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The 2009 exceptional Amazon flood and interannual terrestrial water storage change observed by GRACE

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[1] The Gravity Recovery and Climate Experiment (GRACE) satellite gravity mission provides a new capability for measuring extreme climate events, such as floods and droughts associated with large-scale terrestrial water storage (TWS) change. GRACE gravity measurements show significant TWS increases in the lower Amazon basin in the first half of 2009, clearly associated with the exceptional flood season in that region. The extended record of GRACE monthly gravity solutions reveals the temporal and spatial evolution of both nonseasonal and interannual TWS change in the Amazon basin over the 7 year mission period from April 2002 to August 2009. GRACE observes a very dry season in 2002–2003 and an extremely wet season in 2009. In March 2009 (approximately the peak of the recent Amazon flood), total TWS surplus in the entire Amazon basin is ~624 ± 32 Gt, roughly equal to U.S. water consumption for a year. GRACE measurements are consistent with precipitation data. Interannual TWS changes in the Amazon basin are closely connected to ENSO events in the tropical Pacific. The 2002–2003 dry season is clearly tied to the 2002–2003 El Niño and the 2009 flood to the recent La Niña event. The most significant contribution of this study in the area of water resources is to confront the hydrological community with the latest results of the GRACE satellite mission and further demonstrates the unique strength of GRACE and follow-up satellite gravity observations for measuring large-scale extreme climate events.

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1. Introduction

[2] The Amazon basin (see Figure 1) is the largest drainage basin in the world, covering about 40% of South America and portions of six countries. The basin covers a total area of ~7.05×10^6 km^2 (~2.72×10^6 square miles). The Amazon River system plays a significant role in the global hydrological cycle since its total river flow is greater than the combined flow of the next ten largest rivers. Amazon flow accounts for approximately one fifth of the world's total river discharge to the oceans. Average rainfall across the basin is approximately 2130 mm (or 7 ft) annually, and in some areas of the northern portions, yearly rainfall can exceed 4000 mm (13 ft) [*Costa and Foley*, 1998]. The surface area covered by the river and its tributaries can increase by more than a factor of 3 during the course of a year. In an average dry season, ~110,000 km^2 is water covered, while in the wet season this rises to 350,000 km^2 [*Guo*, 2006].

[3] The Amazon basin has experienced a number of extreme climate events in recent decades, apparently driven by more frequent El Niño and La Niña episodes. In 1997 and 1998, the most intense El Niño in recent history provoked the worst drought of the last 3 decades. Then in 2005, central and southern portions were hit again by an exceptional drought, regarded as the worst in over a century in many regions [*Rohter*, 2005]. The 2005 Amazon drought is linked both to prolonged (2002–2005) El Niño conditions in the tropical Pacific and to abnormal warming of the northern tropical Atlantic, up to 2° warmer than average [*Zeng et al.*, 2008a]. The 2005 drought was relieved within a few months by heavy precipitation in late 2005 and early 2006 [*Chen et al.*, 2009].

[4] Because of the excessively large annual precipitation, seasonal floods are very common in the Amazon basin and typically reach a maximum in April or May [*Costa and Foley*, 1998]. However, in the first half of 2009, central and northern regions experienced their worst flooding in over half a century (see Figure 2), while southern Amazon and northern La Plata basins suffered a severe drought. The 2009 flooding created many casualties, left more than 376,000 people homeless, and was apparently connected to the 2008–2009 La Niña event (A. Clendenning, Amazon hit by climate chaos of floods, drought, *USA Today*, 2009, available at http://www.usatoday.com/weather/2009-05-25-amazon-drought-and-floods_N.htm).

[5] The lack of adequate data resources for large basins makes quantification of hydrologic events difficult. This is particularly true for the Amazon basin, with its complex river systems and extensive rain forest coverage. Soil types and surface conditions are poorly known, and conventional observations, especially in situ meteorological and hydrological, are limited. Satellite remote sensing data are often

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Figure 1. Map of the Amazon basin (light-shaded area) and countries in South America. The Amazon basin is the largest drainage basin in the world, covering part of six countries (with the majority in Brazil) and about 40% of South America and with a total area of ~7.05 million km^2 (~2.72 × 10^6 square miles).

useful means for monitoring large-scale floods and droughts, but with 80% rain forest coverage are of limited value in forming quantitative estimates.

[6] Terrestrial water storage (TWS) represents total water stored in soil, snow cover, and surface water over land and in groundwater reservoirs. TWS change reflects the sum of accumulated precipitation (*P*), evapotranspiration (*E*), and surface and (subsurface) runoff (*R*) and provides a good measure of flood and drought extent and intensity. Traditionally, accurate estimation of TWS change relies on

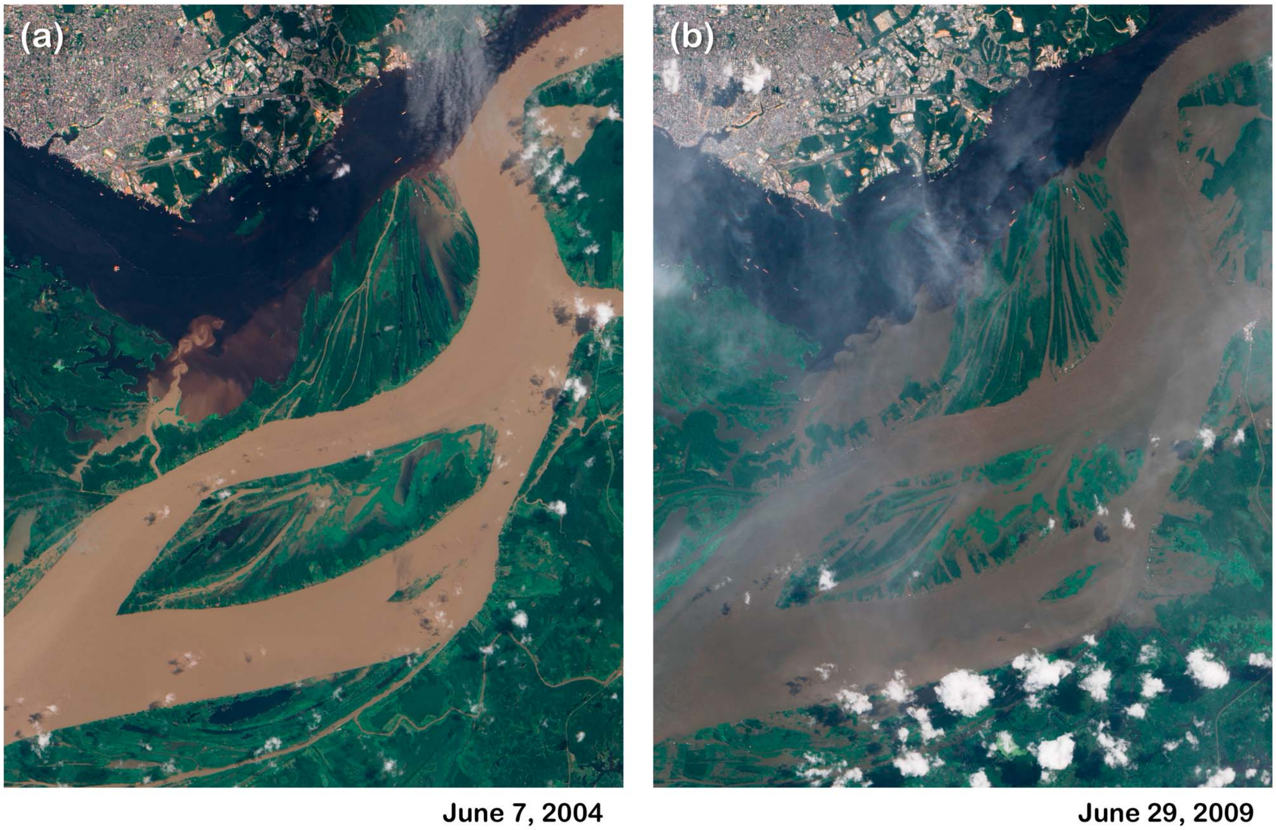


Figure 2. Satellite images of the flooding Amazon River near Manaus, Brazil, acquired on (a) 7 June 2004, in a year when seasonal flooding was not as extreme, and (b) 27 June 2009, when the region experienced the worst flood in over half a century. These images were acquired by the Advanced Land Imager on NASA's EO-1 satellite (courtesy of NASA Earth Observatory; raw satellite image is available at http://earthobservatory.nasa.gov/NaturalHazards/view.php?id=39359).

accurate measurements of all related hydrological parameters [*Crowley et al.*, 2008; *Zeng et al.*, 2008b], including *P*, *E*, and *R* or related quantities of water storage in soil and snow, surface water, and ground reservoirs. Measurements of such parameters are not generally available at sufficient spatial and temporal scales, and given the lack of observations as constraints, numerical weather models may not accurately estimate TWS changes, especially at interannual and longer time scales [e.g., *Matsuyama et al.*, 1995; *Chen et al.*, 2009].

[7] The Gravity Recovery and Climate Experiment (GRACE) is a twin satellite mission, jointly sponsored by NASA and the German Aerospace Center (DLR). Since launch in March 2002, GRACE has provided global measurements of gravity change with unprecedented accuracy at approximately monthly intervals [*Tapley et al.*, 2004]. Gravity changes are due to mass redistribution within the Earth system associated with TWS change and other geophysical processes.

[8] Early GRACE time-variable gravity observations showed an accuracy of ~1.5 cm of equivalent water thickness change with a resolution of about 1000 km [*Wahr et al.*, 2004, 2006], enabling studies of a variety of problems, including TWS change [e.g., *Güntner et al.*, 2007; *Syed et al.*, 2008; *Strassberg et al.*, 2009; *Xavier et al.*, 2010], polar ice sheets 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]. With improved background geophysical models and data processing techniques [*Bettadpur*, 2007a], reprocessed GRACE release 4 (RL04) time-variable gravity fields show significantly improved accuracy and spatial resolution, now at ~300 km or better [e.g., *Chen et al.*, 2008, 2009]. These reprocessed data enable application of GRACE data to a wider class of problems than before, and full 8 year (by the time this article is in press) GRACE time series provide a unique view of interannual and long-term changes in Earth's climate system.

[9] In this study we examine TWS change in the Amazon basin from 2002 to 2009, using RL04 solutions. The goal is to better understand and quantify extent and intensity of the 2009 Amazon flood and to compare GRACE estimates of the event with precipitation data. We also examine connections between recent major floods and droughts in the Amazon basin with abnormal climate conditions driven by El Niño and La Niña events.

2. Data Processing

[10] GRACE RL04 data are determined by the Center for Space Research (CSR), University of Texas at Austin [*Bettadpur*, 2007b], and now include 86 approximately monthly gravity fields from April 2002 through August 2009. RL04 consists of normalized spherical harmonic

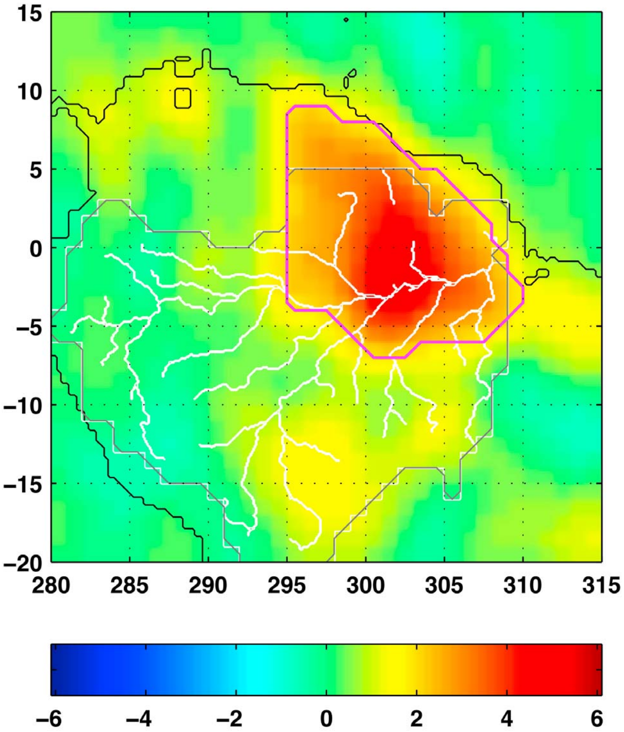


Figure 3. GRACE average mass rates (cm/yr of equivalent water thickness change) in the Amazon River basin for April 2002 to August 2009. The two-step filtering scheme (P4M6 and 300 km Gaussian smoothing) is applied, as described in the text. The area circled by the magenta line indicates where GRACE rates exceed ~2 cm/yr.

coefficients to degree and order 60. At high degrees and orders, GRACE spherical harmonic coefficients are contaminated by noise, including longitudinal stripes, and other errors. The longitudinal stripes have been tied to correlations among certain spherical harmonics coefficients [*Swenson and Wahr*, 2006]. To suppress the longitudinal stripes, we apply a decorrelation filter (called P4M6) to each GRACE solution. At spherical harmonic orders 6 and above, a degree 4 polynomial is fitted by least squares and is removed from even and odd coefficient pairs [*Swenson and Wahr*, 2006]. To further suppress remaining spatial noise, a 300 km Gaussian low-pass filter is applied [*Jekeli*, 1981]. Finally, the mean of all 86 monthly solutions is removed from each solution. Long-term variability of low-degree zonal harmonics (C_{20}, C_{30}, and C_{40}) removed during data processing has been restored using estimates based on laser ranging to the Lageos and other geodetic satellites [*Cheng and Ries*, 2007]. GRACE solutions are referred to Earth's mass center so degree 1 spherical harmonics, representing geocenter motion, are set to be zero. After these steps, gravity field variations are represented as monthly model of mass changes on a 1° × 1° grid [*Wahr et al.*, 1998].

[11] The absence of geocenter terms is expected to have a notable effect on GRACE-derived TWS change [*Chen et al.*, 2005]. However, no reliable geocenter time series is available at the present. As the focus of this study is regional TWS change, the geocenter effect should be minimal (less than a few centimeters of TWS on seasonal scales) [*Chen et al.*, 2005]. Effects of atmospheric and oceanic mass redistribution have been removed from RL04 during GRACE processing using estimates from atmospheric and oceanic general circulation models [*Bettadpur*, 2007b]. Therefore, GRACE-observed mass variations over land should be due primarily to TWS and snow/ice mass changes and to other geophysical signals such as postglacial rebound (PGR). In the Amazon basin, the primary signal is expected to be from water storage changes. GRACE estimates may be contaminated by spatial leakage associated with the finite range of spherical harmonics coefficients, attenuation from spatial filtering, and residual atmospheric signals (due to errors in atmospheric models) plus intrinsic errors associated with the GRACE measurement.

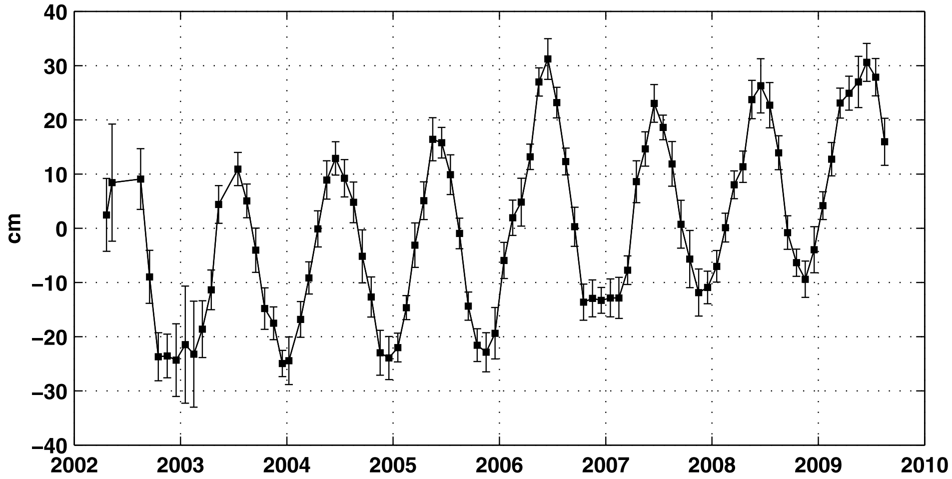
3. Results

3.1. Nonseasonal Variability

[12] The GRACE time series provides a unique measure of interannual and longer-term TWS variability for the Amazon and other basins (Figure 3). GRACE shows apparent mass rates in the Amazon and surrounding regions. At each grid point (or pixel), apparent rate is the linear trend computed from a time series of 86 monthly mass fields via unweighted least squares. The magenta line encloses an area where apparent rates exceed 2 cm/yr. Along with the linear trend, we simultaneously fit seasonal sinusoids (annual and semiannual) and a 161 day sinusoid associated with a recognized S2 alias error [*Ray and Luthcke*, 2006]. GRACE shows significant TWS increases (up to ~4 cm/yr of equivalent water thickness change) in northern and central regions for April 2002 to August 2009. Average GRACE TWS time series within the magenta contour of Figure 3 is shown in Figure 4a. A cosine of latitude weighting (i.e., cos(θ), where θ is latitude) is applied to each grid point when forming average time series for the area. The GRACE time series shows a larger seasonal variation superimposed on an increasing trend. Figure 4b shows GRACE TWS time series after annual, semiannual, and 161 day S2 alias sinusoids have been removed.

[13] The true uncertainty level of GRACE observations is unknown. Here we approximately estimate the uncertainty for each GRACE estimate (in the time series shown in Figures 4a and 4b) using mean RMS of residuals in the tropical Pacific Ocean within the area between 10°S–10°N and 150°E–260°E, which is located at the roughly the same latitude zone as the studied area (within the magenta contour of Figure 3) and also far away from the coasts with less impact from hydrological leakage from lands.

[14] The GRACE TWS time series in Figure 4b reveals a number of interesting features. Spring 2003 shows a dry period with a mean TWS deficit near −20 cm (equivalent water thickness). Spring 2009 is a relatively wet season with mean TWS surplus of ~+24 cm in March 2009. On average, 2006–2009 is wetter than 2002–2005. In Figure 4a the 2006 seasonal peak is slightly larger than the 2009 peak (both occur in June). However, in Figure 4b, TWS surplus in spring 2009 is significantly greater than in 2006, although 2006 is the second wettest season in 2002–2009. The large TWS surplus in spring 2009 is associated with the exceptional 2009 floods in the region. The 2005 Amazon drought is not reflected in GRACE time series in Figures 4a and 4b


(a) TWS change in Northeast Amazon (area circled by magenta line)

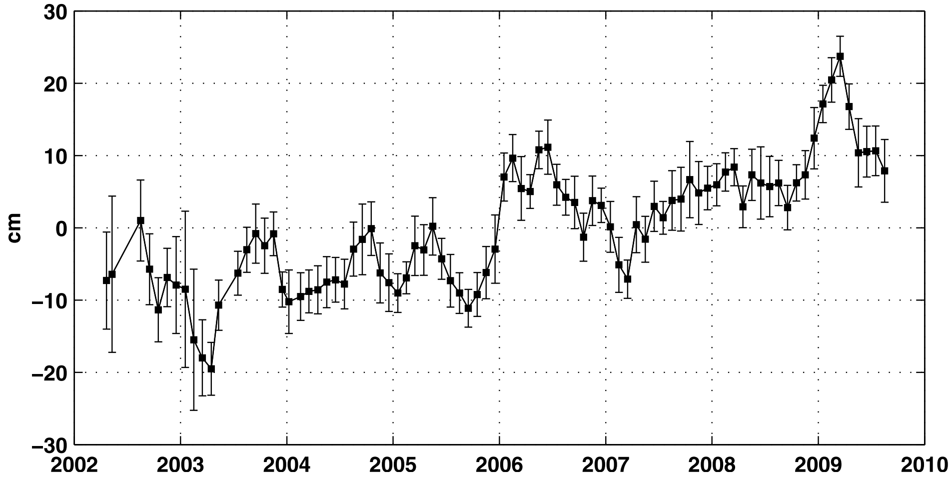

(b) Nonseasonal TWS change in Northeast Amazon (area circled by magenta line)

Figure 4. (a) TWS changes in the northeast Amazon basin (average within the area circled by the magenta line in Figure 3) from GRACE. (b) Nonseasonal TWS changes in the northeast Amazon basin from GRACE. Annual, semiannual, and the 161 day S2 alias errors have been removed through unweighted least squares fit.

because of its location in the middle and southern portions of the basin, outside the region considered in this study.

3.2. Temporal and Spatial Evolutions of TWS Change

[15] Maps of annual average TWS anomalies are shown in Figures 5a–5g. Each map is the mean over 12 months from July of the previous year through June. The July–June average makes better use of available 2002 and 2009 GRACE data and effectively illustrates abnormal conditions in 2003 and 2009 (see Figure 4b). Seasonal (annual and semiannual) and 161 day sinusoids were removed before computing each yearly mean. The 2009 map (July 2008 to June 2009) shows a very broad region in the north with large TWS increases (up to ~20 cm). The 2008 map also shows a relatively wet period. However, the 2003 map (July 2002 to June 2003) shows the eastern Amazon and Orinoco basins with relatively dry conditions. This is consistent with precipitation analysis in section 3.3. In general, 2003–2005 maps are characterized by relatively dry conditions in the eastern region, with later maps (especially 2008 and 2009) showing the opposite. The maps do not show the 2005 Amazon drought because the July–June period includes both the drought and the excessive rainfall that followed it [*Chen et al.*, 2009].

[16] Figures 6a–6f show monthly GRACE TWS anomalies for 2 month intervals from September 2008 through July 2009 to further illustrate temporal and spatial development of the exceptional 2009 Amazon flood. By late 2008 the northern basin shows wetter than average conditions for this period, and by January 2009 lower and northern parts of the basin are significantly wetter than normal (note the change of color scales from Figure 5 to Figure 6). The flood continued to develop and reached a maximum in March 2009. The flood in the northern Amazon gradually abated by July 2009. However, in the central Amazon flooding continued into July 2009 (a wetter month than May 2009). By August 2009 (map not shown here), the exceptional Amazon flood

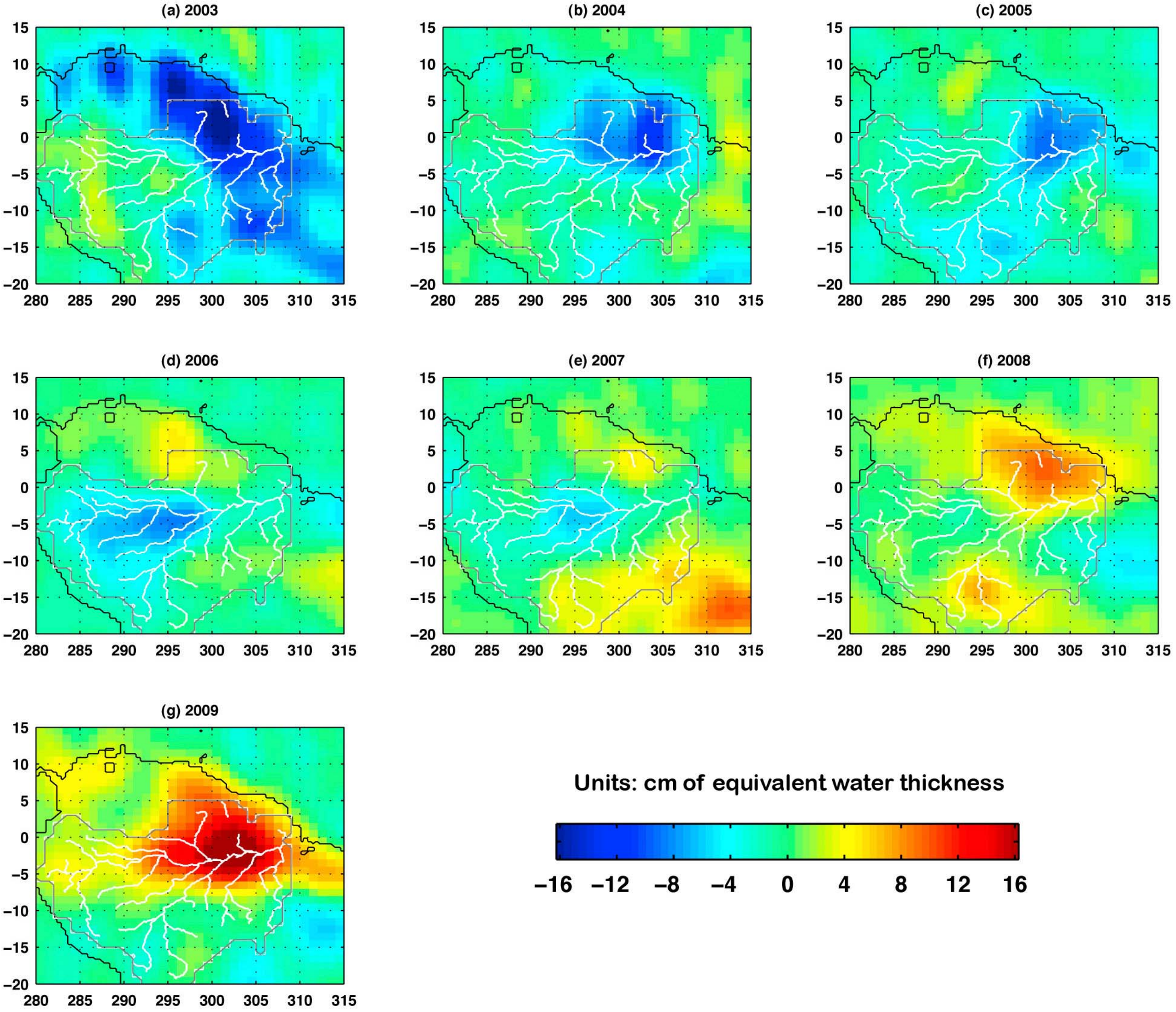


Figure 5. The evolution of yearly TWS anomalies (in cm of equivalent water thickness change) in the Amazon basin and surrounding regions during the 7 year period from August 2002 to June 2009. Yearly averages are mean TWS changes from July of the previous year through June of the current year; for example, the 2004 TWS anomalies are the mean during July 2003 through June of 2004. Seasonal (annual and semiannual) signals and the 161 day S2 alias error have been removed through unweighted least squares fit as well as the mean field for the 7 year period.

was over. In March 2009, during the peak of the flood, total TWS surplus in the entire basin was about 624 Gt, enough to supply U.S. water consumption for a full year [*Kenny et al.*, 2009]. This is only a rough estimate. The leakage effect has not been corrected. However, on the basis of previous study [*Chen et al.*, 2007; *Xavier et al.*, 2010], at 300 km the Gaussian smoothing leakage effect of GRACE estimates for the entire Amazon basin should not be very significant, at ~5% of the true signal (at seasonal scales), which is equivalent an uncertainty level of ±32 Gt.

3.3. Additional Observations and Connections With El Niño and La Niña

[17] We compare GRACE nonseasonal TWS variations (Figure 7a) averaged in the region encircled by the magenta contour in Figure 3 with mean monthly precipitation anomalies (Figure 7b) over the same area from the global precipitation data set (version 2.1) of the Global Precipitation Climatology Project (GPCP) [*Adler et al.*, 2003]. GPCP data are a combined 1° × 1° gridded analysis based on gauge measurements and satellite data for 1979 to present [*Adler et al.*, 2003]. Monthly anomalies are computed by removing the mean for each calendar month (January through December) from 1997 to 2008 (2009 data were not available at the time of this analysis). A 5 month moving average window was then applied to yield the precipitation anomaly time series in Figure 7b.

[18] The precipitation anomaly time series correlates well with GRACE nonseasonal TWS changes. During fall 2008 through spring 2009, the precipitation anomaly is large and positive in agreement with the GRACE TWS surplus. In the

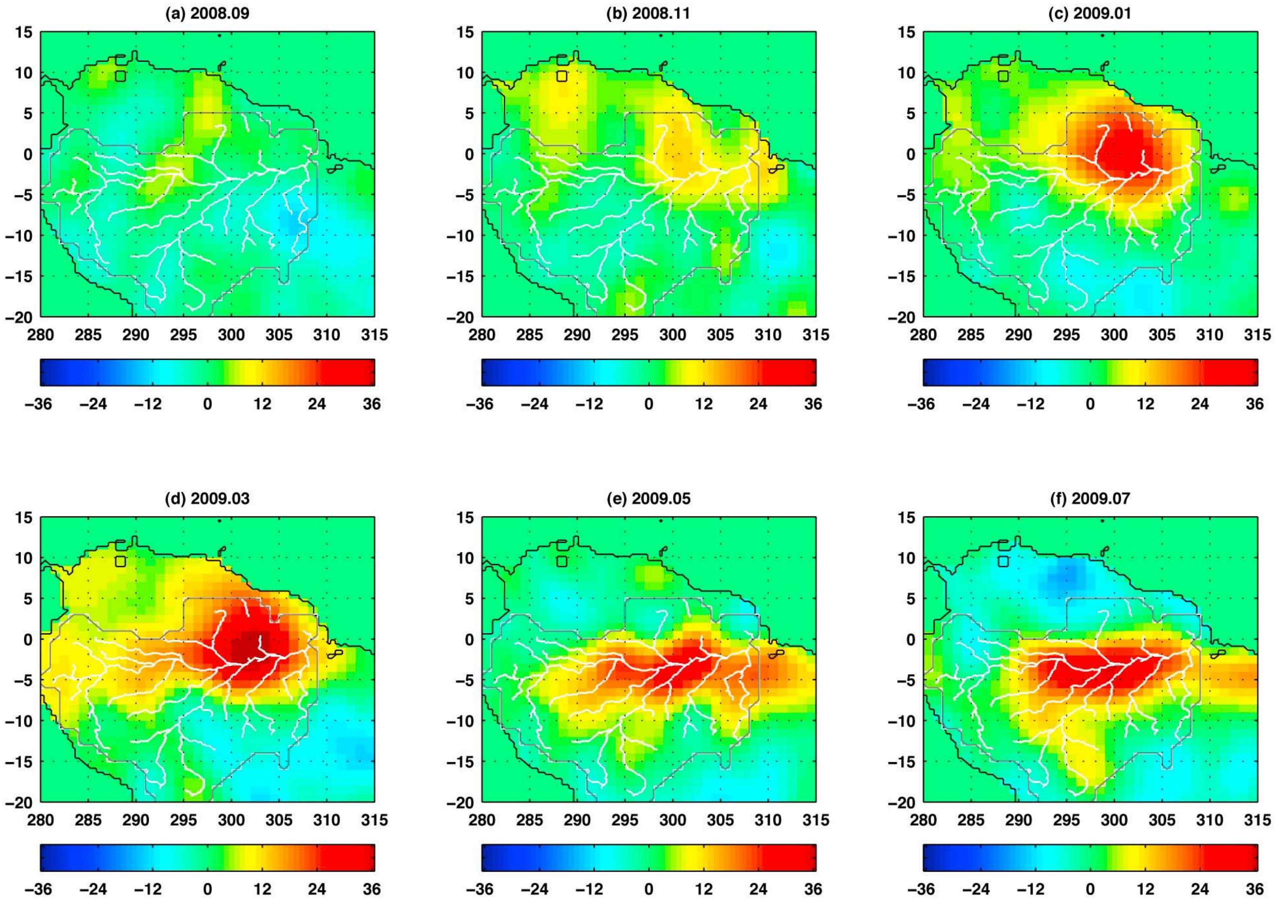


Figure 6. The evolution of monthly TWS anomalies (in cm of equivalent water thickness change) in the Amazon basin and surrounding regions every 2 months during the period from September 2008 to July 2009. Seasonal (annual and semiannual) and 161 day sinusoids have been removed along with the mean field over the 7 year period. Residual signals over the oceans are masked out.

period July 2002 to June 2003, the precipitation anomaly is strongly negative, coincident with the dry condition observed by GRACE. Again consistent with GRACE, mostly negative anomalies are evident before 2006, and mostly positive precipitation anomalies are evident afterward. The negative 2007 anomaly is also consistent with GRACE results.

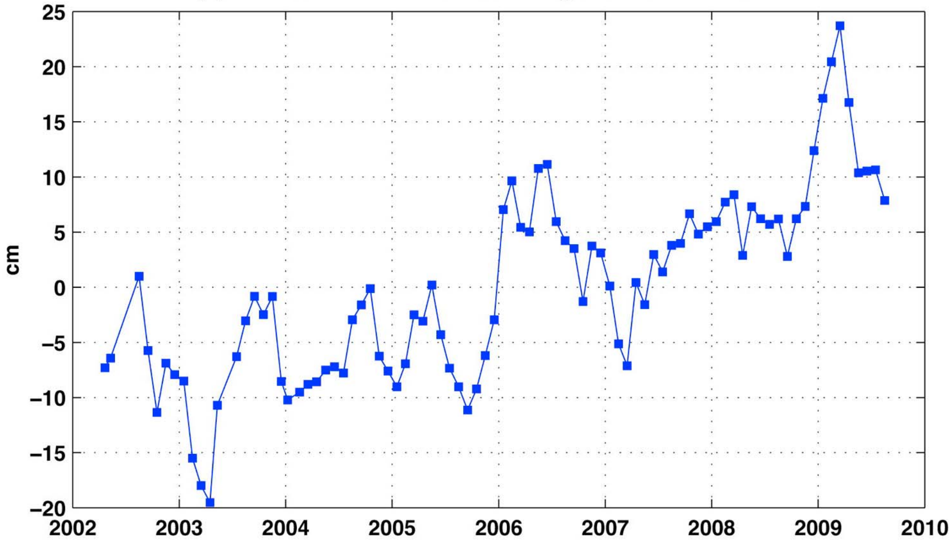
[19] GRACE interannual TWS change and precipitation anomalies in the Amazon basin (in the area encircled by the magenta contour) are connected to El Niño and La Niña events as can be seen via comparison with NINO3.4 sea surface temperature (SST) anomaly index from 1997 to 2009 (see Figure 8). The NINO3.4 index represents an average SST anomaly in the region bounded by 5°N–5°S, 170°W–120°W in the eastern tropical 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].

[20] There is a clear negative correlation between precipitation anomalies in lower and northern Amazon regions (i.e., the area encircled by the magenta contour) and the NINO3.4 index. Major El Niño periods (e.g., 1997–1998, 2002–2005, and 2007–2008) correspond to dry periods (negative precipitation anomalies) in the lower and northern Amazon, and wet periods are associated with La Niña (1998–2000 and 2008–2009). However, precipitation anomalies are not necessarily proportional to El Niño and La Niña event strength as measured by the index. For example, the 2009 Amazon flood peaked when the 2008–2009 La Niña started to weaken.

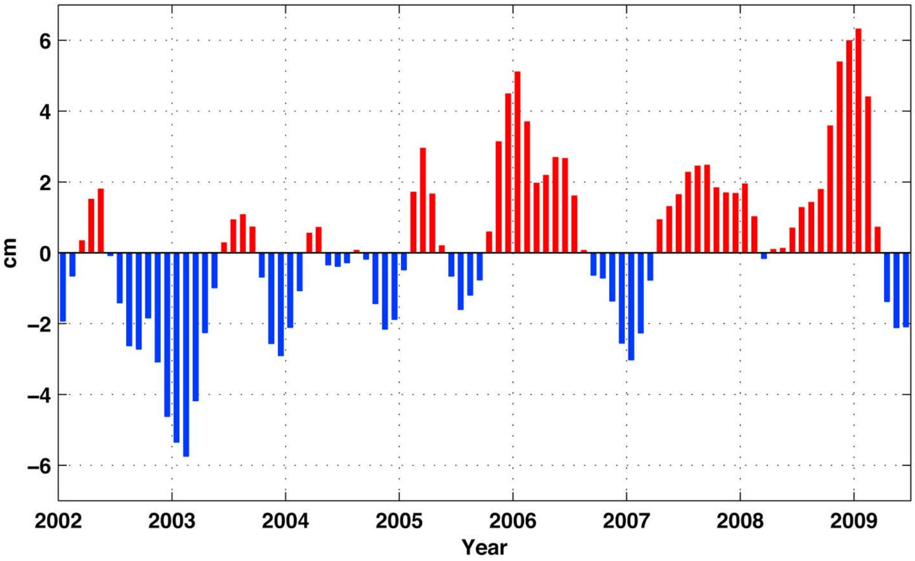
4. Conclusions and Discussion

[21] GRACE has measured the exceptional 2009 Amazon flood and its temporal and spatial evolution, showing TWS increases in lower and northern Amazon regions since late 2008 associated with extensive flooding. The flood began in early 2009 and reached the maximum in March 2009, continuing through July 2009 in the middle and central Amazon basins. During its peak, total TWS surplus relative to the mean over the GRACE observation period in the entire basin is estimated at 624 ± 32 Gt.

[22] During the first 7 years of the mission, GRACE data also reveal significant interannual TWS changes in the Amazon, including an extremely dry 2003 season and an exceptionally wet 2009 season. Interannual variability includes an increasing trend in TWS in the lower and northern Amazon



(a) GRACE Nonseasonal TWS Change in Northeast Amazon



(b) Monthly Precipitation Anomalies (cm) in Lower Amazon

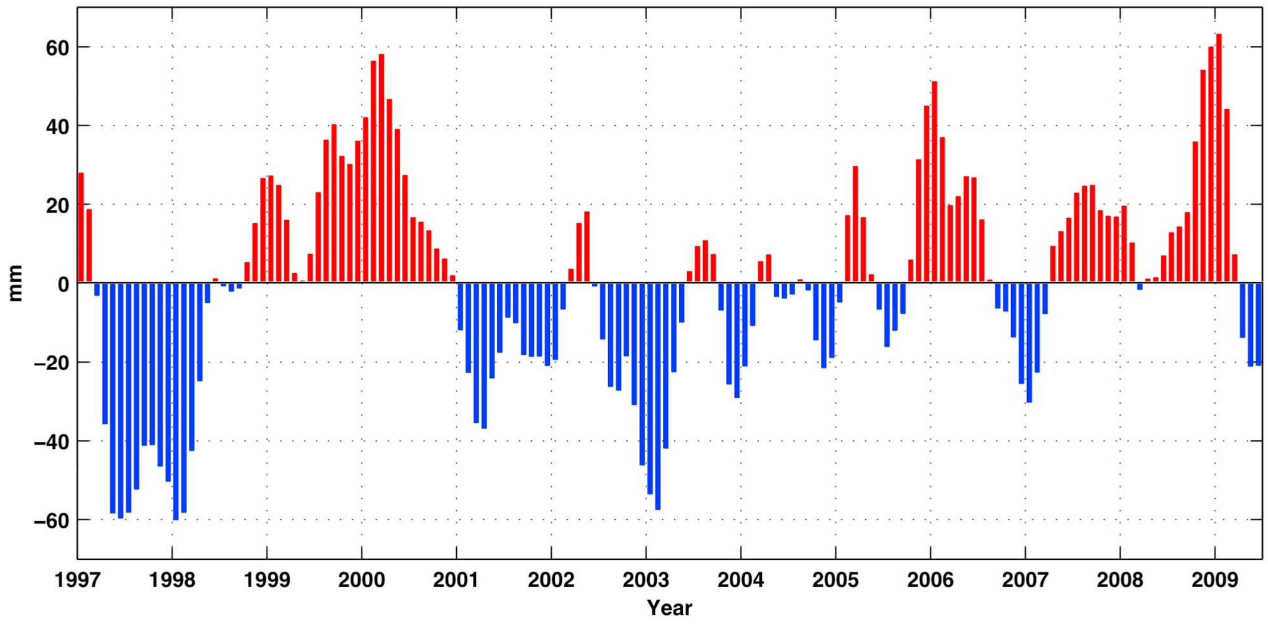
Figure 7. (a) Nonseasonal TWS changes in the northeast Amazon (area circled by the magenta line in Figure 3) from GRACE (the same curve shown in Figure 4b but without error bar for clarity). (b) Monthly precipitation anomalies in the same region during the same period. The monthly precipitation anomalies are computed by removing the monthly means (for each month from January to December) estimated over the 12 year period 1997–2008.

basin. It is a challenge to accurately model TWS change in the Amazon basin in hydrological models. One particular reason is the complicated surface water storage (i.e., water stored in rivers and floodplains), which could account for a significant part of GRACE-observed TWS change [e.g., *Papa et al.* 2008; *Trigg et al.*, 2009], especially during abnormal climate conditions, such as floods and droughts.

[23] GRACE interannual TWS changes in the Amazon basin are consistent with GPCP precipitation data, and TWS changes in the Amazon basin are clearly connected with the El Niño and La Niña events. During 1997–2009, precipitation anomalies in the lower and northern Amazon are well correlated with the NINO3.4 index, with dry periods linked to major El Niño events and wet periods linked to La Niña. GRACE interannual TWS changes also correlate well with precipitation anomalies and NINO3.4 SST anomalies. The close connections between GRACE-observed TWS anomalies in the Amazon basin and ENSO events reinforce similar results from previous studies [*Morishita and Heki*, 2008; *Xavier et al.*, 2010].

[24] It is challenging to accurately quantify uncertainty in GRACE estimates, mainly because of the lack of adequate

(a) Monthly Precipitation Anomaly (mm) in Lower Amazon



(b) Monthly SST Anomaly in El Nino 3 & 4

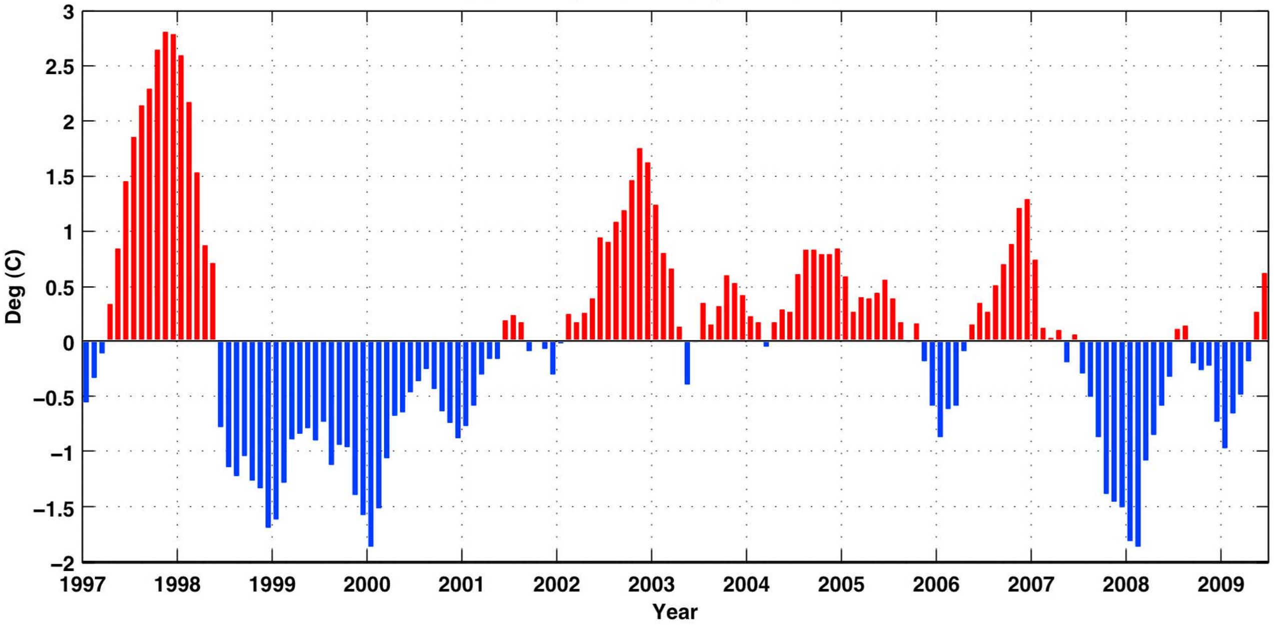


Figure 8. (a) Monthly precipitation anomalies for 1997–2009 in the lower Amazon basin (the area encircled by the magenta contour in Figure 3). Each monthly precipitation anomaly is computed by removing the mean monthly precipitation (for that month), estimated for 1997–2008. (b) The NINO3.4 index over the period 1997–2009. NINO3.4 is the average sea surface temperature (SST) anomaly in the region bounded by 5°N–5°S, 170°W–120°W. This region has large variability on El Niño time scales and is close to the region where changes in local sea surface temperature are important for shifting the large region of rainfall typically located in the far western Pacific. The NINO3.4 index time series is provided by the Royal Netherlands Meteorological Institute (http://www.knmi.nl).

in situ TWS or gravity measurements for validation. However, we can use residuals over the ocean to approximate the GRACE noise level [*Wahr et al.*, 2004]. In some cases (e.g., at seasonal time scales or in GRACE monthly mass fields), this approximation may considerably overestimate the GRACE noise level, as residual signals over the ocean could be significant. The TWS signals seen in the Amazon are well above this level, and we are confident that the

GRACE estimates accurately represent variations in this region. The most significant contribution of this study in the area of water resources is to confront the hydrological community with the latest results of the GRACE satellite mission and further demonstrates the unique strength of GRACE and follow-up satellite gravity observations for measuring large-scale extreme climate events.

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