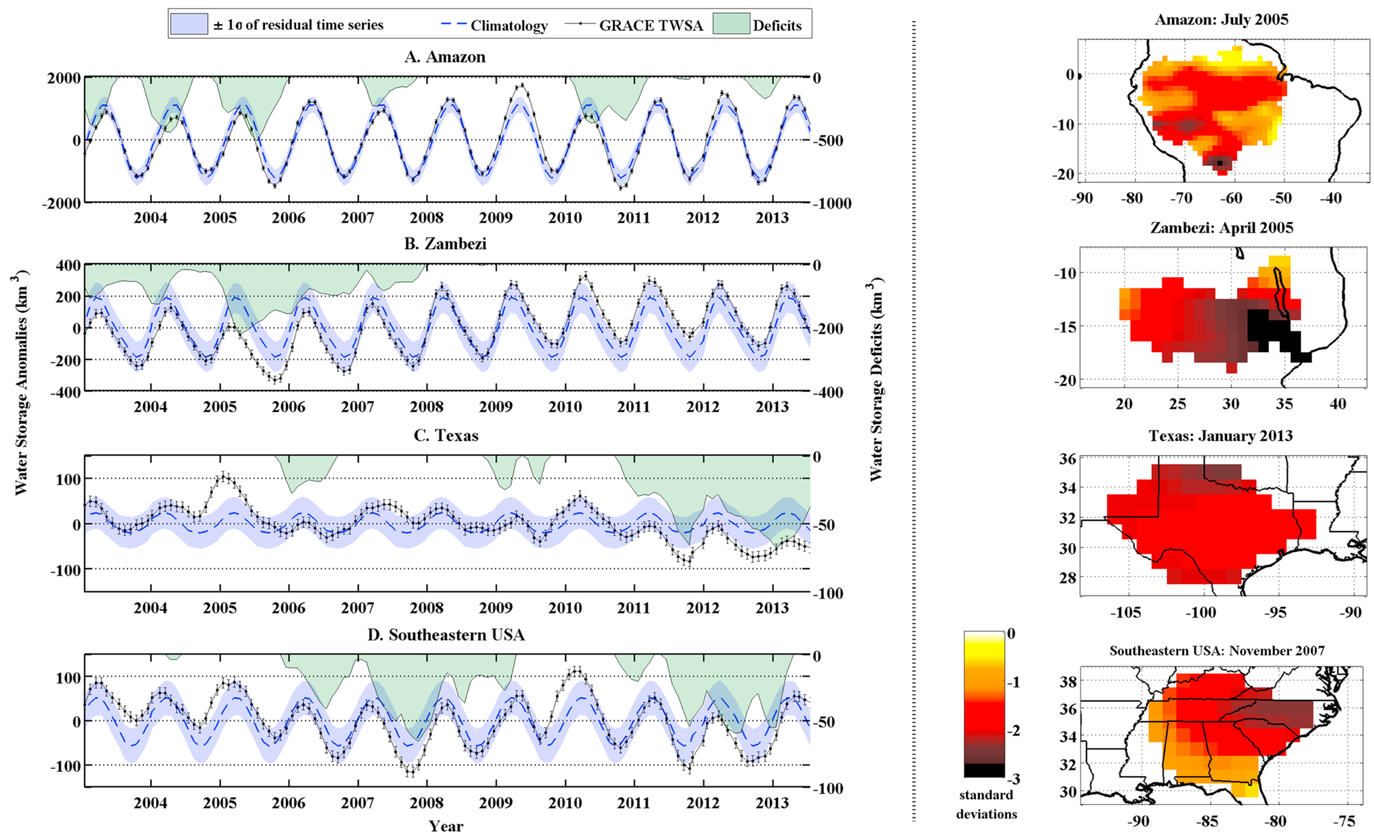

Figure 1. (left) GRACE-observed water storage anomalies and deficits for each study region. Black lines: regional, spatial average storage anomalies with error bars (km^3), blue dashed lines: monthly climatology (km^3), and green-shaded areas: water storage deficits (km^3). Light purple shading around the climatology represents ± 1 standard deviation of the residual time series. (right) Regional maps of 1°, gridded GRACE-identified water storage deficits, on a regionally standardized scale, highlighting the month with the largest peak magnitude for each study region. (a) Amazon, October 2010, (b) Zambezi, May 2005, (c) Texas, November 2011, and (d) southeastern United States, November 2011.

3. Water Storage Deficits and Hydrological Drought Characterization

We computed a 127 month climatology (January 2003 to July 2013) for the GRACE TWSA time series in each study region by averaging the TWSA values of each month of the GRACE record (e.g., all Januaries in the ~10 year record are averaged). This climatology (in units of cubic kilometers) represents the characteristic variability of water storage and serves as a baseline for identifying the occurrence and severity of water storage deficits. This allows us to characterize unique events that are different from the typical annual cycle and to account for regions that have little or strong seasonality. We recognize that a climatology of at least 30 years is preferable; nevertheless, a consistent measure of water storage with global coverage from the GRACE mission is currently the best available. While the GRACE record is relatively short, note that in this paper we are proposing a method for drought characterization that can be continuously updated as the GRACE record length grows.

Water storage deficits were calculated as the negative residuals after subtracting the GRACE climatology from the GRACE TWSA time series. Our calculated residual time series depicts the substantial deviation from the normal annual or seasonal cycle that can then be considered a true deficit and are used to distinguish between relatively dry (negative residuals shown in Figure 1) and wet (positive residuals, not shown) conditions in the four study regions. For convention, deficits and severity are denoted here with a negative sign.

Monthly water storage deficits provide a direct measure of the magnitude, M (km^3), of the volumetric departure from "normal" (climatological) hydrological conditions, or the volume of water required, in any month, to return to normal conditions. M serves as a rolling, monthly measure of the instantaneous deficit magnitude. We calculate 1 standard deviation of the residual time series and plot it above and below the climatology for reference.

Any instance where water storage deficits (M) last three or more continuous months is designated as a hydrological drought "event," which allows us to quantify the importance of departures from the GRACE

Table 1. Summary Table of GRACE-Identified Hydrological Drought Events[a]

A. Region	B. No. of events ≥ 3 months	C. Time span of each event	D. Peak Magnitude (P) km^3	E. Duration (D) (months)	F. Average water storage deficit km^3	G. Total Severity (S) (km^3 months)	H. Coincides with a meteorological drought?
Amazon Area: 6,140,600 km^2	7	Jan-03 to Jun-03	-407 (Mar-03)	6	-277	-1662	N
		Nov-03 to Jul-04	-442 (Apr-04)	9	-283	-2547	**Y**
		Dec-04 to Dec-05	-512 (Jul-05)	13	-279	-3627	**Y**
		Feb-07 to Oct-07	-235 Apr-07)	9	-129	-1161	N
		Feb-10 to Feb-11	-370 (May-10)	13	-253	-3289	**Y**
		Aug-11 to Oct-11	-23 (Oct-11)	3	-19	-57	N
		Aug-12 to Jan-13	-175 Nov-12)	6	-109	-654	N
Zambezi 1,340,600 km^2	1	Jan-03 to Dec-07	-222 (Apr-05)	60	-88	-5280	**Y**
Texas Area: 778,770 km^2	4	Nov-05 to Aug-06	-28 (Jan-06)	10	-17	-170	**Y**
		Nov-08 to Apr-09	-25 (Feb-09)	6	-15	-90	N
		Jun-09 to Sep-09	-21 (Aug-09)	4	-11	-44	N
		Oct-10 to Jul-13	-68 (Jan-13)	34	-43	-1462	**Y**
Southeastern United States Area: 733,760 km^2	3	Dec-05 to Mar-09	-66 (Nov-07)	14	-42	-588	**Y**
		Oct-10 to Mar-11	-21 (Jan-11)	3	-24	-72	N
		Jun-11 to Mar-13	-60 (Jun-12)	6	-15	-90	N

[a]A.: region name with boundary area, B.: number of events, C.: time span of each event, D.: peak magnitude (*P*, the largest value of the deficit *M* that occurs during a hydrological drought in km^3), E.: duration (*D*, the number of months of continuous storage deficits), F.: average water storage deficit (km^3), and G.: total severity (*S*, km^3 month). A hydrological drought period that corresponds with a major, documented meteorological drought is indicated with a bold "Y" (column H), and the row is shaded. Only events lasting 3 months or longer are listed.

climatology on an event-by-event basis. We cross-reference these hydrological drought events with the database records of widespread, regional meteorological drought (refer to Table 1 for all drought characterization variables).

Figure 1 (left column) displays plots of monthly regional average GRACE TWSA's (black line) with error bars, GRACE TWSA monthly climatology (blue dashed line) with confidence bounds (light purple shading), and water storage deficits (green-shaded area, scale on right axis). Figure 1 (right column) highlights months with the largest peak magnitude for each study region (refer to Table 1d) of the residual time series in Figure 1 (left column). Deficits are presented on 1° grids, masked for each study region, and are standardized by dividing each value by the standard deviation of the residual time series for each grid cell.

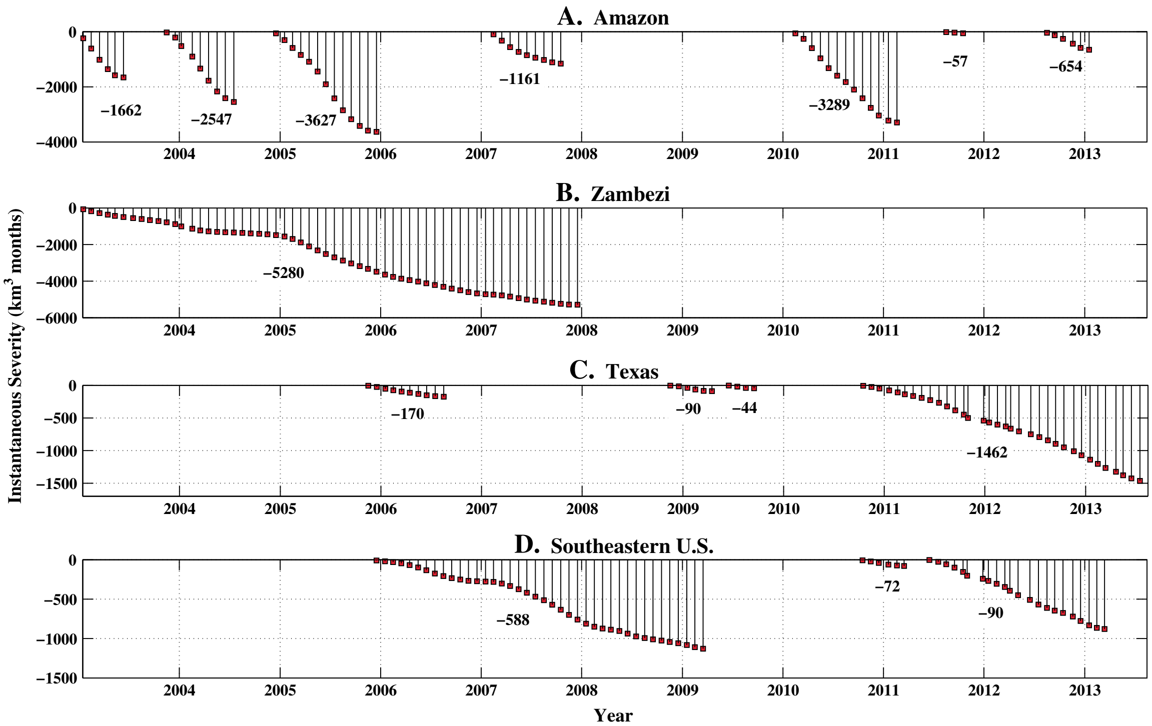

Figure 2. Instantaneous severity for GRACE-observed, regional-average water storage deficits: (a) Amazon, (b) Zambezi, (c) Texas, and (d) southeastern United States. Total severity (*S*) values for each hydrological drought event are given in bold (km^3 months).

To capture the combined impact of water storage deficits and duration, we define the severity, $S(t)$ (km^3 months), of each month within a hydrological drought event as the product of the average deficit since the onset of the deficit period, $\overline{M}(t)$ (km^3), and the duration $D(t)$ (months) since deficit onset, or

$$S(t) = \overline{M}(t) \times D(t) \tag{1}$$

Additionally, at the termination of an event, the total event severity, calculated as S, is equal to $\overline{M}$ times D for the total months of continuous storage deficits (Table 1g). Note that S, $\overline{M}$, P, and D are determined after the termination of the event and will be helpful for intercomparison of events identified by the storage-deficit and other methods, while M serves as the instantaneous measure of the magnitude of the hydrological drought event (i.e., the instantaneous water storage deficit).

4. Results

Table 1 provides a summary of results for each region. While Figure 1 shows all negative departures from the storage climatology, only those lasting for three or more consecutive months are listed in the table. Figure 2 features the severity time series with each uninterrupted deficit period labeled with its corresponding total hydrological drought severity value (also listed in Table 1g).

4.1. Amazon

There were seven occurrences of GRACE-identified hydrological drought events in the Amazon basin (Figures 1a and 2a and Table 1). The largest peak magnitude occurred in July 2005 with 512 km^3 of storage below climatological conditions. Drought events in 2004, 2005, and 2010 had similar total severities (−2547, −3627, and −3289 km^3 months, respectively), with durations of 9 and 13 months. These results are consistent with the OFDA/

CRED EM-DAT database, which documented three major meteorological droughts affecting countries within the Amazon River basin (in 2004, 2005, and 2010) [*EM-DAT: The OFDA/CRED International Disaster Database*, 2013].

4.2. Zambezi

The Zambezi River basin experienced the longest GRACE-identified hydrological drought event of the areas studied (60 months, from January 2003 to December 2007). It is also the one with the greatest total severity (-5280 km^3 months) (Figures 1b and 2b and Table 1c). The region's peak deficit of 222 km^3 below climatology occurred in April 2005. The OFDA/CRED EM-DAT database documented meteorological droughts for territories sharing the Zambezi River basin in 2005 and 2007 [*EM-DAT: The OFDA/CRED International Disaster Database*, 2013]. This is considerably shorter than the 5 years of nearly continuous water storage deficits identified using GRACE, which continued across several wet and dry seasons.

4.3. Texas

There were four GRACE-identified hydrological drought periods within the Texas region (Figures 1c and 2c and Table 1c). One month of surplus storage interrupted events from November 2008 to September 2009. The largest peak magnitude occurred during the most recent event, which began in October 2010 (-68 km^3 in January 2013). The U.S. Drought Monitor detailed two major, widespread meteorological drought periods in this region, in 2006 and from 2011 to 2013, which is consistent with the storage deficit-based hydrological droughts observed with GRACE.

4.4. Southeastern United States

The southeastern United States experienced three GRACE-identified hydrological drought events (Figures 1d and 2d and Table 1c). Two months of surplus storage punctuated the events from October 2010 to March 2013 (April and May 2011). The peak magnitude for this region was -66 km^3 in November 2007. U.S. Drought Monitor time series show two major meteorological drought periods during the GRACE record from 2007–2009 to 2010–2013, which is consistent with storage deficits identified by GRACE from February 2008 to November 2008 and July 2011 to March 2013.

4.5. Using Deficits to Estimate Drought Recovery

The monthly deficit (*M*) quantifies the volume of water required to recover from below-normal water storage conditions. One of the strengths of the storage-based approach is that the time evolution of storage deficits, including their rates of increase or decrease, can be evaluated by estimating the time derivative of the deficit, d*M*/d*t*. This is done as a backward difference calculation

$$\frac{dM}{dt}(t_i) = \frac{M(t_i) - M(t_{i-1})}{t_i - t_{i-1}}, \text{for i} = 1:\text{N} \tag{2}$$

where *M* is the monthly deficit, *t* is time, and *N* is the length of the GRACE record. Since the GRACE record is short and may contain few instances of drought (or drought recovery), we have assumed that the entire d*M*/d*t* time series (not only those points in previous drought recoveries) can be used to represent a range of typical d*M*/d*t* values. To test this assertion, we calculate the d*M*/d*t* distribution and statistical percentiles of the empirical (Kaplan-Meier) cumulative distribution (eCDF) of d*M*/d*t* within the Texas region, which follows a standard normal distribution according to a one-sample Kolmogorov-Smirnov test. For demonstration, the 95th percentile (2 standard deviations) of the eCDF represents the maximum positive rate of change for deficits, and the 68th percentile (1 standard deviation) represents the average positive rate of change for deficits, for any deficit month.

The quotient of a monthly deficit value (*M*) and either the maximum or average rate of change yields the minimum or average time to recovery, allowing us to assign a likely time range for recovery for every month through the end of the event. Based on the 95th (11 km^3/month) and 68th (3 km^3/month) percentiles of the eCDF (Figure 3c, inset), the likely minimum and average times to recovery from the July 2013 deficit (-38 km^3) are ~3 and ~13 months, respectively (Figure 3c).

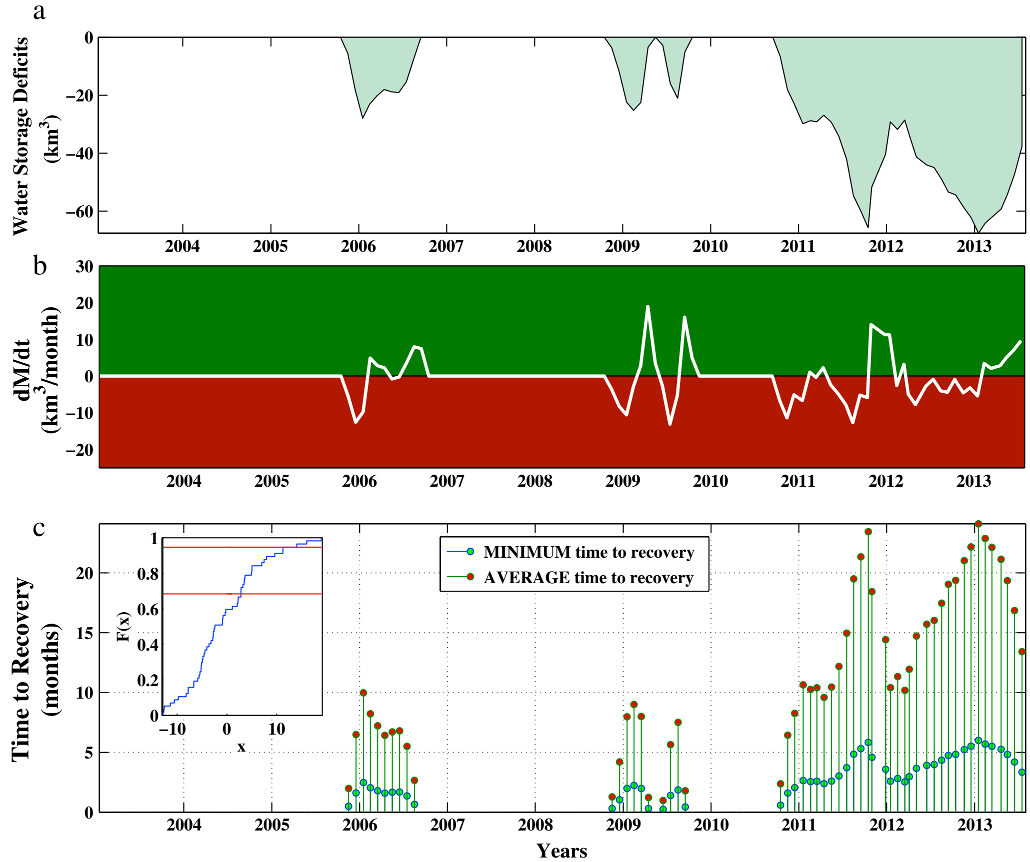

Figure 3. Texas region: (a) GRACE water storage deficits (km^3), (b) monthly rate of change of deficits (dM/dt) in cubic kilometers per month, and (c) the minimum and average times to hydrological drought recovery. Inset: empirical cumulative distribution of dM/dt; the 68th and 95th percentiles (red lines) are used to determine the average and minimum time to recovery, all for January 2003 through July 2013.

5. Discussion

The GRACE-based drought characterization framework presented here offers three key contributions to drought characterization efforts: a framework that provides additional information about the effects of meteorological drought, specifically, how much water is missing from a region during a drought, a clear identification of water storage deficits and quantification of their severity with an observation that integrates both surface and subsurface storage, and a consistent method for severity calculation that can be applied globally.

Instances where meteorological drought occurred without a storage deficit-based hydrological drought (e.g., in the Texas and southeastern U.S. regions compared with the U.S. Drought Monitor) likely suggest that the meteorological drought was not widespread enough to produce an absence of water large enough to be detected by the GRACE satellites. These events may have had an impact on local resources and livelihoods and were reported in the disaster database, without having a major impact on the regional water cycle, which may present as normal or even surplus storage in the time series. There were no instances of significant GRACE storage deficit droughts not matched by meteorological drought reports.

Differences in the timing of meteorological drought and GRACE-identified hydrological drought may be due to inherent lags within the hydrologic system (i.e., subsurface water storage can be slow to react to precipitation changes). Our analysis shows that it is the severity metric (S), and not the magnitude or duration alone, that is most associated with reports of widespread, catastrophic meteorological drought, and corresponds best with major, region-wide meteorological droughts (Table 1h).

There is currently very little understanding of subsurface water supply (e.g., root zone moisture and groundwater, described as the saturated zone extending to the bedrock); hence, this is an important feature captured by our drought characterization framework. For example, the response of groundwater is slower compared to changes in rainfall and snowmelt [*Elathir and Yeh*, 1999]; hence, GRACE-observed deficits within a region may appear later and persist longer in these subsurface reservoirs. Because many common drought metrics tend to be based on the accumulation of precipitation deficits or anecdotal accounts of events, they cannot easily capture the extent of drought influence on subsurface hydrology. Though surface storage may be quickly (seasonally) replenished, deficits in the subsurface leave the region vulnerable to future droughts. When the surface supply is once again depleted and subsurface supply is still inadequate, the consequences for water availability and management can be severe. Because we did not partition water storage into its components, it is not evident how much water is explicitly missing from the subsurface; however, since the integrated signal observed deficits, groundwater in these regions is likely declining as well.

With this framework, it is possible to monitor the intraseasonal persistence of total water storage deficits and surpluses. This presence, even during a wet season, indicates that an interannual drought event is still occurring (though maybe not visible) and may not be resolved in the coming year. This offers potential for drought forecasting for the upcoming dry season and for improving drought-monitoring systems [*Famiglietti and Rodell*, 2013]. Understanding the time evolution of deficit severity is also important for drought monitoring efforts. Two events with similar severity but with differing durations imply that the deficits accelerated (i.e., deficits worsened) at different rates.

In the GRACE-based approach described here, the selection of an averaging area and an understanding of relevant hydrological processes are important in characterizing the intensity of one regional event relative to others. Regional land characteristics, regional land surface and atmospheric coupling, and regional water management decisions influence drought severity. Our quantification of the timing and severity of water storage deficits is described in a manner that can be quickly applied as new GRACE data arrive. Ongoing work will explore using GRACE data to identify drought independently of meteorological drought indices and boundaries, in an effort to provide a truly independent characterization of drought occurrence and severity.

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