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Scanlon

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1 **Recent La Plata basin drought conditions observed by satellite gravimetry**

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11

12 **Abstract.** The Gravity Recovery and Climate Experiment (GRACE) provides quantitative  
13 measures of terrestrial water storage (TWS) change. GRACE data show a significant decrease in  
14 TWS in the lower (southern) La Plata river basin of South America over the period 2002 – 2009,  
15 consistent with recognized drought conditions in the region. *GRACE data reveal a detailed*  
16 *picture of temporal and spatial evolution of this severe drought event, which suggests that the*  
17 *drought began in lower La Plata in around austral Spring 2008 and then spread to the entire La*  
18 *Plata basin and peaked in austral Fall 2009. During the peak, GRACE data show an average*  
19 *TWS deficit of ~ 12 cm (equivalent water layer thickness) below the 7-year mean, in a broad*  
20 *region in lower La Plata. GRACE measurements are consistent with accumulated precipitation*  
21 *data from satellite remote sensing, and with vegetation index changes derived from Terra*  
22 *satellite observations. The Global Land Data Assimilation System (GLDAS) model captures the*  
23 *drought event, but underestimates its intensity. Limited available groundwater level data in*

24 *southern La Plata show significant groundwater depletion, which is likely associated with the*  
25 *drought in this region. GRACE-observed TWS change and precipitation anomalies in the studied*  
26 *region appear to closely correlate with the ENSO climate index, with dry and wet seasons*  
27 *corresponding to La Niña and El Niño events, respectively.*

28

29 **Keywords:** GRACE, gravity, La Plata basin, drought, climate model, precipitation, vegetation.

30

### 31 **1. Introduction**

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

40 The La Plata basin shows evidence of changes that may be identified with long-term  
41 climate variation [Barros et al., 2006; Viglizzo and Frank, 2006]. Over the past several decades,  
42 the basin has been seeing frequent floods [Minetti et al., 2004; Barros et al., 2006], and more  
43 recently has experienced drought. For many areas, especially in the south, the last few years have  
44 seen the worst drought in over a century, with official declarations of calamity, a sharp decline in  
45 grain and meat output, and economic havoc [Valente, 2009]. The consequences have been  
46 especially significant for Argentina, the world's second largest exporter of corn and coarse grains,

47 and the third largest exporter of wheat [FOA, 2000]. The recent drought is likely connected to  
48 abnormal climate conditions related to the prolonged 2007/2009 La Niña event [Diaz et al., 1998; de  
49 Rojas and Alicia, 2000; Grimm et al., 2000].

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

58 TWS change is a major component of the global water cycle, and represents the total  
59 change of water stored in soil, as snow over land, and in groundwater reservoirs. In a given  
60 basin, TWS change reflects the sum of accumulated precipitation, evapotranspiration, and  
61 surface and subsurface runoff, and provides a good measure of abnormal climate conditions such  
62 as droughts and floods. Quantification of TWS change is difficult because of the lack of  
63 fundamental observations of groundwater, soil moisture, snow water equivalent, precipitation,  
64 evapotranspiration, and river discharge at basin or smaller scales. Numerical models often poorly  
65 estimate TWS changes, especially at interannual and longer time scales [Matsuyama et al., 1995;  
66 Chen et al., 2009]. Remote sensing data (e.g., TRMM satellite precipitation data) and *in situ*  
67 measurements (e.g., river discharge at gauge stations) are valuable in estimating TWS changes  
68 [Crowley et al., 2007; Zeng et al., 2008], but other hydrological parameters are also required  
69 (e.g., evapotranspiration).

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

80 With improved background geophysical models and data processing techniques  
81 [Bettadpur, 2007a, Swenson and Wahr, 2006], reprocessed GRACE release-04 (RL04) gravity  
82 fields show significantly improved quality and spatial resolution near 500 km or better [Chen et  
83 al., 2008, 2009]. These improvements have enabled applications to a much wider class of  
84 problems than during the first few years of the mission, and with nearly eight years of  
85 observations, an understanding of interannual and longer-term changes in TWS is now possible.  
86 Here we examine TWS change in the La Plata basin using GRACE RL04 data, along with TWS  
87 estimates from the global land data assimilation system (GLDAS) [Rodell et al., 2004]. The goal  
88 is to quantify the extent and intensity of the recent La Plata basin drought, and to compare  
89 GRACE estimates with others from satellite remote sensing and precipitation data and GLDAS.

## 90 **2. Data Processing**

### 91 2.1 TWS Changes from GRACE Gravity Measurements

92 We use GRACE RL04 time-variable gravity solutions, provided by the Center for Space  
93 Research (CSR), University of Texas at Austin [Bettadpur, 2007b]. The 86 approximately  
94 monthly gravity solutions cover the period April 2002 through August 2009, and consist of  
95 normalized spherical harmonic (SH) coefficients, to degree and order 60. *GRACE SH*  
96 *coefficients are contaminated by noise, including longitudinal stripes (when SH coefficients are*  
97 *converted into mass fields), and other errors, especially at high degrees and orders. The*  
98 *longitudinal stripes have been demonstrated to be associated with unquantified correlations*  
99 *among certain SH coefficients, and removal of these correlations significantly reduces the stripes*  
100 *[Swenson and Wahr, 2006]. For SH orders 6 and above, a least square fit degree 4 polynomial*  
101 *is removed from even and odd degree coefficient pairs [Swenson and Wahr, 2006]. For example,*  
102 *for SH coefficients of order 6 (e.g.,  $C_{n,6}$ ,  $n=6, 7, \dots, 60$ ), we fit a degree 4 polynomial to the even*  
103 *degree pair (e.g.,  $C_{6,6}$ ,  $C_{8,6}$ , ...,  $C_{60,6}$ ) and remove the polynomial fit from the coefficients, and*  
104 *apply the same to the odd degree pair (e.g.,  $C_{7,6}$ ,  $C_{9,6}$ , ...,  $C_{59,6}$ ). We call this decorrelation filter*  
105 *P4M6. After P4M6 filtering, a 300 km Gaussian low-pass filter is applied to further suppress the*  
106 *remaining short-wavelength errors [Jekeli, 1981] and the mean of all 86 monthly solutions is*  
107 *removed from SH coefficient. Monthly mass change fields, expressed as equivalent water layer*  
108 *thickness change on a  $1^\circ \times 1^\circ$  grid, are then computed [Wahr et al., 1998].*

109 *GRACE data have had atmospheric and oceanic mass changes removed using estimates*  
110 *from numerical models during solving GRACE gravity solutions, in a procedure to reduce alias*  
111 *errors in GRACE monthly solutions, due to high frequency atmospheric and oceanic signals*  
112 *[Bettadpur, 2007b]. Therefore, GRACE mass variations over land should reflect primarily TWS*  
113 *change (including snow/ice) and solid Earth geophysical signals such as postglacial rebound*  
114 *(PGR). Over the La Plata basin, surface mass variations should be dominantly due to near-*

115 surface water storage changes. Errors in GRACE estimates over the La Plata basin are expected  
116 to arise from spatial leakage associated with a finite range of SH coefficients, attenuation due to  
117 spatial filtering, residual atmospheric signals, and GRACE measurement errors. *Spatial leakage*  
118 *has been a major error source to GRACE estimates, because the truncation of SH coefficients up*  
119 *to degree and order 60 and especially the needed spatial filtering will attenuate the true signal,*  
120 *as a portion of the TWS variance is spread into the surrounding regions (e.g., oceans) (see Fig.*  
121 *2). Here, we use a 300 km Gaussian low-pass filter (a less strong filter - as 300 km is a relatively*  
122 *shorter spatial scale to GRACE filters) to reduce possible leakage effect, which is likely ~ 5 -*  
123 *10% of observed signal at seasonal time scales for large basin scale average [Chen et al., 2007].*

124

## 125 2.2 TWS Changes from GLDAS Model Estimates

126 GLDAS ingests satellite- and ground-based observations, using advanced land surface  
127 modeling and data assimilation techniques, to generate estimates of land surface states and fluxes  
128 [Rodell et al., 2004]. *Precipitation gauge observations, satellite and radar precipitation*  
129 *measurements, and downward radiation flux and analyses from atmospheric data assimilation*  
130 *systems are used as forcing. In the particular simulation used in this study, GLDAS drove the*  
131 *Noah land surface model [Ek et al., 2003], with inputs of precipitation from a spatially and*  
132 *temporally downscaled version of the NOAA Climate Prediction Center's Merged Analysis of*  
133 *Precipitation, and solar radiation data from the Air Force Weather Agency's AGRMET system.*  
134 Monthly average soil moisture (2 m column depth) and snow water equivalent were computed  
135 from 1979 to present, with TWS at each grid point computed from the sum of soil and snow  
136 water. Greenland and Antarctica are excluded because the model omits ice sheet physics.  
137 Groundwater is also not modeled by GLDAS.

138 GLDAS fields need to be spatially filtered in a similar way to the GRACE data for fair  
139 comparisons. To accomplish this, GLDAS TWS gridded fields were represented in a SH  
140 expansion to degree and order 100, and the P4M6 and 300 km Gaussian smoothing filters were  
141 applied. SH coefficients were truncated at degree and order 60, and SH coefficients for degree-0  
142 and degree-1 were set to zero as they are for GRACE fields. Finally, the GLDAS SH expansion  
143 was evaluated on a global  $1^\circ \times 1^\circ$  grid.

## 144 2.3 Groundwater Level Data

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

## 153 **3. Results**

### 154 3.1 GRACE and Climate Model Estimates

155 At each  $1^\circ \times 1^\circ$  grid point there is a time series of TWS variations relative to the mean.  
156 We use unweighted least squares to estimate a linear trend, and to evaluate non-seasonal  
157 changes, we fit and remove sinusoids at annual, semiannual, and 161-day periods (161 days is  
158 the recognized alias period of the S2 tide) [Ray and Luthcke, 2006]. Figure 2a shows mass rates



159 (slope of the linear trend) in the La Plata basin (circled by the gray lines) in units of cm/yr of  
160 equivalent water thickness change. GRACE shows significant TWS negative trends (up to  $\sim 3.5$   
161 cm/yr) in the lower La Plata basin during the period April 2002 to August 2009. The area circled  
162 by magenta lines identifies the region where negative trends exceed  $-1$  cm/yr. TWS decreases  
163 are seen primarily in eastern Argentina and Uruguay. During the same period, the northern La  
164 Plata and southern Amazon basins show slight TWS increases. GRACE observations of TWS  
165 decrease are consistent with reported drought conditions in the La Plata basin. TWS rate  
166 estimates from GLDAS are shown in Figure 2b (the same magenta contour line in Fig. 2a is  
167 superimposed here for comparison). GLDAS shows similar TWS decreases in the lower La Plata  
168 basin, but the magnitudes are significantly lower than GRACE values ( $-2.2$  vs.  $-3.5$  cm/yr in  
169 peak values).

170 To examine temporal evolution of the drought event, we show in Figure 3a mean TWS  
171 changes over the lower La Plata basin (circled by magenta lines in Figs. 2a and 2b) estimated  
172 from GRACE and GLDAS. *For a given month, the GRACE uncertainty level is estimated using*  
173 *RMS residuals over the Pacific Ocean in the same latitude zone within the area of  $40^{\circ}\text{S}$ - $25^{\circ}\text{S}$  and*  
174  *$180^{\circ}\text{E}$ - $270^{\circ}\text{E}$ . This is an approximation of GRACE uncertainty level, as the true error in GRACE*  
175 *estimates is unknown, due to the lack of other independent measurements of TWS change.*  
176 Consistent with the TWS rate maps (Figs. 2a and 2b), both GRACE measurements and GLDAS  
177 estimates show a long-term decrease with superimposed seasonal variability. The two estimates  
178 (GRACE and GLDAS) agree with each other reasonably well over much of this period.  
179 However, GRACE shows much larger TWS increases in the austral spring of 2002 and greater  
180 decreases in the falls of 2008 and especially 2009 (the seasons discussed in the present study are  
181 referred to the southern hemisphere).

182 Figure 3b shows non-seasonal GRACE and GLDAS time series, with both indicating a  
183 steady decrease in TWS over time. GRACE shows a greater rate of loss. *However, it appears*  
184 *that the large discrepancies in 2002 and 2008/2009 between GRACE and GLDAS primarily*  
185 *drive the slopes difference.* During 2007, both GRACE and GLDAS estimates show significant  
186 TWS increase, indicating a reasonably wet season in the lower La Plata. GRACE data indicate  
187 that by Fall 2009, average TWS deficit (with respect to the 7 year mean) is about  $-12$  cm,  
188 equivalent to  $\sim 248$  Gigatonne (Gt) of water - almost enough water to supply the entire United  
189 States for one-half year [Kenny et al., 2009]. The  $\sim 248$  Gt only represents the apparent TWS  
190 deficit in the region and the actual amount could be considerably larger, as we have neglected  
191 leakage effects from spatial filtering and truncation of spherical harmonic coefficients here,  
192 *which are likely not very significant for large regional average as discussed above (see 2.1)*  
193 *[Chen et al., 2007].*

194 *The present study appears to reveal a different picture of 'long-term' TWS change in the*  
195 *La Plata basin than that from a previous study [Klees et al., 2008], which doesn't show evident*  
196 *TWS decrease during its studied period (January 2003 – February 2006). The discrepancy is*  
197 *mainly from two factors: 1) the present study uses a much longer record ( $\sim 7$  years) of GRACE*  
198 *data than that in Klees et al. (2008) ( $\sim 3$  years); and 2) in the present study, we focus in the*  
199 *lower (or southern) La Plata (outlined in magenta in Figs. 2a and 2b), while Klees et al. (2008)*  
200 *targets the entire La Plata basin.*

201 We compute yearly average GRACE nonseasonal TWS changes for 2003 through 2009  
202 (see Figs. 4a-g). *Each map is the mean over 12 months from July of the previous year to June of*  
203 *current year (solutions for July 2002 and June 2003 are not available, so the 2003 mean is based*  
204 *on 10 solutions). Ocean areas are masked out for clarity. This effectively illustrates the recent*

205 *drought condition in the La Plata basin, which appears to become worsening in Spring 2008,*  
206 *and reach the maximum in Fall 2009 (Fig. 3b). The TWS decrease during Spring 2008 and Fall*  
207 *2009 is clearly shown by GRACE (Fig. 4f, the 12-month average over July 2008 to June 2009).*  
208 *In 2007 (i.e., average over July 2006 to June 2007), northern La Plata and southern Amazon*  
209 *(and Tocantins Sao Francisco basins) show significant TWS increases, while the lower La Plata*  
210 *TWS remained about average.*

211 *To further illustrate the temporal and spatial development of this severe drought, we*  
212 *show in Figures 5a - 5l monthly TWS anomalies for a 12-month period from September 2008 to*  
213 *August 2009. Annual and semiannual variations have been removed from each grid point (pixel)*  
214 *using unweighted least squares fit (ocean areas are masked out for clarity). The drought*  
215 *apparently began in lower (southern) La Plata in Spring 2008 (see Figs. 5a-5d), and peaked in*  
216 *Fall 2009 (see Figs. 5h-5j). During the peak months (April – June 2009), the drought spread out*  
217 *to the entire La Plata. By August 2009, the upper (northern) La Plata became mostly normal and*  
218 *even wetter, while the lower La Plata remained in drought condition with decreased magnitude.*  
219 *More recent GRACE data (not shown here) suggest that the drought is completely relieved (and*  
220 *actually wetter than normal) by late 2009.*

221

### 222 3.2 Comparisons with Other Observations

223 From the Global Precipitation Climatology Project (GPCP) daily precipitation estimates  
224 (V1.1) [Adler et al., 2003], we compute accumulated yearly (July through June, to match periods  
225 represented Figure 4) precipitation totals in the lower La Plata basin (the area circled by magenta  
226 lines on Figs. 2a and 2b) for the period 1998 to 2009. Figure 6a shows the result, with GPCP  
227 precipitation totals for the GRACE period (after 2002) in gray. Precipitation has decreased since

228 2003 and average precipitation from 2003 to 2009 is 1072 mm, considerably less than the 1998  
229 to 2002 average of 1265 mm. GRACE observations began during the relatively wet 2003 season,  
230 while 2009 recorded the least amount of precipitation during the 12 years, up to 500 mm less  
231 than the peak in 2003. These features are qualitatively consistent with GRACE observations  
232 (Fig. 3b). There is clear correlation with the La Plata drought indicated in Figure 4. After 2003,  
233 the lower La Plata basin experienced mostly dry years, although 2007 is relatively wet. The  
234 drought condition strengthened through Fall 2009, consistent with GRACE observations (Fig. 3b  
235 and Fig. 4f). *The variation and decrease of yearly precipitations in the lower La Plata basin are*  
236 *supported by similar estimates (see Fig. 6b) of yearly precipitation totals from the Tropical*  
237 *Rainfall Measuring Mission (TRMM) merged monthly precipitation analysis (3B43, V6)*  
238 *[Huffman et al., 2007]. The TRMM 3B43 precipitation estimates are only available since 1998,*  
239 *so the July-through-June yearly total for 1998 (i.e., the yearly total over July 1997 through June*  
240 *1998) is not available in the TRMM estimates (Fig. 6b). The significantly reduced amount of*  
241 *precipitation in lower La Plata in recent years is clearly the cause of the severe drought*  
242 *condition in the region, and is expected to be associated with decreased evapotranspiration,*  
243 *river discharge, and groundwater recharge.*

244 Figure 6c shows the NINO3.4 index for 1997 to 2009. NINO3.4 is the average sea  
245 surface temperature (SST) anomaly in the tropical Pacific region bounded by 5°N to 5°S, from  
246 170°W to 120°W. This area has large variability on El Niño time scales, and changes in local  
247 sea-surface temperature there shift the region of rainfall typically located in the far western  
248 Pacific. An El Niño or La Niña event is identified if the 5-month running-average of the  
249 NINO3.4 index exceeds +0.4°C for El Niño or -0.4°C for La Niña for at least 6 consecutive  
250 months. The NINO3.4 index time series is provided by the Royal Netherlands Meteorological

251 Institute (<http://www.knmi.nl>) [Burgers, 1999]. Comparing Figs. 6a and 6c, wet years are well  
252 correlated with major El Niño events (e.g., 1997/1998, 2002/2003, and 2007), and dry years with  
253 La Niña (e.g., 1999/2000 and 2006, 2008/2009) or weak El Niño events (e.g., 2004) (see Figs. 6a  
254 and 6c).

255 *We also compute yearly precipitation anomaly maps (using GPCP data) in the La Plata*  
256 *river basin and surrounding regions over the same period (July 2002 - June 2009). Following*  
257 *the similar definition used in GRACE yearly TWS maps (Figs. 4a-4g), yearly precipitation totals*  
258 *are the sum from July of the previous year to June of current year. The yearly precipitation*  
259 *anomalies are the yearly totals with respect to the mean of the 7 yearly totals (2003 to 2009),*  
260 *i.e., the average yearly total precipitation over the 7 years is removed from each of the yearly*  
261 *maps (Figs. 7a-7g). Consistent with GRACE observations, during the 2009 season (i.e., July*  
262 *2008 to June 2009), the La Plata basin, especially the south part, received significantly less*  
263 *amount (up to over 30 cm) of precipitation than the average years, and during the 2003 season*  
264 *(i.e., July 2002 to June 2003), the lower La Plata received up to over 50 cm more precipitation*  
265 *than usual. Both GRACE and precipitation data show that 2007 is a wet season. It's interesting*  
266 *to see that GRACE sees a relatively wet season in lower La Plata in 2004 (Fig. 4b), while*  
267 *precipitation data (Fig. 7b) appear to show an average or even dry season. This may suggest*  
268 *that there may be a lag between precipitation and TWS anomalies. As precipitation is only one of*  
269 *the three major parameters (along with evapotranspiration and runoff) that contribute to TWS*  
270 *change (when groundwater pumping due to human activities is neglected), it is difficult to*  
271 *directly or quantitatively compare GRACE TWS and precipitation anomalies (Fig. 4 vs. Fig.7).*

272 Figure 8 shows satellite-based normalized difference vegetation index (NDVI) [Sims et  
273 al., 2002; Wang and Qu, 2007] for the lower La Plata from the Moderate Resolution Imaging

274 Spectroradiometer (MODIS) from the NASA Terra satellite. This NDVI map (NASA Earth  
275 Observatory) represents the index for January 17–February 1, 2009, relative to the average index  
276 during the same period from 2000–2008. The brown color indicates below average vegetation,  
277 corresponding to a dry season; white shows normal conditions; and green indicates higher than  
278 average, a wet season. Dry conditions are evident in the lower La Plata basin in early 2009.  
279 Although NDVI is not a quantitative measure of TWS change, it is useful for monitoring surface  
280 drought conditions and is consistent with GRACE estimates.

281           Currently groundwater level data are not available for the entire area (lower and southern  
282 La Plata) examined in this study. Limited groundwater level data are available in a small area in  
283 the southern La Plata basin (see Fig. 2a). In this area, the topography is extremely flat and strong  
284 interconnections link surface water and the shallow groundwater [Aragon et al., 2010].  
285 Groundwater storage changes were compared with GRACE and GLDAS TWS estimates in the  
286 area circled by the red box in Fig. 2a. The discrepancy between GRACE and GLDAS estimates  
287 (in this area, Figs. 9a and 9b) appears much greater than that for the broad drought area (shown  
288 in Figs. 2 and 3). It is interesting to see that the groundwater storage data from the wells show a  
289 significant decreasing trend, consistent with GRACE observations. When groundwater storage  
290 data from the wells is added to GLDAS estimates (which does not include a groundwater  
291 component), GRACE estimates and the combined GLDAS and well time series show  
292 significantly better agreements, at both seasonal and long-term time scales (Fig. 9b). *The*  
293 *decreasing trend in groundwater storage may not necessarily be resulted from the drought*  
294 *condition in the region, and more likely reflects the combined effect from increased groundwater*  
295 *pumping (due to agricultural and industrial usage) and decreased groundwater recharge due to*

296 *the drought condition on the surface. Quantification of these two separate contributions is*  
297 *difficult and also beyond the scope of this study.*

#### 298 **4. Conclusions and Discussion**

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

306 The GLDAS land surface model shows similar TWS changes in the lower La Plata, but  
307 with considerably smaller magnitude at longer time scales. The lack of a groundwater component  
308 in GLDAS appears to be partly responsible for this discrepancy, at least in the examined area in  
309 the south La Plata basin where well water level data are available (Figs. 9a and 9b). Available  
310 groundwater data in this region show significant groundwater depletion, *which is likely*  
311 *associated with the drought. Supplementing GLDAS TWS estimates with groundwater level data*  
312 *significantly improves the agreement with GRACE estimates. Unfortunately, there are no*  
313 *adequate in situ TWS measurements to fully validate GRACE estimates. Precipitation data are*  
314 *helpful for qualitatively understanding TWS changes, but cannot be used quantitatively in the*  
315 *absence of evapotranspiration and runoff. This highlights the unique strength of satellite gravity*  
316 *observations in monitoring large spatial scale TWS changes, and providing an independent*

317 measurement for calibrating, evaluating, and improving climate and land surface models (Oleson  
318 et al., 2008).

319 *Drought and flood conditions in the La Plata basin appear closely connected to El Niño*  
320 *and La Niña events. These events cause abnormal changes in general circulation patterns and*  
321 *bring increased or decreased precipitation to affected regions [Diaz et al., 1998; de Rojas and*  
322 *Alicia, 2000; Grimm et al., 2000]. This relationship is reinforced by good correlation between*  
323 *precipitation changes in the lower La Plata (Figs. 6a and 6b) and the NINO3.4 SST anomaly*  
324 *index (Fig. 6c) over the period 1997 to 2009. GRACE nonseasonal TWS estimates (Fig. 3b) also*  
325 *correlate well with and the NINO3.4 SST index (Fig. 6c). The 2008/2009 drought in the lower La*  
326 *Plata is likely connected to the 2008/2009 La Niña event. It's interesting to notice that the much*  
327 *stronger 1999/2000 La Niña event also corresponds to a major drought in La Plata [Zanvettor*  
328 *and Ravelo, 2000], however its magnitude (at least in lower La Plata) appears not as significant*  
329 *as the recent drought, as suggested by precipitation data (see Fig. 6a). This indicates that other*  
330 *factors (in addition to 2008/2009 La Niña event) might have contributed to the recent severe*  
331 *drought in lower La Plata as well.*

332 It is difficult to directly validate GRACE estimates in the absence of adequate *in situ*  
333 TWS or related measurements. *Residual variations over the oceans (where the expected signal is*  
334 *zero, if the ocean model estimates used in GRACE dealiasing process are correct) can serve as*  
335 *an approximate of GRACE error [Wahr et al., 2004]. GRACE-observed TWS anomalies in*  
336 *lower La Plata are well over the residuals over the ocean, providing confidence that that the*  
337 *signal is reliable.* The GRACE mission has been extended until at least 2013, and a reprocessed  
338 GRACE data set (release 5) will soon incorporate improved background geophysical models and



339 processing methods. These should lead to improved estimates of TWS change for monitoring the  
340 climate and providing independent constraints on climate and land surface models.

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480 **Figure Captions:**

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

483

484 Figure 2. (a) GRACE mass rates (in cm/yr of water thickness change) in the La Plata basin and  
485 surrounding regions from April 2002 to August 2009. A 2-step filtering scheme (P4M6 and 300  
486 km Gaussian smoothing) is applied, as described in the text. The area circled by magenta lines  
487 indicates where GRACE rates are in excess of  $-1$  cm/yr. The red dots mark 27 well locations  
488 and the well water level data are used in later analysis. (b) GLDAS average mass rates (in cm/yr  
489 of water thickness change) in the same regions and over the same period (April 2002- August  
490 2009). (P4M6 and 300 km Gaussian smoothing are also applied).

491

492 Figure 3. a) Comparison of TWS change in the lower La Plata basin (average within the area  
493 circled by magenta lines in Figs. 1 and 2) from GRACE (blue curve) and GLDAS (red curve); b)  
494 Comparison of nonseasonal TWS changes in the lower La Plata basin from GRACE (blue curve)  
495 and GLDAS (red curve). Annual and semiannual signals have been removed using an  
496 unweighted least squares fit. The GRACE uncertainty level is estimated using RMS residuals  
497 over the Pacific Ocean in the same latitude zone within the area of 40°S-25°S and 180°E-270°E.

498

499 Figure 4. Evolution of yearly TWS deficits (cm of water thickness change) from GRACE in the  
500 La Plata river basin and surrounding regions over the 7 years (August 2002 - June 2009). Yearly  
501 averages are mean TWS changes from July of the previous year through June (solutions for July  
502 2002 and June 2003 are not available). For example, the 2004 TWS deficit is the mean from



503 July 2003 through June 2004. The mean over the 7 year period is removed from all seven maps.  
504 Ocean areas are masked out for clarity.

505

506 Figure 5. Monthly TWS anomalies during a 12 months period from September 2008 to August  
507 2009. Annual and semiannual variations have been removed from each grid point (pixel) using  
508 unweighted least squares fit. Ocean areas are masked out for clarity.

509

510 Figure 6. a) Accumulated yearly (July-June) total precipitation in the lower La Plata basin  
511 (circled by the magenta lines in Figs. 2a and 2b) for 1998 – 2009 from GPCP (V1.1). Gray bars  
512 are the period spanned by GRACE; b) Accumulated yearly (July-June) total precipitation in the  
513 lower La Plata basin (circled by the magenta lines in Figs. 2a and 2b) for 1999 – 2009 from  
514 TRMM 3B43 (V6). Gray bars are the period spanned by GRACE; and c) The NINO3.4 index  
515 1997-2009. NINO3.4 is the average sea surface temperature (SST) anomaly in the region  
516 bounded by 5°N to 5°S, from 170°W to 120°W. This region has large variability on El Niño time  
517 scales, and is associated with the area of rainfall that is typically located in the far western  
518 Pacific. The NINO3.4 time series is provided by the Royal Netherlands Meteorological Institute  
519 (<http://www.knmi.nl>).

520

521 Figure 7. Evolution of yearly precipitation anomalies (cm of water thickness) from GPCP in the  
522 La Plata river basin and surrounding regions over the 7 years (July 2002 - June 2009). Yearly  
523 precipitation totals are the sum of July of the previous year through June. The yearly  
524 precipitation anomalies are the yearly totals with respect to the mean yearly total over the 7 years

525 period (i.e., the mean yearly total precipitation over the 7 years is removed from each of the 7  
526 maps).

527

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529 Figure 8. Normalized difference vegetation index (NDVI) for the lower La Plata basin from the  
530 Moderate Resolution Imaging Spectroradiometer (MODIS) and NASA Terra satellite  
531 observations. This shows the index for January 17–February 1, 2009, relative to the average  
532 index of 2000- 2008. Brown indicates vegetation below average levels, associated with a dry  
533 season; white shows normal conditions; and greens shows a higher than average index,  
534 associated with a wet season. (NASA image from

535 <http://earthobservatory.nasa.gov/NaturalHazards/view.php?id=37239>).

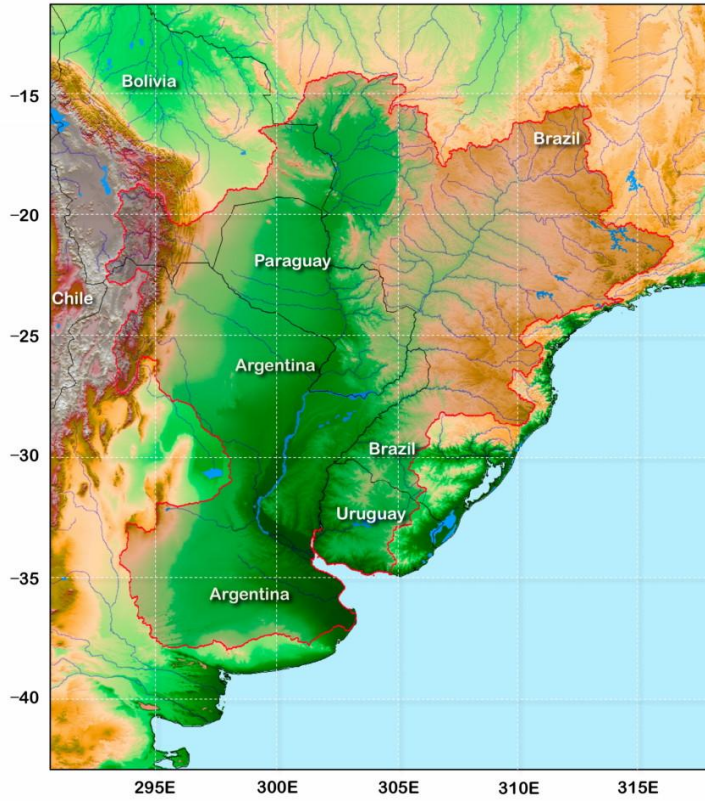
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537 Figure 9. (a) Comparison of TWS changes from GRACE, GLDAS, and average groundwater  
538 storage change from 27 wells (marked by red dots in Fig. 2a) in the south La Plata basin.  
539 GRACE and GLDAS time series are the average estimates within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

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Figure 1

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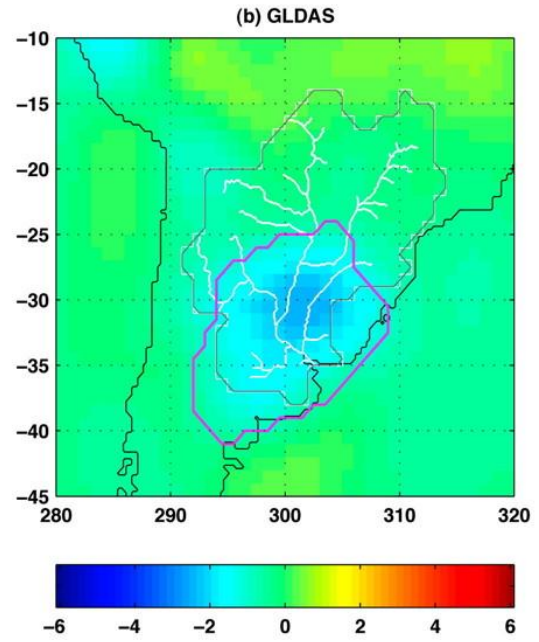
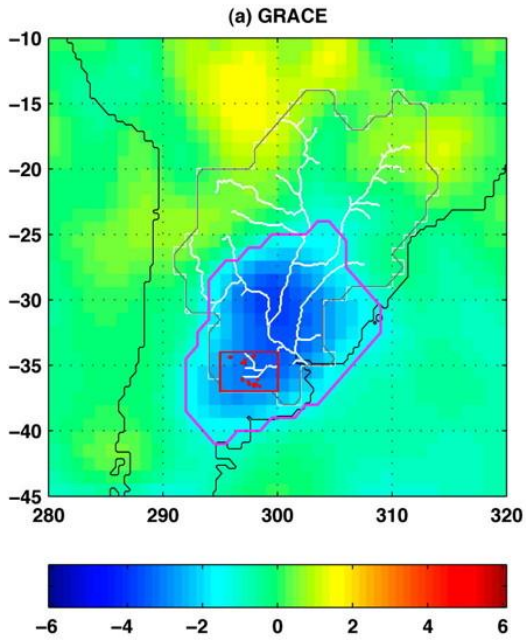
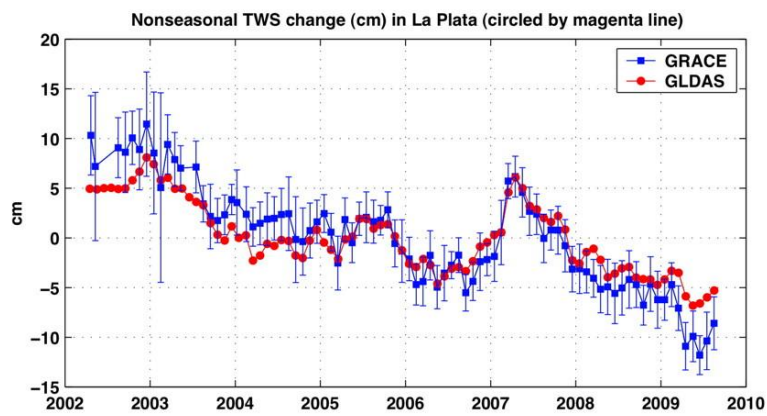
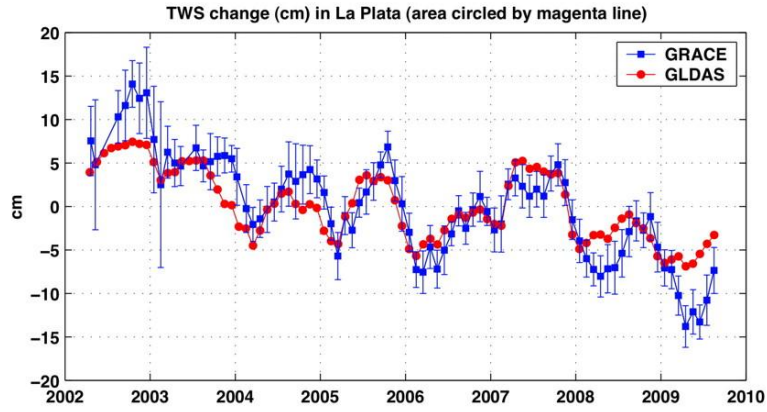
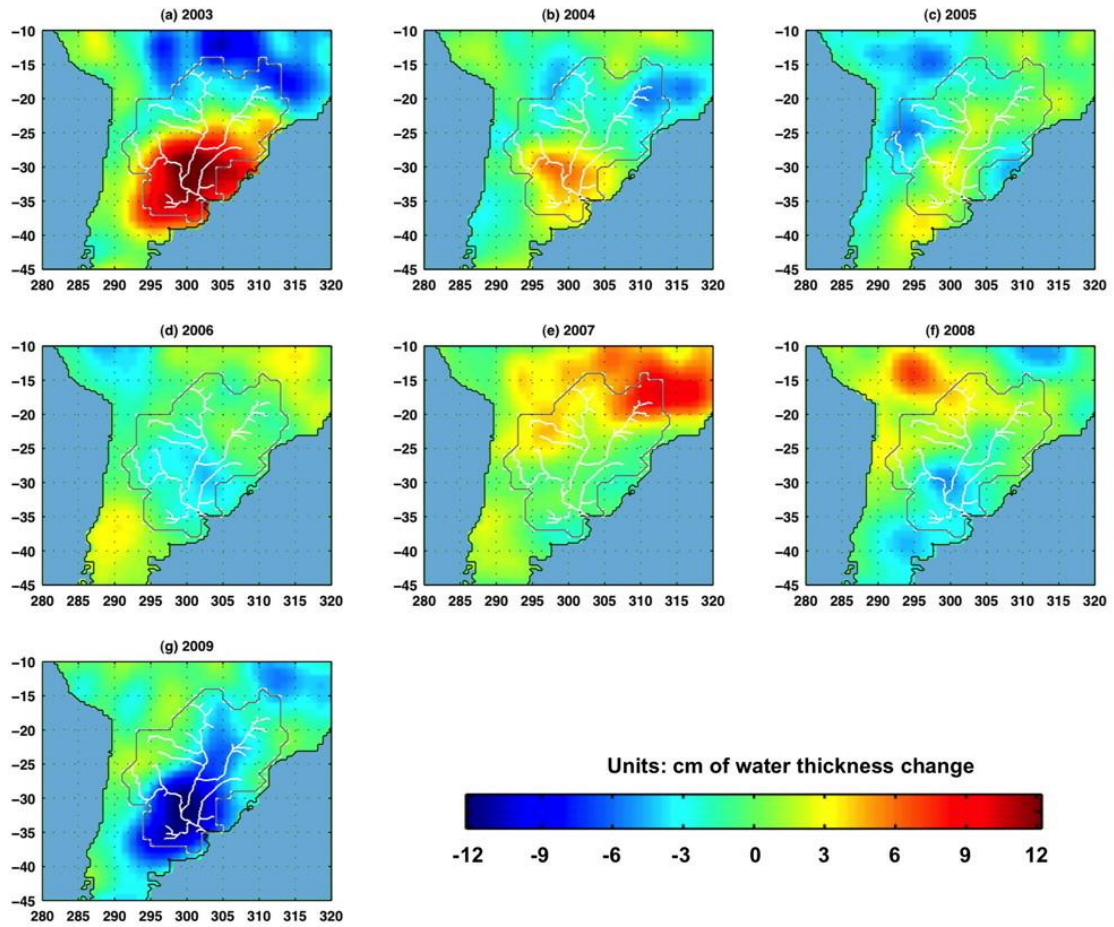


Figure 2



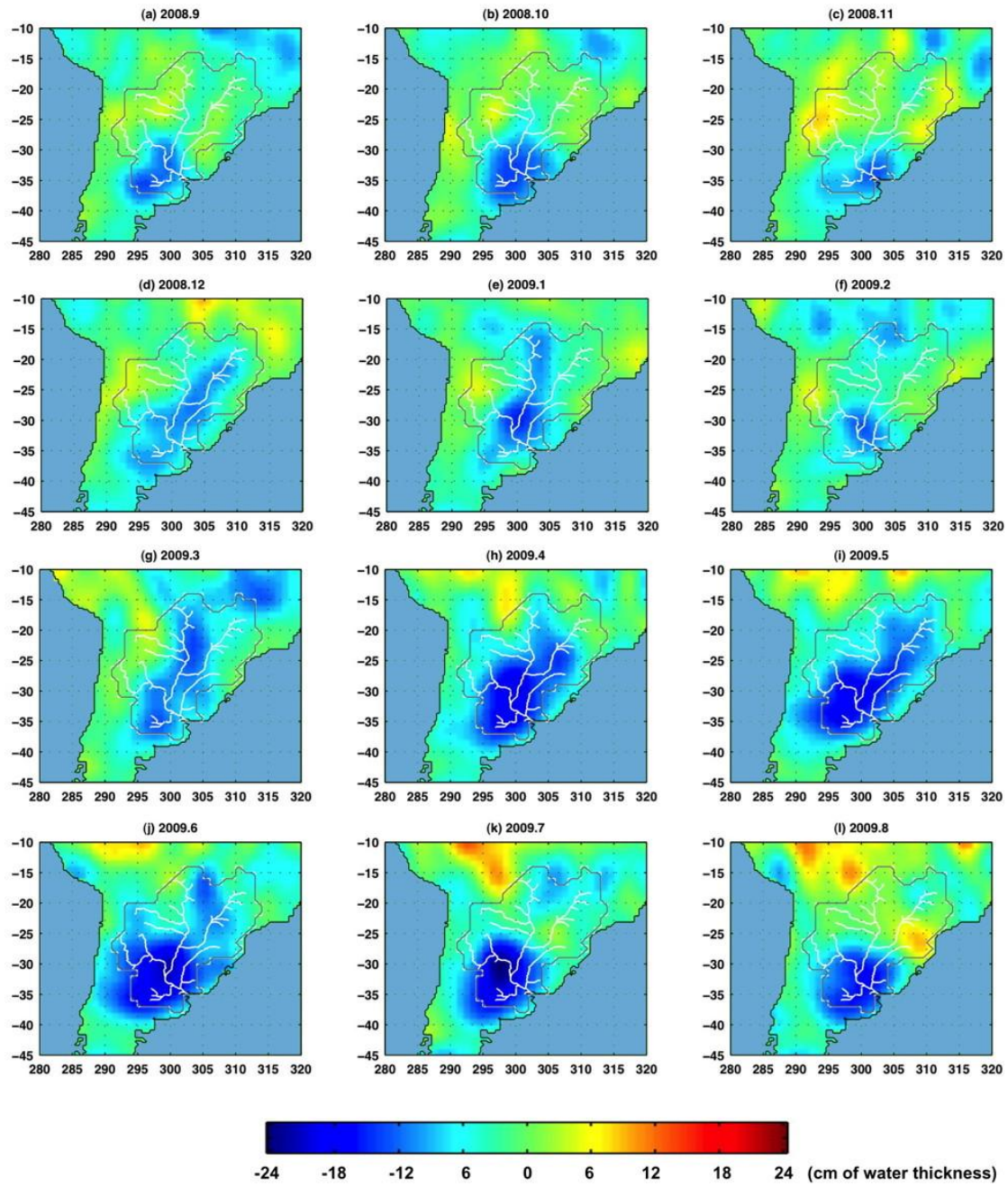
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Figure 3



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Figure 4



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Figure 5

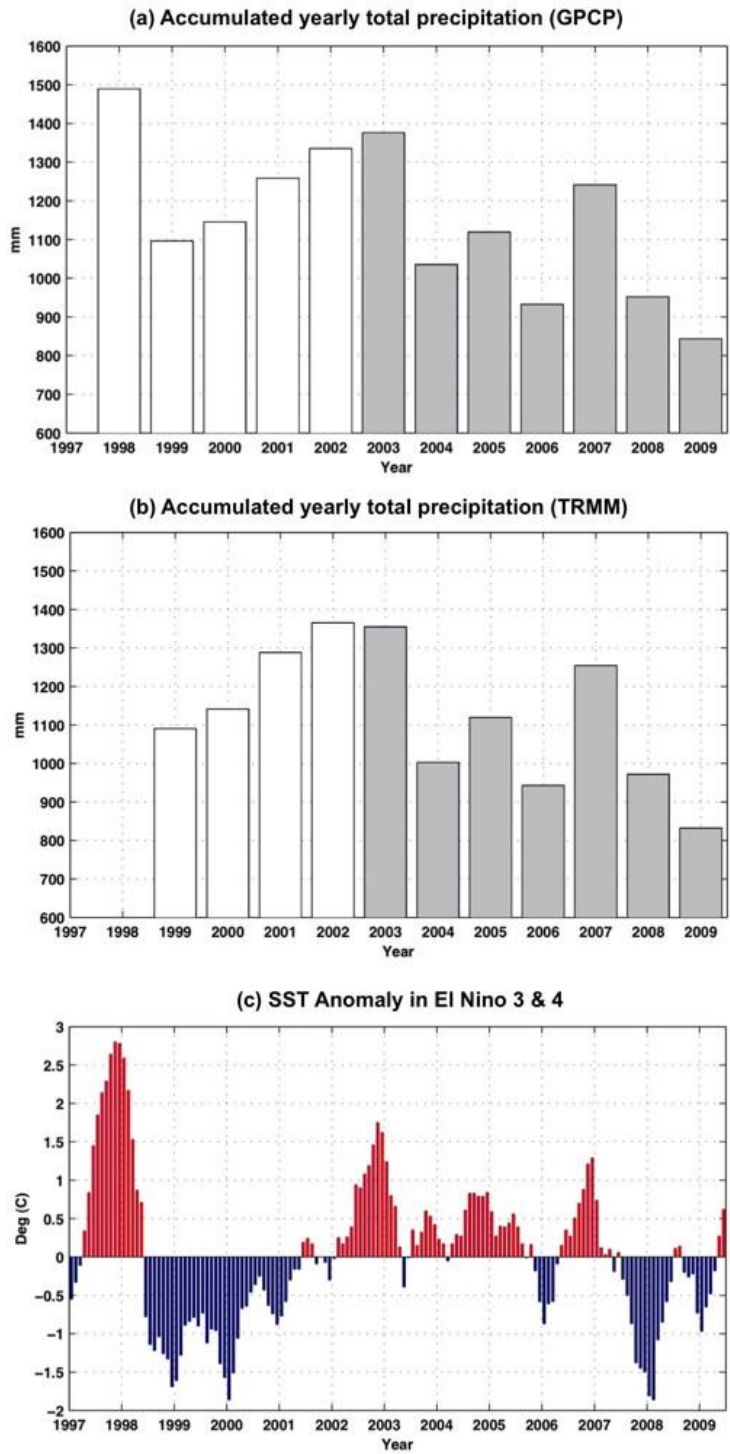
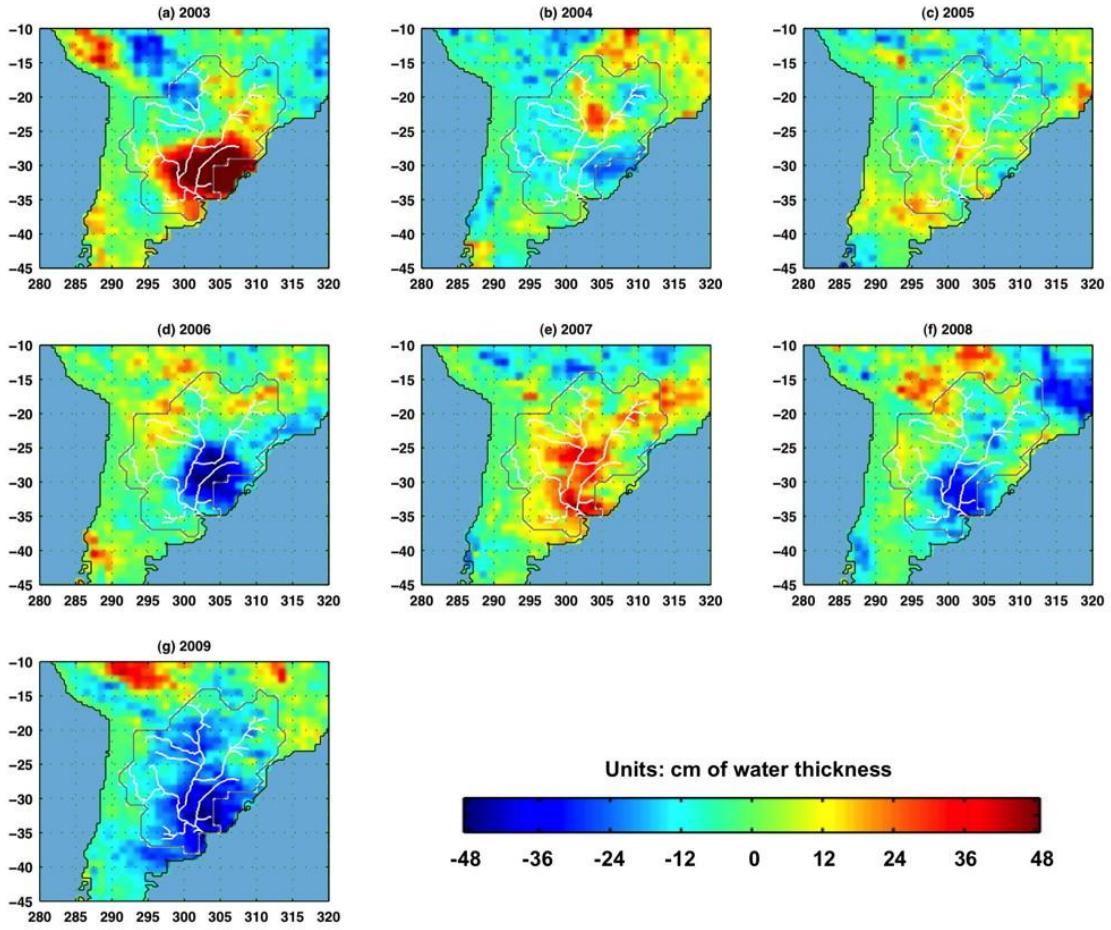


Figure 6

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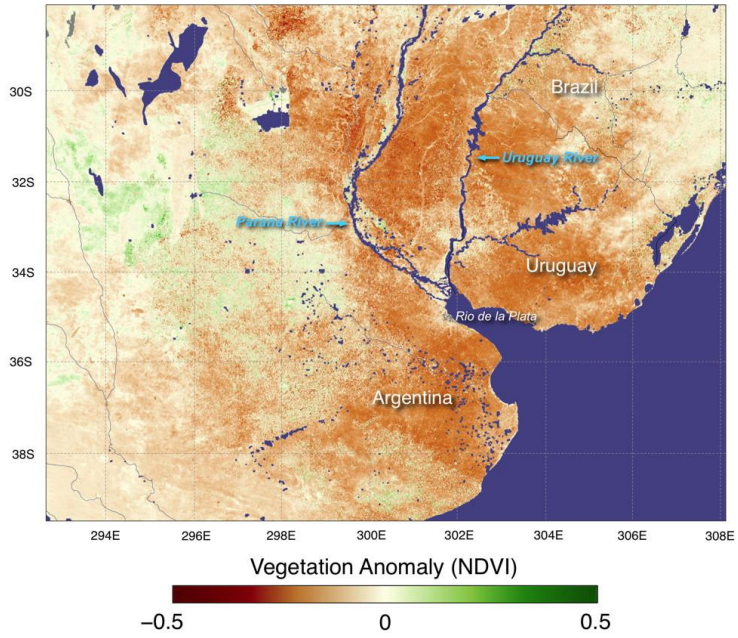


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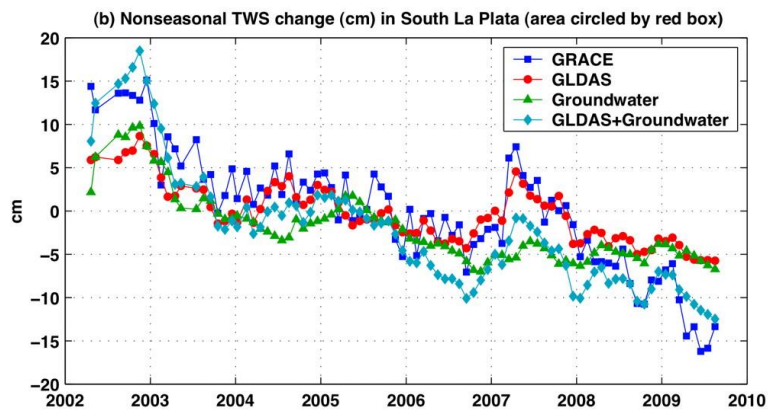
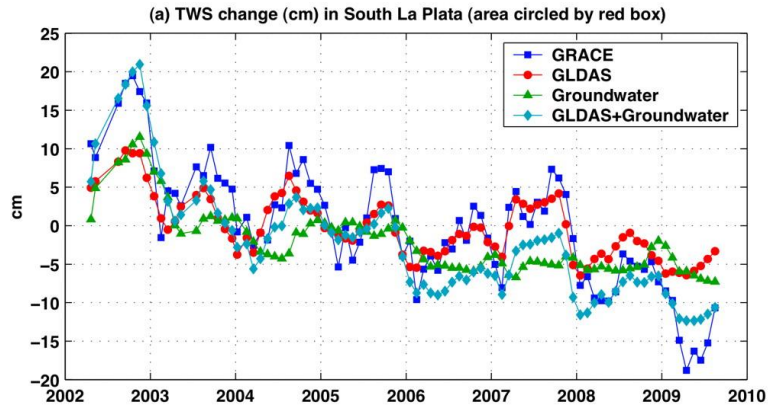
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Figure 7



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Figure 8



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Figure 9