JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 115, D22108, doi:10.1029/2010JD014689, 2010

Recent La Plata basin drought conditions observed by satellite gravimetry

J. L. Chen,[1] C. R. Wilson,[1,2] B. D. Tapley,[1] L. Longuevergne,[2,3] Z. L. Yang,[2]
and B. R. Scanlon[3]

Received 28 June 2010; revised 10 August 2010; accepted 17 August 2010; published 18 November 2010.

[1] The Gravity Recovery and Climate Experiment (GRACE) provides quantitative measures of terrestrial water storage (TWS) change. GRACE data show a significant decrease in TWS in the lower (southern) La Plata river basin of South America over the period 2002–2009, consistent with recognized drought conditions in the region. GRACE data reveal a detailed picture of temporal and spatial evolution of this severe drought event, which suggests that the drought began in lower La Plata in around austral spring 2008 and then spread to the entire La Plata basin and peaked in austral fall 2009. During the peak, GRACE data show an average TWS deficit of ~12 cm (equivalent water layer thickness) below the 7 year mean, in a broad region in lower La Plata. GRACE measurements are consistent with accumulated precipitation data from satellite remote sensing and with vegetation index changes derived from Terra satellite observations. The Global Land Data Assimilation System model captures the drought event but underestimates its intensity. Limited available groundwater-level data in southern La Plata show significant groundwater depletion, which is likely associated with the drought in this region. GRACE-observed TWS change and precipitation anomalies in the studied region appear to closely correlate with the ENSO climate index, with dry and wet seasons corresponding to La Niña and El Niño events, respectively.

Citation: Chen, J. L., C. R. Wilson, B. D. Tapley, L. Longuevergne, Z. L. Yang, and B. R. Scanlon (2010), Recent La Plata basin drought conditions observed by satellite gravimetry, *J. Geophys. Res.*, *115*, D22108, doi:10.1029/2010JD014689.

1. Introduction

[2] The La Plata basin is the fifth largest basin in the world and second largest in South America, next to the Amazon basin. With a total area of about 3.5 million km^2, covering parts of five countries (Argentina, Uruguay, Paraguay, Brazil, and Bolivia) (Figure 1), the basin is of great ecological and economic significance, with challenging problems including vulnerability to excess floods and increasing demands as a water resource and source of hydropower [*Barros et al.*, 2004, 2006]. The basin is also home to the Pampas (the dark green area in Figure 1), one of the world's richest grasslands in terms of size and biodiversity and a major agricultural resource [*Viglizzo and Frank*, 2006].

[3] The La Plata basin shows evidence of changes that may be identified with long-term climate variation [*Barros et al.*, 2006; *Viglizzo and Frank*, 2006]. Over the past several decades, the basin has been experienced frequent floods [*Minetti et al.*, 2004; *Barros et al.*, 2006], and more recently has experienced drought. For many areas, especially in the south, the last few years have seen the worst drought in over a century, with official declarations of calamity, a sharp decline in grain and meat output, and economic havoc (M. Valente, AGRICULTURE-ARGENTINA: Worst drought in 100 years, 2009, http://ipsnews.net/news.asp?idnews = 45498). The consequences have been especially significant for Argentina, the world's second largest exporter of corn and coarse grains, and the third largest exporter of wheat [*Food and Agriculture Organization*, 2000]. The recent drought is likely connected to abnormal climate conditions related to the prolonged 2007/2009 La Niña event [*Diaz et al.*, 1998; *de Rojas and Alicia*, 2000; *Grimm et al.*, 2000; *Seiler and Kogan*, 2002].

[4] Monitoring and quantification of the spatial extent and intensity of drought are limited by conventional data resources (in situ meteorological and hydrological observations with sparse spatial and temporal sampling). Deficits in terrestrial water storage (TWS) are particularly difficult to estimate from such data. Drought indices from satellite remote sensing of soil moisture and vegetation change have been used for monitoring drought extent and intensity [e.g., *Sims et al.*, 2002; *Wang and Qu*, 2007]. Numerical climate and land surface models are valuable in analyzing and diagnosing climate variability, but are imperfect at quantifying extreme climate events, including droughts [*Chen et al.*, 2009].

---

[1] Center for Space Research, University of Texas at Austin, Austin, Texas, USA.

[2] Department of Geological Sciences, Jackson School of Geosciences, University of Texas at Austin, Austin, Texas, USA.

[3] Bureau of Economic Geology, Jackson School of Geosciences, University of Texas at Austin, Austin, Texas, USA.

0148-0227/10/2010JD014689

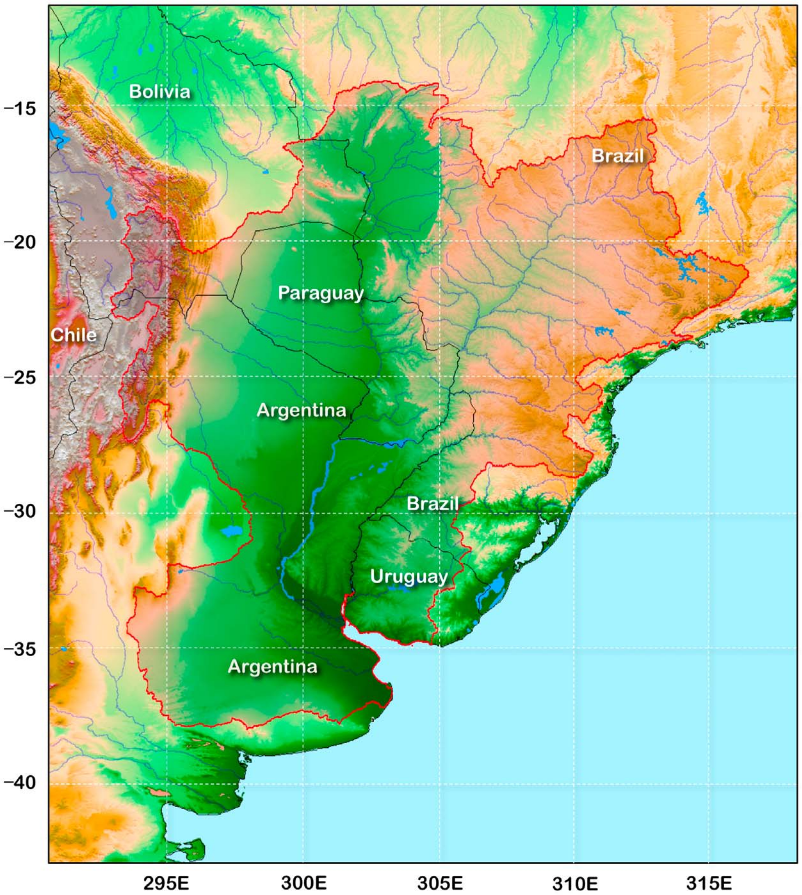


Figure 1. Map of the La Plata basin (outlined in red) in South America.

[5] TWS change is a major component of the global water cycle, and represents the total change of water stored in soil, as snow over land, and in groundwater reservoirs. In a given basin, TWS change reflects the sum of accumulated precipitation, evapotranspiration, and surface and subsurface runoff, and provides a reliable measure of abnormal climate conditions such as droughts and floods. Quantification of TWS change is difficult because of the lack of fundamental observations of groundwater, soil moisture, snow water equivalent, precipitation, evapotranspiration, and river discharge at basin or smaller scales. Numerical models often poorly estimate TWS changes, especially at interannual and longer time scales [*Matsuyama et al.*, 1995; *Chen et al.*, 2009]. Remote sensing data (e.g., TRMM satellite precipitation data) and in situ measurements (e.g., river discharge at gauge stations) are valuable in estimating TWS changes [*Crowley et al.*, 2008; *Zeng et al.*, 2008], but other hydrological parameters are also required (e.g., evapotranspiration).

[6] Satellite gravity measurements from the Gravity Recovery And Climate Experiment (GRACE) provide a means to estimate TWS by direct monitoring of water mass changes. Since March 2002, GRACE measurements of gravity change at monthly intervals [*Tapley et al.*, 2004] have been used to infer mass variation at Earth's surface [*Wahr et al.*, 1998]. GRACE time-variable gravity observations are able to monitor mass changes with a precision of ~1.5 cm of equivalent water thickness change [*Wahr et al.*, 2004, 2006]. Early studies applied GRACE data to a variety of problems including TWS change [e.g., *Wahr et al.*, 2004; *Tapley et al.*, 2004; *Strassberg et al.*, 2009; *Longuevergne et al.*, 2010], polar ice sheet mass balance [e.g., *Velicogna and Wahr*, 2006; *Chen et al.*, 2006], and oceanic mass change [e.g., *Chambers et al.*, 2004; *Lombard et al.*, 2007].

[7] With improved background geophysical models and data processing techniques [*Swenson and Wahr*, 2006; *Bettadpur*, 2007a], reprocessed GRACE release-04 (RL04) gravity fields show significantly improved quality and spatial resolution, ≤500 km [*Chen et al.*, 2008, 2009]. These improvements have enabled applications to a much wider class of problems than during the first few years of the mission, and with nearly 8 years of observations, an understanding of interannual and longer-term changes in TWS is now possible. Here we examine TWS change in the La Plata basin using GRACE RL04 data, along with TWS estimates from the Global Land Data Assimilation System (GLDAS) [*Rodell et al.*, 2004]. The goal is to quantify the extent and intensity of the recent La Plata basin drought, and to compare GRACE estimates with others from satellite remote sensing and precipitation data and GLDAS.

2. Data Processing

2.1. TWS Changes From GRACE Gravity Measurements

[8] We use GRACE RL04 time-variable gravity solutions, provided by the Center for Space Research (CSR), University

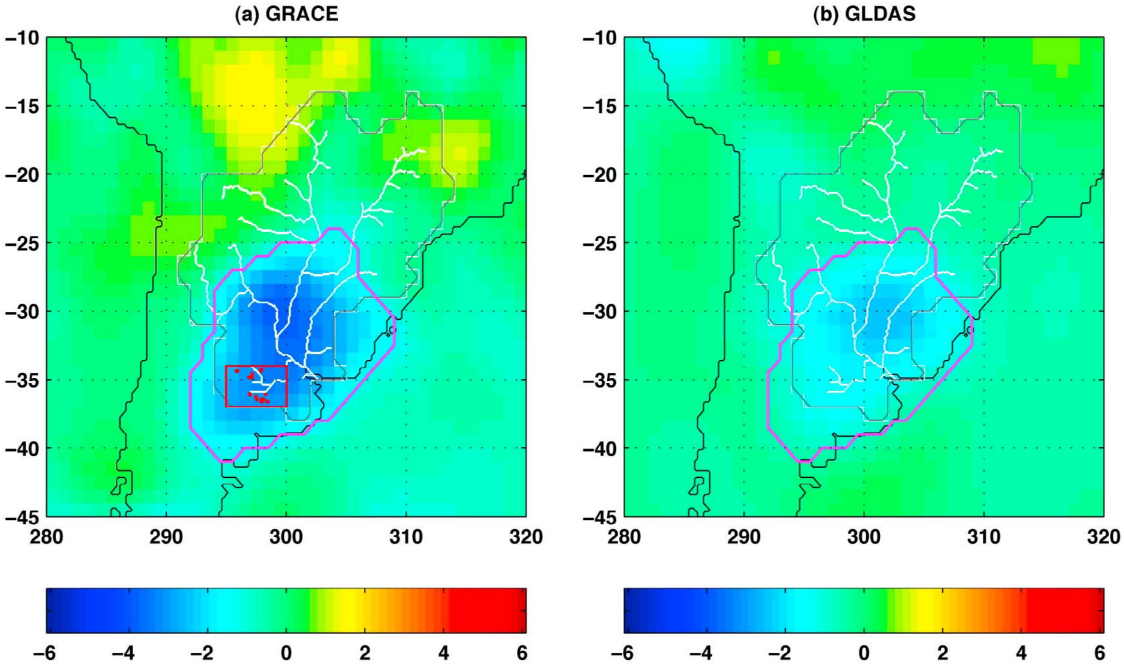


Figure 2. (a) GRACE mass rates (in cm/yr of water thickness change) in the La Plata basin and surrounding regions from April 2002 to August 2009. A two-step filtering scheme (P4M6 and 300 km Gaussian smoothing) is applied, as described in the text. The area delineated by magenta lines indicates where GRACE rates are in excess of −1 cm/yr. The red dots mark 27 well locations and the well water level data are used in later analysis. (b) GLDAS average mass rates (in cm/yr of water thickness change) in the same regions and over the same period (April 2002 to August 2009). P4M6 and 300 km Gaussian smoothing are also applied.

of Texas at Austin [*Bettadpur*, 2007b]. The 86 approximately monthly gravity solutions cover the period April 2002 through August 2009, and consist of normalized spherical harmonic (SH) coefficients, to degree and order 60. GRACE SH coefficients are contaminated by noise, including longitudinal stripes (when SH coefficients are converted into mass fields), and other errors, especially at high degrees and orders. The longitudinal stripes have been shown to be associated with unquantified correlations among certain SH coefficients, and removal of these correlations significantly reduces the stripes [*Swenson and Wahr*, 2006]. For SH orders 6 and above, a least square fit of degree 4 polynomial is removed from even and odd degree coefficient pairs [*Swenson and Wahr*, 2006]. For example, for SH coefficients of order 6 (e. g., $C_{n,6}$, n = 6, 7, …, 60), we fit a degree 4 polynomial to the even degree pair (e.g., $C_{6,6}$, $C_{8,6}$, …, $C_{60,6}$) and remove the polynomial fit from the coefficients, and apply the same to the odd degree pair (e.g., $C_{7,6}$, $C_{9,6}$, …, $C_{59,6}$). We call this decorrelation filter P4M6. After P4M6 filtering, a 300 km Gaussian low-pass filter is applied to further suppress the remaining short-wavelength errors [*Jekeli*, 1981] and the mean of all 86 monthly solutions is removed from SH coefficient. Monthly mass change fields, expressed as equivalent water layer thickness change on a 1° × 1° grid, are then computed [*Wahr et al.*, 1998].

[9] Atmospheric and oceanic mass changes have been removed in GRACE data using estimates from numerical models during solving GRACE gravity solutions, in a procedure to reduce alias errors in GRACE monthly solutions, due to high-frequency atmospheric and oceanic signals [*Bettadpur*, 2007b]. Therefore, GRACE mass variations over land should reflect primarily TWS change (including snow/ice) and solid Earth geophysical signals such as postglacial rebound (PGR). Over the La Plata basin, surface mass variations should be dominantly due to near-surface water storage changes. Errors in GRACE estimates over the La Plata basin are expected to arise from spatial leakage associated with a finite range of SH coefficients, signal attenuation due to spatial filtering, residual atmospheric signals, and GRACE measurement errors. Spatial leakage has been a major source of error in GRACE TWS estimates, because SH coefficients are limited to degrees and orders below 60. Additional filtering is required to attenuate noise in high degree and order coefficients, leading to attenuation of some signal. As a result, TWS variance leaks into surrounding regions (e.g., oceans) (see Figure 2). In this study, a 300 km Gaussian low-pass filter is applied. This relatively modest filter causes about 5–10% leakage to adjacent regions when estimating large basin-scale TWS averages at seasonal time scales [*Chen et al.*, 2007].

2.2. TWS Changes From GLDAS Model Estimates

[10] GLDAS ingests satellite- and ground-based observations, using advanced land surface modeling and data assimilation techniques, to generate estimates of land surface states and fluxes [*Rodell et al.*, 2004]. Precipitation gauge observations, satellite and radar precipitation measurements, and downward radiation flux and analyses from atmospheric

data assimilation systems are used as forcing. The GLDAS estimates used in this study are from the Noah land surface model [*Ek et al.*, 2003], with inputs of precipitation from a spatially and temporally downscaled version of the NOAA Climate Prediction Center's Merged Analysis of Precipitation, and solar radiation data from the Air Force Weather Agency's AGRMET system. Monthly average soil moisture (2 m column depth) and snow water equivalent were computed from 1979 to present, with TWS at each grid point computed from the sum of soil and snow water. Greenland and Antarctica are excluded because the model omits ice sheet physics. Groundwater is also not modeled by GLDAS.

[11] GLDAS fields need to be spatially filtered in a similar way to the GRACE data to compare the two. To accomplish this, GLDAS TWS gridded fields were represented in a SH expansion to degree and order 100, and the P4M6 and 300 km Gaussian smoothing filters were applied. SH coefficients were truncated at degree and order 60, and SH coefficients for degree 0 and degree 1 were set to zero as they are for GRACE fields. Finally, the GLDAS SH expansion was evaluated on a global 1° × 1° grid.

2.3. Groundwater Level Data

[12] A collaborative groundwater monitoring project has been set up under the coordination of GEA (Grupo de Estudios Ambientales, Universidad Nacional de San Luis and CONICET) and IyDA-Agritest in the Argentinean Pampas, the southern part of the study area. A total of 27 wells (marked by red dots on Figure 2a) monitor the shallow groundwater. For each well, monthly water levels were transformed into equivalent water layer using a uniform specific yield (effective porosity) of 0.1 [*Aradas et al.*, 2002]. For each month, water layers were then interpolated using kriging [*Wackernagel*, 1995] and spatially averaged to extract regional groundwater storage variations.

3. Results

3.1. GRACE and Climate Model Estimates

[13] At each 1° × 1° grid point there is a time series of TWS variations relative to the mean. We use unweighted least squares to estimate a linear trend, and to evaluate non seasonal changes, we fit and remove sinusoids at annual, semiannual, and 161 day periods (161 days is the recognized alias period of the S2 tide) [*Ray and Luthcke*, 2006]. Figure 2a shows mass rates (slope of the linear trend) in the La Plata basin (delineated by the gray lines) in units of cm/yr of equivalent water thickness change. GRACE shows significant TWS negative trends (up to ~3.5 cm/yr) in the lower La Plata basin during the period April 2002 to August 2009. The area delineated by magenta lines identifies the region where negative trends exceed 1 cm/yr. TWS decreases are seen primarily in eastern Argentina and Uruguay. During the same period, the northern La Plata and southern Amazon basins show slight TWS increases. GRACE observations of TWS decrease are consistent with reported drought conditions in the La Plata basin. TWS rate estimates from GLDAS are shown in Figure 2b (the same magenta contour line in Figure 2a is superimposed here for comparison). GLDAS shows similar TWS decreases in the lower La Plata basin, but the magnitudes are significantly less than GRACE values (−2.2 versus −3.5 cm/yr in peak values).

[14] To examine temporal evolution of the drought event, we show mean TWS changes over the lower La Plata basin (delineated by magenta lines in Figures 2a and 2b) estimated from GRACE and GLDAS (Figure 3, top). For a given month, the GRACE uncertainty level is estimated using RMS residuals over the Pacific Ocean within the same latitude zone of 40°S–25°S and at longitudes distant from land, 180°E–270°E. This provides an approximate measure of GRACE error. The true error is unknown, due to the lack of independent measurements of TWS change. Consistent with the TWS rate maps (Figures 2a and 2b), both GRACE measurements and GLDAS estimates show a long-term decrease with superimposed seasonal variability. The two estimates (GRACE and GLDAS) agree with each other reasonably well over much of this period. However, GRACE shows much larger TWS increases in the austral spring of 2002 and greater decreases in the falls of 2008 and especially 2009 (the seasons discussed in the present study refer to the Southern Hemisphere).

[15] Nonseasonal GRACE and GLDAS time series both indicate a steady decrease in TWS over time; however, GRACE shows a sharper decrease (Figure 3, bottom). It seems that the large discrepancies in 2002 and 2008/2009 between GRACE and GLDAS primarily drive the difference in slopes. During 2007, both GRACE and GLDAS estimates show significant TWS increases, indicating a reasonably wet season in the lower La Plata basin. GRACE data indicate that by fall 2009, average TWS deficit in lower La Plata (with respect to the 7 year mean) is about −12 cm, equivalent to ~248 Gigatonne (Gt) of water: almost enough water to supply the entire United States for one half year [*Kenny et al.*, 2009]. The ~ 248 Gt only represents the apparent TWS deficit in the region and the actual amount could be considerably larger, as we have neglected leakage effects due to filtering and truncation of spherical harmonic coefficients here. However, these effects are likely not very significant for large regional average as discussed previously (see section 2.1) [*Chen et al.*, 2007].

[16] The present study reveals a different picture of 'long-term' TWS change in the La Plata basin than that of a previous study [*Klees et al.*, 2008], which does not show a TWS decrease during the period (January 2003 to February 2006). The discrepancy is mainly attributed to two factors: (1) the present study uses a much longer record (~7 years) of GRACE data, relative to ~3 years from *Klees et al.* [2008], and (2) the present study focuses on the lower (or southern) La Plata (outlined in magenta in Figures 2a and 2b), while *Klees et al.* [2008] target the entire La Plata basin. The recent drought mainly affects the southern part of the La Plata basin (see Figure 2a).

[17] We compute yearly average GRACE nonseasonal TWS changes for 2003 through 2009 (see Figures 4a–4g). Each map is the mean over 12 months from July of the previous year to June of current year (solutions for July 2002 and June 2003 are not available, so the 2003 mean is based on 10 solutions). Ocean areas are masked out for clarity. This effectively illustrates the recent drought condition in the La Plata basin, which appears to become worse in spring 2008, and reach the maximum in fall 2009 (Figure 3, bottom). The TWS decrease during spring 2008 and fall 2009 is clearly shown by GRACE (Figure 4f, the 12 month average over July 2008 to June 2009). In 2007 (average of July 2006 to June

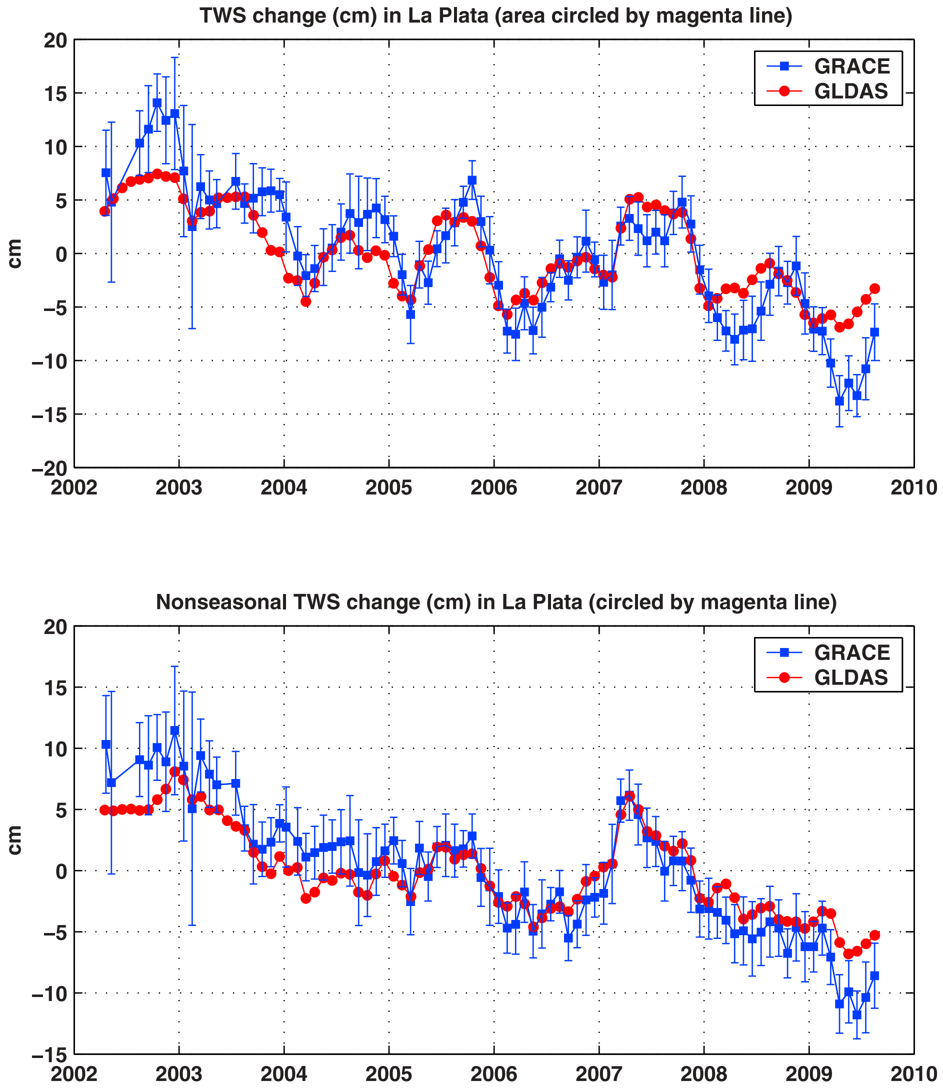


Figure 3. (top) Comparison of TWS change in the lower La Plata basin (average within the area delineated by magenta lines in Figures 1 and 2) from GRACE (blue curve) and GLDAS (red curve). (bottom) Comparison of nonseasonal TWS changes in the lower La Plata basin from GRACE (blue curve) and GLDAS (red curve). Annual and semiannual signals have been removed using an unweighted least squares fit. The GRACE uncertainty level is estimated using RMS residuals over the Pacific Ocean in the same latitude zone within the area of 40°S–25°S and 180°E–270°E.

2007), northern La Plata and southern Amazon (and Tocantins Sao Francisco basins) show significant TWS increases, while lower La Plata TWS remained about average.

[18] To further illustrate the temporal and spatial development of this severe drought, we show monthly TWS anomalies for a 12 month period from September 2008 to August 2009 (Figures 5a–5l). Annual and semiannual variations have been removed from each grid point (pixel) using an unweighted least squares fit to these frequencies (ocean areas are masked out for clarity). The recent drought apparently began in the lower (southern) La Plata in spring 2008 (see Figures 5a–5d), and peaked in fall 2009 (see Figures 5h–5j). During the peak months (April–June 2009), the drought spread over the entire La Plata basin. By August 2009, the upper (northern) La Plata basin returned to normal and even slightly wetter condition, while the lower La Plata remained in a drought condition with reduced magnitude. More recent GRACE data (not shown here) suggest that the drought has ended and conditions are actually wetter than normal by late 2009.

3.2. Comparisons With Other Observations

[19] From the Global Precipitation Climatology Project (GPCP) daily precipitation estimates (V1.1) [*Adler et al.*, 2003], we also compute yearly precipitation anomaly maps (using GPCP data) in the La Plata river basin and surrounding regions over the same period (July 2002 through June 2009). Following a similar definition as used in GRACE yearly TWS maps (Figures 4a–4g), yearly precipitation totals are the sum from July of the previous year through June of current year. The yearly precipitation anomalies are the yearly totals with respect to the mean of the 7 yearly totals (2003 through 2009);

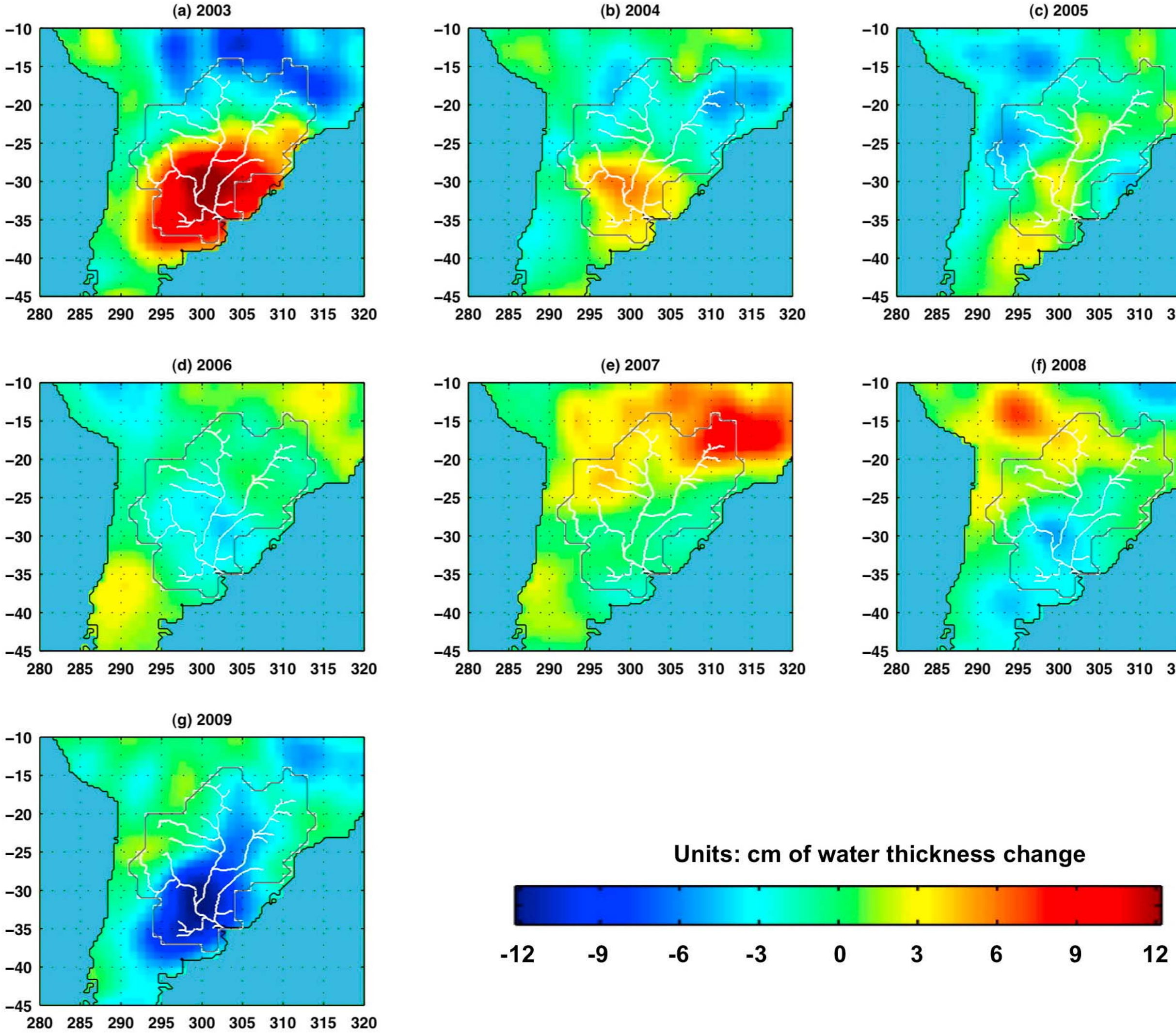


Figure 4. Evolution of yearly TWS deficits (cm of water thickness change) from GRACE in the La Plata river basin and surrounding regions over the 7 years (August 2002 to June 2009). Yearly averages are mean TWS changes from July of the previous year through June (solutions for July 2002 and June 2003 are not available). For example, the 2004 TWS deficit is the mean from July 2003 through June 2004. The mean over the 7 year period is removed from all seven maps. Ocean areas are masked out for clarity.

that is, the average yearly total precipitation over the 7 years is removed from each of the yearly maps (Figures 6a–6g). Consistent with GRACE observations, during the 2009 season (i.e., July 2008 through June 2009), the La Plata basin, especially the south part, received significantly less amount (up to over 30 cm) of precipitation than the average years, and during the 2003 season (i.e., July 2002 through June 2003), the lower La Plata basin received up to over 50 cm more precipitation than usual. Both GRACE and precipitation data show that 2007 is a wet season. It’s interesting to see that GRACE sees a relatively wet season in lower La Plata in 2004 (Figure 4b), while precipitation data (Figure 6b) appear to show an average or even dry season. This suggests that there may be a lag between precipitation and TWS anomalies. As precipitation is only one of the three major parameters (along with evapotranspiration and runoff) that contribute to TWS change (when groundwater pumping due to human activities is neglected), it is difficult to directly or quantitatively compare GRACE TWS and precipitation anomalies (Figure 4 versus Figure 6).

[20] We also compute accumulated yearly (July through June, to match periods represented Figure 4) precipitation totals in the lower La Plata basin (the area delineated by magenta lines on Figures 2a and 2b) for the period 1998 through 2009. Figure 7a shows the result, with GPCP precipitation totals for the GRACE period (after 2002) in gray. Precipitation has decreased since 2003 and average precipitation from 2003 through 2009 is 1072 mm, considerably less than the 1998 through 2002 average of 1265 mm. GRACE observations began during the relatively wet 2003 season, while 2009 recorded the least amount of precipitation during the 12 years, up to 500 mm less than the peak in 2003. These

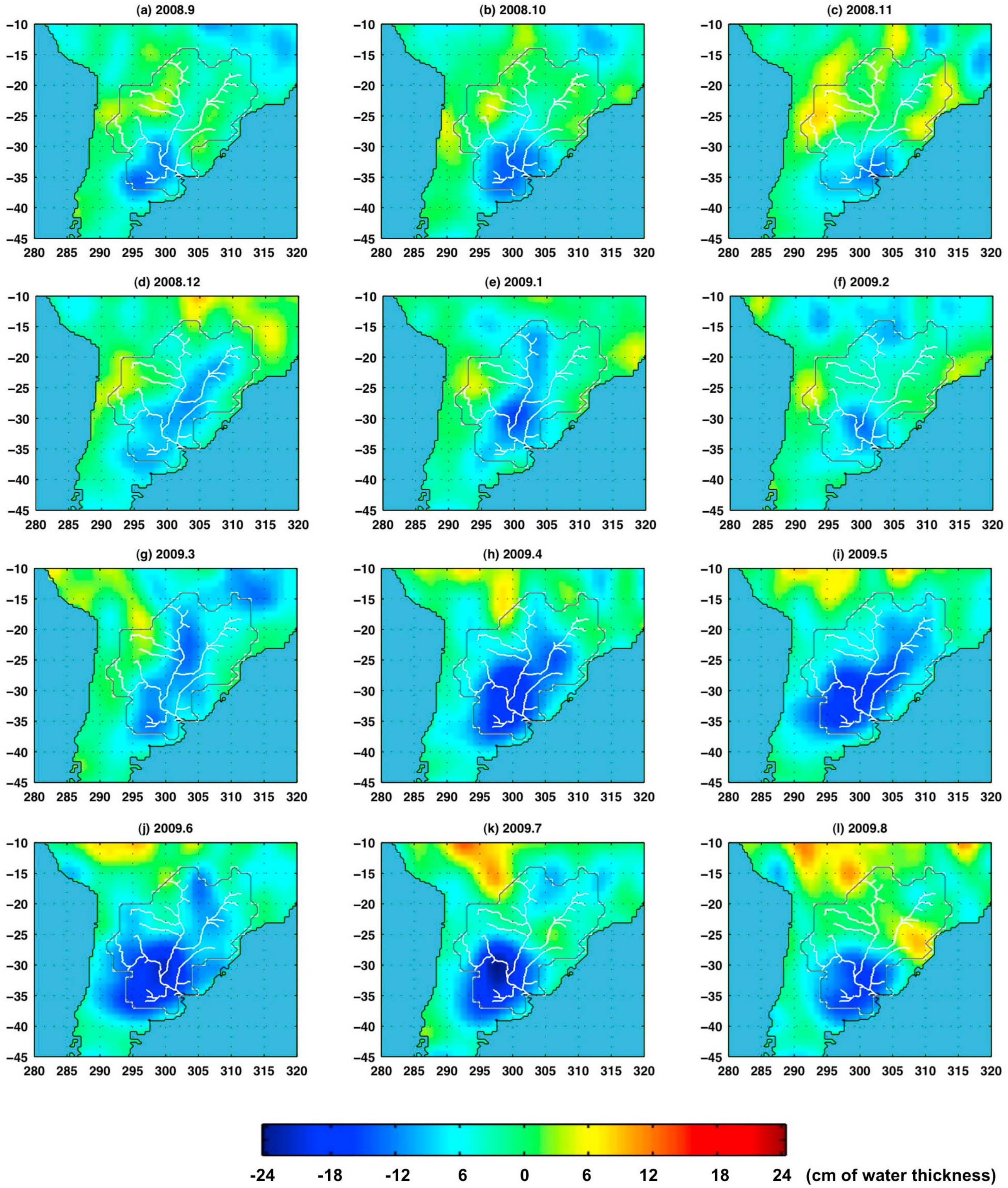


Figure 5. Monthly TWS anomalies during a 12 month period from September 2008 to August 2009. Annual and semiannual variations have been removed from each grid point (pixel) using unweighted least squares fit. Ocean areas are masked out for clarity.

features are qualitatively consistent with GRACE observations (Figure 3, bottom). There is clear correlation with the La Plata drought indicated in Figure 4. After 2003, the lower La Plata basin experienced mostly dry years, although 2007 is relatively wet. The drought condition strengthened through-fall 2009, consistent with GRACE observations (Figure 3 (bottom) and Figure 4f). The variation and decrease of yearly precipitation in the lower La Plata basin are supported

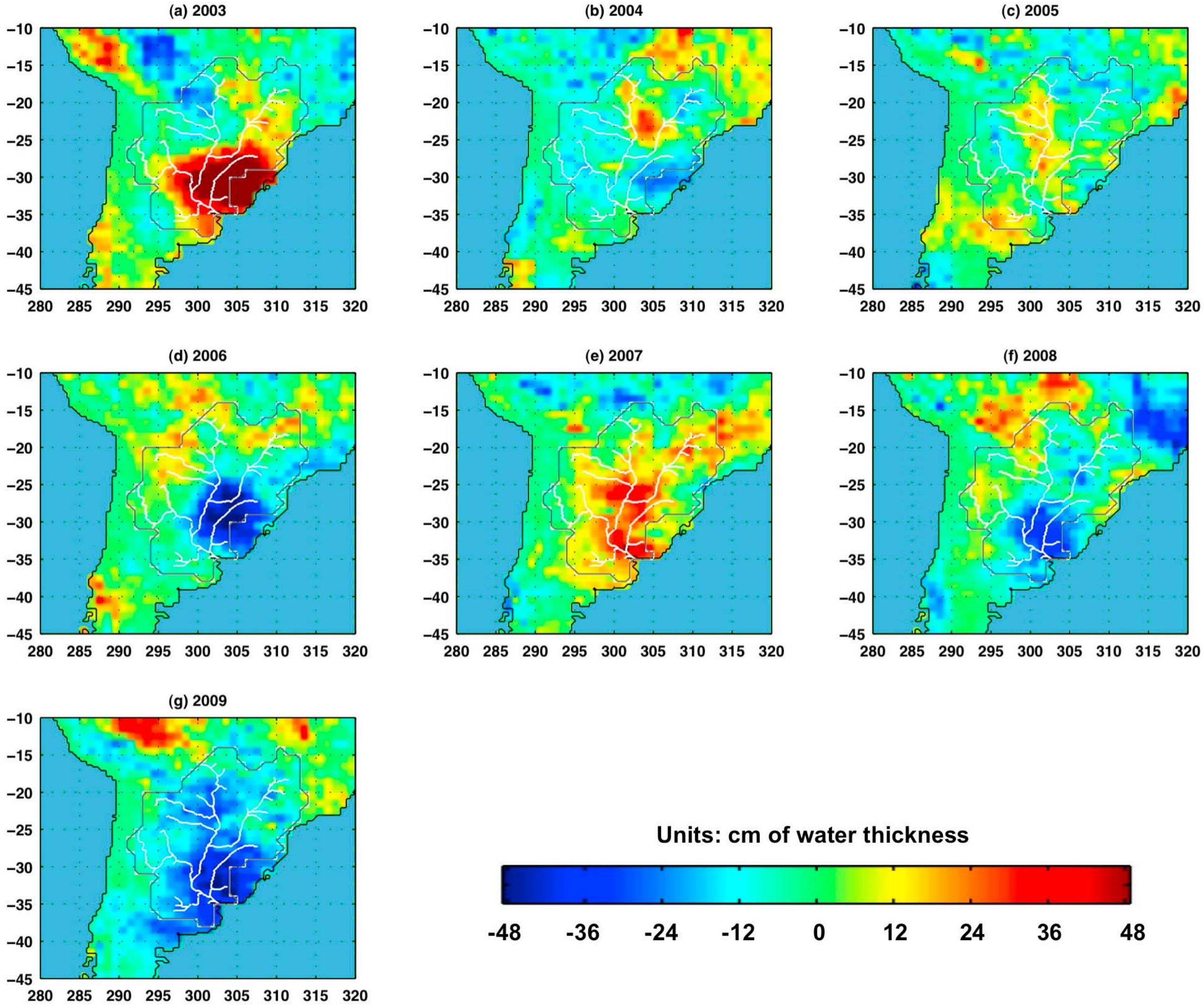


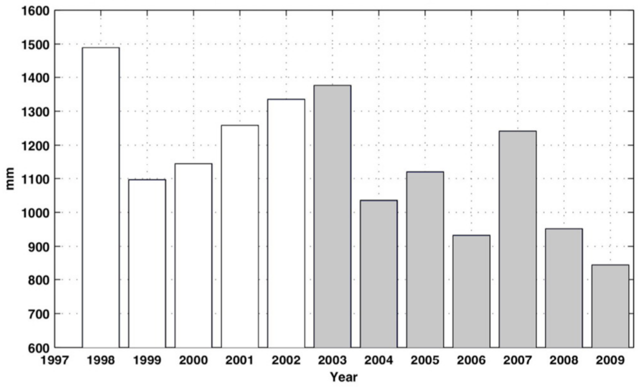
Figure 6. Evolution of yearly precipitation anomalies (centimeters of water thickness) from GPCP in the La Plata river basin and surrounding regions over the 7 years (July 2002 to June 2009). Yearly precipitation totals are the sum of July of the previous year through June. The yearly precipitation anomalies are the yearly totals with respect to the mean yearly total over the 7 year period (i.e., the mean yearly total precipitation over the 7 years is removed from each of the seven maps).

by similar estimates (see Figure 7b) of yearly precipitation totals from the Tropical Rainfall Measuring Mission (TRMM) merged monthly precipitation analysis (3B43, V6) [*Huffman et al.*, 2007]. The TRMM 3B43 precipitation estimates are only available since 1998, so the July through June yearly total for 1998 (i.e., the yearly total over July 1997 through June 1998) is not available from TRMM (Figure 7b). The significantly reduced amount of precipitation in the lower La Plata basin in recent years is clearly the cause of the severe drought condition in the region, and is expected to be associated with reduced evapotranspiration, river discharge, and groundwater recharge.

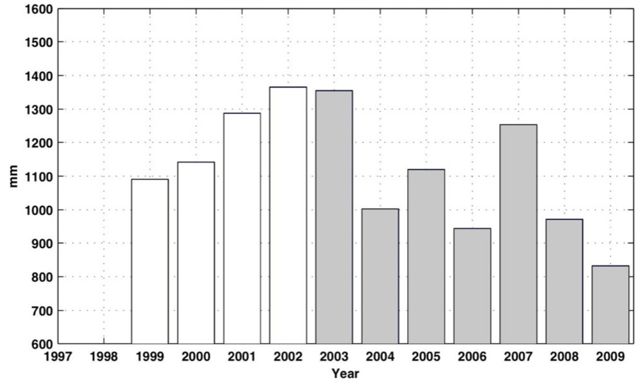
[21] Figure 7c shows the NINO3.4 index for 1997 through 2009. NINO3.4 is the average sea surface temperature (SST) anomaly in the tropical Pacific region bounded by 5°N to 5°S, from 170°W to 120°W. This area shows large variability at El Niño time scales, and changes in local SST there shift the region of rainfall typically located in the far western Pacific. An El Niño or La Niña event is identified if the 5 month running average of the NINO3.4 index exceeds +0.4°C for El Niño or −0.4°C for La Niña for at least 6 consecutive months. The NINO3.4 index time series is provided by the Royal Netherlands Meteorological Institute (http://www.knmi.nl) [*Burgers*, 1999]. Comparing Figures 7a and 7c, wet years are well correlated with major El Niño events (e.g., 1997/1998, 2002/2003, and 2007), and dry years with La Niña (e.g., 1999/2000 and 2006, 2008/2009) or weak El Niño events (e.g., 2004).

[22] Figure 8 shows satellite-based normalized difference vegetation index (NDVI) [*Sims et al.*, 2002; *Wang and Qu*, 2007] for the lower La Plata from the Moderate Resolution Imaging Spectroradiometer (MODIS) from the NASA Terra satellite. This NDVI map (NASA Earth Observatory) represents the index for 17 January to 1 February 2009 relative

(a) Accumulated yearly total precipitation (GPCP)



(b) Accumulated yearly total precipitation (TRMM)



(c) SST Anomaly in El Nino 3 & 4

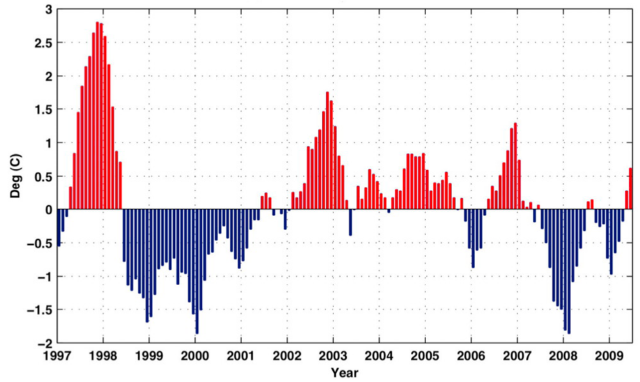


Figure 7. (a) Accumulated yearly (July–June) total precipitation in the lower La Plata basin (delineated by the magenta lines in Figures 2a and 2b) for 1998–2009 from GPCP (V1.1). Gray bars are the period spanned by GRACE. (b) Accumulated yearly (July–June) total precipitation in the lower La Plata basin (delineated by the magenta lines in Figures 2a and 2b) for 1999–2009 from TRMM 3B43 (V6). Gray bars are the period spanned by GRACE. (c) The NINO3.4 index 1997–2009. NINO3.4 is the average sea surface temperature (SST) anomaly in the region bounded by 5°N to 5°S, from 170°W to 120°W. This region has large variability on El Niño time scales and is associated with the area of rainfall that is typically located in the far western Pacific. The NINO3.4 time series is provided by the Royal Netherlands Meteorological Institute (http://www.knmi.nl).

to the average index during the same period from 2000 through 2008. The brown color indicates below average vegetation, corresponding to a dry season; white shows normal conditions; and green indicates above average, a wet season. Dry conditions are evident in the lower La Plata basin in early 2009. Although NDVI is not a quantitative measure of TWS change, it is useful for monitoring surface drought conditions and is consistent with GRACE estimates.

[23] Currently groundwater level data are not available for the entire area (lower and southern La Plata) examined in this study. Limited groundwater level data are available in a small area in the southern La Plata basin (see Figure 2a). In this area, the topography is extremely flat and surface water and shallow groundwater are strongly interconnected [*Aragon et al.*, 2010]. Groundwater storage changes were compared with GRACE and GLDAS TWS estimates in the area delineated by the red box in Figure 2a. The discrepancy between GRACE and GLDAS estimates (in this area, Figures 9a and 9b) appears much greater than that for the broad drought area (shown in Figures 2 and 3). Groundwater storage data from the wells show a significant decreasing trend, consistent with GRACE observations. When groundwater storage data from the wells is added to GLDAS estimates (which does not include a groundwater component or surface water routing), GRACE TWS estimates and the combined GLDAS and well time series show significantly better agreement, at both seasonal and long-term time scales (Figure 9b). The decreasing trend in groundwater storage may not necessarily be resulted from the drought condition in the region, and more likely reflects the combined effect from increased groundwater pumping (due to agricultural and industrial usage) and decreased groundwater recharge due to the drought condition on the surface. However, the area of interest (i.e., southern La Plata) is not well equipped with irrigation system, compared to other agricultural regions (e.g., Central Valley, California, or the High Plains Aquifer) [*Siebert et al.*, 2005]. Groundwater pumping might have been increased during the drought to meet water needs, but it might not contribute to a significant part of the groundwater level decrease. Nevertheless, quantification of these two separate contributions is difficult and beyond the scope of this study.

4. Conclusions and Discussion

[24] GRACE data indicate a significant decrease in TWS in the lower La Plata basin in recent years and provide a quantitative measure of recent drought conditions. GRACE TWS estimates provide a detailed picture of temporal and spatial evolution of this severe drought event, and suggest that the drought conditions worsened in 2009, with average TWS deficit (with respect to the 7 year mean) reaching ~12 cm equivalent water thickness by fall 2009 (in a broad region in lower La Plata). GRACE estimates are consistent with GPCP and TRMM precipitation analysis and vegetation index measurements from satellite remote sensing.

[25] The GLDAS land surface model shows similar water storage changes in the lower La Plata, but with considerably smaller magnitude at longer time scales. The lack of a groundwater component in GLDAS appears to be partly responsible for this discrepancy, at least in the study area in the south La Plata basin where well water level data are available (Figures 9a and 9b). Available groundwater data in

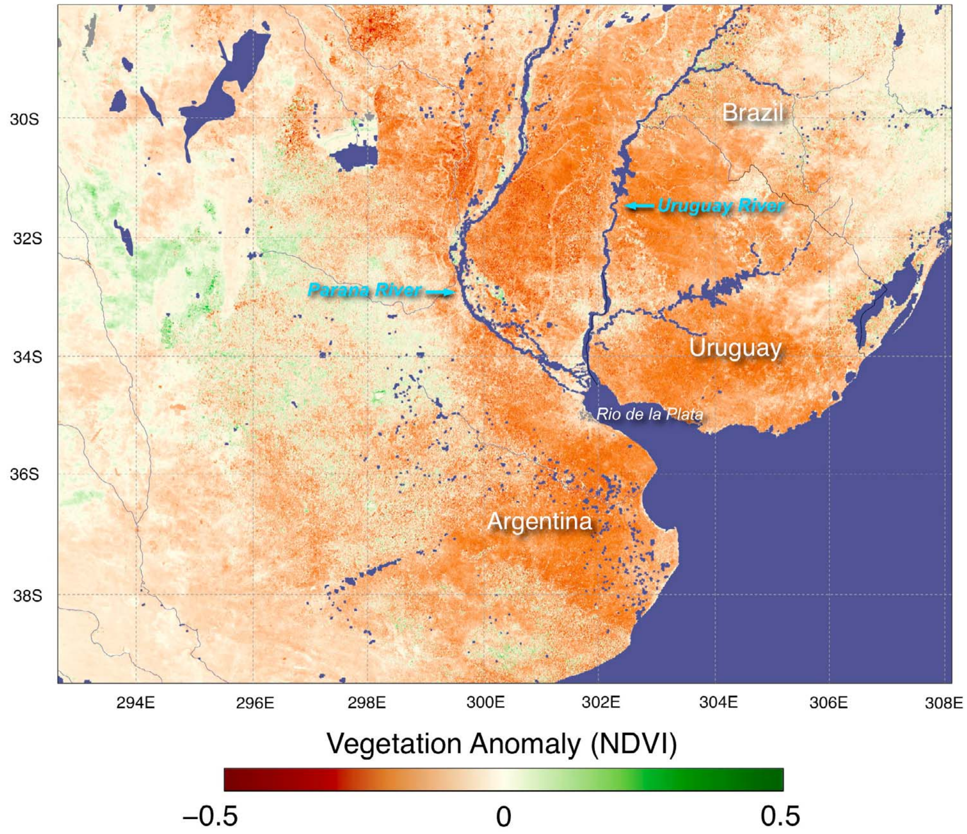


Figure 8. Normalized difference vegetation index (NDVI) for the lower La Plata basin from the Moderate Resolution Imaging Spectroradiometer (MODIS) and NASA Terra satellite observations. This shows the index for 17 January to 1 February 2009, relative to the average index of 2000–2008. Brown indicates vegetation below average levels, associated with a dry season; white shows normal conditions; and green shows a higher than average index, associated with a wet season. (NASA image from http://earthobservatory.nasa.gov/NaturalHazards/view.php?id = 37239.)

this region show significant groundwater depletion, which is likely associated with the drought. Supplementing GLDAS TWS estimates with groundwater level data significantly improves the agreement with GRACE estimates. Unfortunately, there are no adequate in situ TWS measurements to fully validate GRACE estimates. Precipitation data are helpful for qualitatively understanding TWS changes, but cannot be used quantitatively in the absence of evapotranspiration and runoff. This highlights the unique strength of satellite gravity observations in monitoring large spatial-scale TWS changes, and providing an independent measurement for calibrating, evaluating, and improving climate and land surface models [*Oleson et al.*, 2008].

[26] Drought and flood conditions in the La Plata basin appear to be closely connected to El Niño and La Niña events. These events cause abnormal changes in general circulation patterns and bring increased or decreased precipitation to affected regions [*Diaz et al.*, 1998; *de Rojas and Alicia*, 2000; *Grimm et al.*, 2000; *Seiler and Kogan*, 2002]. This relationship is reinforced by high correlation between precipitation changes in the lower La Plata basin (Figures 7a and 7b) and the NINO3.4 SST anomaly index (Figure 7c) over the period 1997 to 2009. GRACE nonseasonal TWS estimates (Figure 3, bottom) also correlate well with and the NINO3.4 SST index (Figure 7c). The 2008/2009 drought in the lower La Plata basin is likely connected to the 2008/2009 La Niña event. The much stronger 1999/2000 La Niña event also corresponds to a major drought in the La Plata basin [*Zanvettor and Ravelo*, 2000], however, its magnitude (at least in the lower La Plata basin) appears less significant than the recent drought, as suggested by precipitation data (see Figure 7a). This indicates that other factors (in addition to the 2008/2009 La Niña event) may have contributed to the recent severe drought in lower La Plata basin as well.

[27] It is difficult to directly validate GRACE estimates in the absence of adequate in situ TWS or related measurements. Residual variations over the oceans (where the expected signal is zero, if the ocean model estimates used in GRACE dealiasing processing are correct) can serve as an approximate of GRACE error [*Wahr et al.*, 2004]. GRACE-observed TWS anomalies in the lower La Plata basin greatly exceed the residuals over the ocean, providing confidence that that the signal is reliable. The GRACE mission has been extended until at least 2013, and a reprocessed GRACE data set (release 5) will soon incorporate improved background geophysical models and processing methods. These should lead to improved estimates of TWS change for monitoring climate

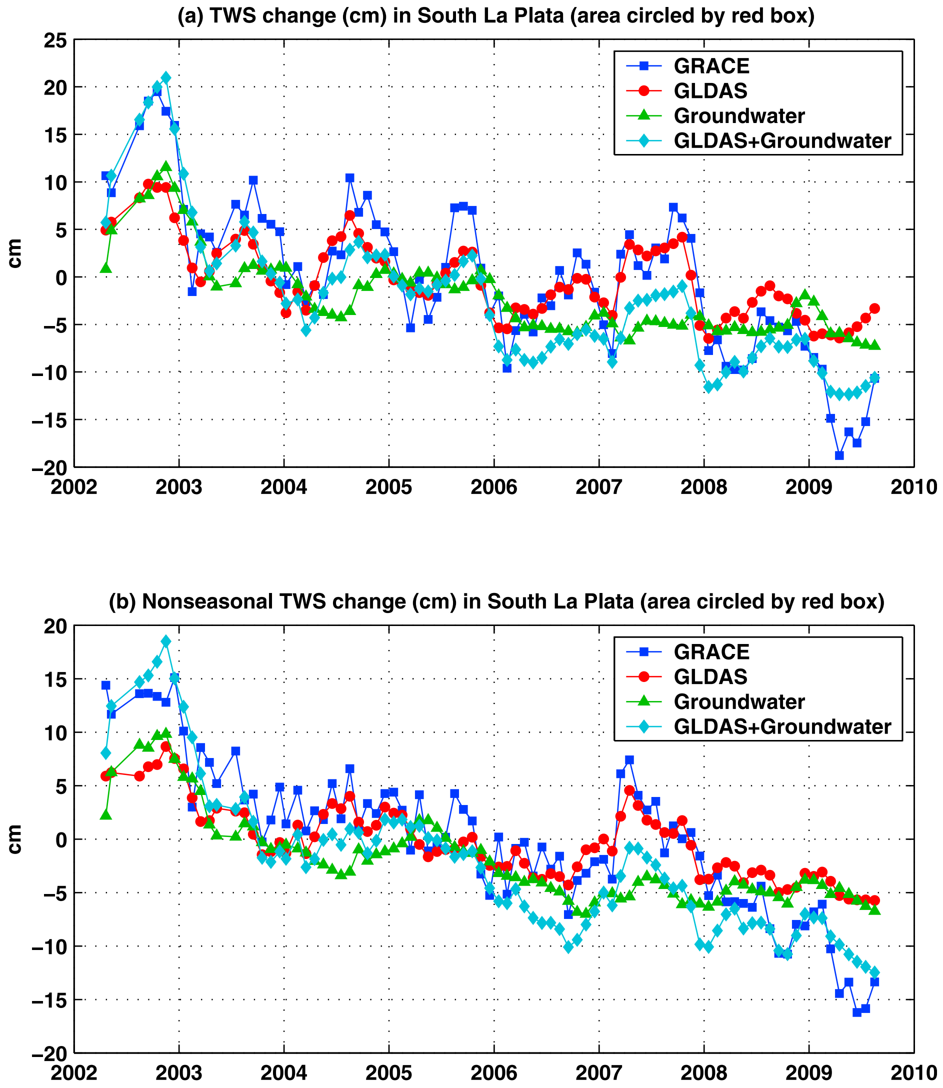


Figure 9. (a) Comparison of TWS changes from GRACE, GLDAS, and average groundwater storage change from 27 wells (marked by red dots in Figure 2a) in the south La Plata basin. GRACE and GLDAS time series are the average estimates within the area delineated by red box in Figure 2a. (b) Same as 9a but with seasonal variations removed using unweighted least squares fit. A specific yield (effective porosity) of 10% is applied when computing groundwater storage from well water level data.

impacts on water resources and providing independent constraints on climate and land surface models.

[28] **Acknowledgments.** We are grateful to the three anonymous reviewers for their insightful comments, which led to improved presentation of the results. We would like to thank the "Grupo de Estudios Ambientales, Universidad Nacional de San Luis and CONICET" and IyDA-Agritest for sharing groundwater data. This study was supported by NASA PECASE Award (NNG04G060G), NASA GRACE Program (NNX08AJ84G), and NSF IPY program (ANT-0632195).

References

Adler, R. F., et al. (2003), The version 2 Global Precipitation Climatology Project (GPCP) monthly precipitation analysis (1979–present), *J. Hydrometeorol.*, *4*, 1147–1167, doi:10.1175/1525-7541(2003)004<1147:TVGPCP>2.0.CO;2.

Aradas, R., J. Lloyd, and J. Palmer (2002), Groundwater problems in low elevations regional plains: The Buenos Aires province example, in *Groundwater and Human Development*, edited by E. Bocanegra, D. Martinez, and H. Massone, pp. 613–623, A. A. Balkema, Brookfield, Vt.

Aragon, R., E. G. Jobbag, and E. Viglizzo (2010), Surface and groundwater dynamics in the sedimentary plains of the western Pampas, *Ecohydrology*, doi:10.1002/eco, in press.

Barros, V., L. Chamorro, G. Coronel, and J. Báez (2004), The major discharge events in the Paraguay River: Magnitudes, source regions, and climate forcings, *J. Hydrometeorol.*, *5*(6), 1161–1170, doi:10.1175/JHM-378.1.

Barros, V., R. Clarke, and P. S. Dias (Eds.) (2006), Climate change in the La Plata Basin, report, Inter-Am. Inst. for Global Change Res., São José dos Campos, Brazil.

Bettadpur, S. (2007a), CSR level-2 processing standards document for product release 04, *GRACE 327–742*, Cent. for Space Res., Univ. of Texas at Austin, Austin.

Bettadpur, S. (2007b), Level-2 gravity field product user handbook, *GRACE 327–734*, Cent. for Space Res., Univ. of Texas at Austin, Austin.

Burgers, G. (1999), The El Niño stochastic oscillator, *Clim. Dyn.*, *15*, 521–531, doi:10.1007/s003820050297.

Chambers, D. P., J. Wahr, and R. S. Nerem (2004), Preliminary observations of global ocean mass variations with GRACE, *Geophys. Res. Lett.*, *31*, L13310, doi:10.1029/2004GL020461.

Chen, J. L., C. R. Wilson, and B. D. Tapley (2006), Satellite gravity measurements confirm accelerated melting of Greenland ice sheet, *Science*, *313*(5795), 1958–1960, doi:10.1126/science.1129007.

Chen, J. L., C. R. Wilson, J. S. Famiglietti, and M. Rodell (2007), Attenuation effects on seasonal basin-scale water storage change from GRACE time-variable gravity, *J. Geod.*, *81*(4), 237–245, doi:10.1007/s00190-006-0104-2.

Chen, J. L., C. R. Wilson, B. D. Tapley, D. D. Blankenship, and D. Young (2008), Antarctic regional ice loss rates from GRACE, *Earth Planet. Sci. Lett.*, *266*(1–2), 140–148, doi:10.1016/j.epsl.2007.10.057.

Chen, J. L., C. R. Wilson, B. D. Tapley, Z. L. Yang, and G. Y. Niu (2009), The 2005 drought event in the Amazon River basin as measured by GRACE and climate models, *J. Geophys. Res.*, *114*, B05404, doi:10.1029/2008JB006056.

Crowley, J. W., J. X. Mitrovica, R. C. Bailey, M. E. Tamisiea, and J. L. Davis (2008), Annual variations in water storage and precipitation in the Amazon Basin, *J. Geod.*, *82*(1), 9–13, doi:10.1007/s00190-007-0153-1.

de Rojas, C., and E. Alicia (2000), The climatic impact of La Niña-related droughts in Entre Rios (Argentina), *Drought Network News*, *12*(2), 7–8.

Diaz, A. F., C. D. Studzinski, and C. R. Mechoso (1998), Relationships between precipitation anomalies in Uruguay and southern Brazil and sea surface temperature in the Pacific and Atlantic oceans, *J. Clim.*, *11*, 251–271, doi:10.1175/1520-0442(1998)011<0251:RBPAIU>2.0.CO;2.

Ek, M. B., K. E. Mitchell, Y. Lin, E. Rogers, P. Grunmann, V. Koren, G. Gayno, and J. D. Tarpley (2003), Implementation of the upgraded Noah land-surface model in the NCEP operational mesoscale Eta model, *J. Geophys. Res.*, *108*(D22), 8851, doi:10.1029/2002JD003296.

Food and Agriculture Organization (2000), Crop production statistics, report, Rome.

Grimm, A. M., V. R. Barros, and M. E. Doly (2000), Climate variability in southern South America associated with El Niño and La Niña events, *J. Clim.*, *13*, 35–58, doi:10.1175/1520-0442(2000)013<0035:CVISSA>2.0.CO;2.

Huffman, G. J., R. F. Adler, D. T. Bolvin, G. Gu, E. J. Nelkin, K. P. Bowman, Y. Hong, E. F. Stocker, and D. B. Wolff (2007), The TRMM Multisatellite Precipitation Analysis: Quasi-global, multi-year, combined-sensor precipitation estimates at fine scale, *J. Hydrometeorol.*, *8*(1), 38–55, doi:10.1175/JHM560.1.

Jekeli, C. (1981), Alternative methods to smooth the Earth's gravity field, Ph. D Thesis, Dep. of Geod. Sci. and Surv., Ohio State Univ., Columbus.

Kenny, J. F., N. L. Barber, S. S. Hutson, K. S. Linsey, J. K. Lovelace, and M. A. Maupin (2009), Estimated use of water in the United States in 2005, *U.S. Geol. Surv. Circ.*, *1344*, 52 pp. (Available at http://pubs.usgs.gov/circ/1344/)

Klees, R., X. Liu, T. Wittwer, B. C. Gunter, E. A. Revtova, R. Tenzer, P. Ditmar, H. C. Winsemius, and H. H. G. Savenije (2008), A comparison of global and regional GRACE models for land hydrology, *Surv. Geophys.*, *29*, 335–359, doi:10.1007/s10712-008-9049-8.

Lombard, A., D. Garcia, G. Ramillien, A. Cazenave, R. Biancale, J. M. Lemoine, F. Flechtner, R. Schmidt, and M. Ishii (2007), Estimation of steric sea level variations from combined GRACE and Jason-1 data, *Earth Planet. Sci. Lett.*, *254*(1–2), 194–202, doi:10.1016/j.epsl.2006.11.035.

Longuevergne, L., B. R. Scanlon, and C. R. Wilson (2010), GRACE hydrological estimates for small basins: Evaluating processing approaches on the High Plains Aquifer, USA, *Water Resour. Res.*, doi:10.1029/2009WR008564, in press.

Matsuyama, H., T. Oki, and K. Masuda (1995), Applicability of ECMWF's 4DDA data to interannual variability of the water budget of the Mississippi River basin, *J. Meteorol. Soc. Jpn.*, *73*, 1167–1174.

Minetti, J. L., W. M. Vargas, A. G. Poblete, L. R. Acuña, and G. Casagrande (2004), Non-linear trends and low frequency oscillations in annual precipitation over Argentina and Chile, 1931–1999, *Atmosfera*, *16*, 119–135.

Oleson, K. W., et al. (2008), Improvements to the Community Land Model and their impact on the hydrological cycle, *J. Geophys. Res.*, *113*, G01021, doi:10.1029/2007JG000563.

Ray, R. D., and S. B. Luthcke (2006), Tide model errors and GRACE gravimetry: Towards a more realistic assessment, *Geophys. J. Int.*, *167*(3), 1055–1059, doi:10.1111/j.1365-246X.2006.03229.x.

Rodell, M., et al. (2004), The Global Land Data Assimilation System, *Bull. Am. Meteorol. Soc.*, *85*(3), 381–394, doi:10.1175/BAMS-85-3-381.

Seiler, R. A., and F. Kogan (2002), Monitoring ENSO cycles and their impacts on crops in Argentina from NOAA-AVHRR satellite data, *Adv. Space Res.*, *30*(11), 2489–2493, doi:10.1016/S0273-1177(02)80316-7.

Siebert, S., P. Döll, J. Hoogeveen, J.-M. Faures, K. Frenken, and S. Feick (2005), Development and validation of the global map of irrigation areas, *Hydrol. Earth Syst. Sci.*, *9*, 535–547, doi:10.5194/hess-9-535-2005.

Sims, A. P., D. D. S. Niyogi, and S. Raman (2002), Adopting drought indices for estimating soil moisture: A North Carolina case study, *Geophys. Res. Lett.*, *29*(8), 1183, doi:10.1029/2001GL013343.

Strassberg, G., B. R. Scanlon, and D. Chambers (2009), Evaluation of groundwater storage monitoring with the GRACE Satellite: Case study of the High Plains Aquifer, central United States, *Water Resour. Res.*, *45*, W05410, doi:10.1029/2008WR006892.

Swenson, S., and J. Wahr (2006), Post-processing removal of correlated errors in GRACE data, *Geophys. Res. Lett.*, *33*, L08402, doi:10.1029/2005GL025285.

Tapley, B. D., S. Bettadpur, M. M. Watkins, and C. Reigber (2004), The Gravity Recovery and Climate Experiment: Mission overview and early results, *Geophys. Res. Lett.*, *31*, L09607, doi:10.1029/2004GL019920.

Velicogna, I., and J. Wahr (2006), Measurements of time-variable gravity show mass loss in Antarctica, *Science*, *311*(5768), 1754–1756, doi:10.1126/science.1123785.

Viglizzo, E. F., and F. C. Frank (2006), Ecological interactions, feedbacks, thresholds and collapses in the Argentine Pampas in response to climate and farming during the last century, *Quat. Int.*, *158*(1), 122–126, doi:10.1016/j.quaint.2006.05.022.

Wackernagel, H. (1995), *Multivariate Geostatistics*, 256 pp., Springer, New York.

Wahr, J., M. Molenaar, and F. Bryan (1998), Time variability of the Earth's gravity field: Hydrological and oceanic effects and their possible detection using GRACE, *J. Geophys. Res.*, *103*, 30,205–30,230, doi:10.1029/98JB02844.

Wahr, J., S. Swenson, V. Zlotnicki, and I. Velicogna (2004), Time-variable gravity from GRACE: First results, *Geophys. Res. Lett.*, *31*, L11501, doi:10.1029/2004GL019779.

Wahr, J., S. Swenson, and I. Velicogna (2006), Accuracy of GRACE mass estimates, *Geophys. Res. Lett.*, *33*, L06401, doi:10.1029/2005GL025305.

Wang, L., and J. J. Qu (2007), NMDI: A normalized multi-band drought index for monitoring soil and vegetation moisture with satellite remote sensing, *Geophys. Res. Lett.*, *34*, L20405, doi:10.1029/2007GL031021.

Zanvettor, R., and A. Ravelo (2000), Using the SPI to monitor the 1999–2000 drought in northeastern Argentina, *Drought Network News*, *12*(3), 3–4. (Available at http://digitalcommons.unl.edu/droughtnetnews/108/)

Zeng, N., J. H. Yoon, A. Mariotti, and S. Swenson (2008), Variability of basin-scale terrestrial water storage from a P-E-R water budget method: The Amazon and the Mississippi, *J. Clim.*, *21*, 248–265, doi:10.1175/2007JCLI1639.1.

J. L. Chen, B. D. Tapley, and C. R. Wilson, Center for Space Research, University of Texas at Austin, 3925 West Braker Ln., Ste. 200, Austin, TX 78759, USA. (chen@csr.utexas.edu)

L. Longuevergne and Z. L. Yang, Department of Geological Sciences, Jackson School of Geosciences, University of Texas at Austin, Austin, TX 78712, USA.

B. R. Scanlon, Bureau of Economic Geology, Jackson School of Geosciences, University of Texas at Austin, Austin, TX 78712, USA.