JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 114, B05404, doi:10.1029/2008JB006056, 2009

2005 drought event in the Amazon River basin as measured by GRACE and estimated by climate models

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Received 1 September 2008; revised 8 January 2009; accepted 2 March 2009; published 8 May 2009.

[1] Satellite gravity measurements from the Gravity Recovery and Climate Experiment (GRACE) provide new quantitative measures of the 2005 extreme drought event in the Amazon river basin, regarded as the worst in over a century. GRACE measures a significant decrease in terrestrial water storage (TWS) in the central Amazon basin in the summer of 2005, relative to the average of the 5 other summer periods in the GRACE era. In contrast, data-assimilating climate and land surface models significantly underestimate the drought intensity. GRACE measurements are consistent with accumulated precipitation data from satellite remote sensing and are also supported by in situ water-level data from river gauge stations. This study demonstrates the unique potential of satellite gravity measurements in monitoring large-scale severe drought and flooding events and in evaluating advanced climate and land surface models.

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

1. Introduction

[2] In the summer of 2005, the Amazon basin experienced an extreme drought. Many areas, especially in the west and south, suffered the worst drought in over a century, leading to official declarations of "public calamity", forest fires, crop losses, and economic havoc [*Rohter*, 2005]. The event appears connected both to the 2002–03 El Niño and to abnormal warming of the northern tropical Atlantic, which was up to two degrees warmer than average [*Zeng et al.*, 2008a]. This paper compares measures of this event taken from satellite gravity observations and from data-assimilating hydrologic models.

[3] Understanding and quantification of drought occurrence, extent, and intensity is limited by conventional data resources. Numerical climate models are valuable in analyzing and diagnosing climate variability, but quantifying and simulating abnormal events such as droughts remains a major modeling challenge. Prediction is an even greater challenge. Conventional observations, especially in situ meteorological and hydrological samples, are limited in both space and time. Furthermore, model representations of dynamical connections between boundary conditions and extreme climate events tend to be poor.

[4] Terrestrial water storage (TWS) change, a major component of the global water cycle, includes changes in water stored in soil, as snow over land, and in ground water reservoirs. TWS change reflects accumulated precipitation, evapotranspiration, and surface and subsurface runoff within a given area or basin. TWS change provides a good measure of abnormal climate conditions such as drought, and is valuable for agriculture and other water uses. However, TWS change is difficult to quantify because of limited fundamental observations (ground water, soil moisture, precipitation, evapotranspiration, snow water equivalent, and others) at basin or smaller scales. Numerical model estimates are useful but exhibit limited accuracy [e.g., *Matsuyama et al.*, 1995]. Remote sensing data (such as TRMM satellite precipitation data) and in situ measurements (such as river level and discharge from gauge stations) are valuable assets in estimating TWS changes [e.g., *Crowley et al.*, 2007]. Unfortunately, in situ measurements alone are not sufficient, both because they tend to be point measurements, and because other hydrological parameters (e.g., evapotranspiration) must be estimated separately to determine TWS change.

[5] The Gravity Recovery and Climate Experiment (GRACE) is the first dedicated satellite gravity mission, jointly sponsored by NASA and the German Aerospace Center (DLR). Launched in March 2002, GRACE has been measuring Earth gravity change with unprecedented accuracy [*Tapley et al.*, 2004] for over 6 years. Early GRACE time-variable gravity observations showed an accuracy of $\sim$1.5 cm of equivalent water thickness change at about 1000-km spatial scale [*Wahr et al.*, 2004]. Various studies applied early GRACE results to a variety of problems including TWS change [e.g., *Wahr et al.*, 2004], 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].

[6] In early 2007, reprocessed GRACE release-04 (RL04) time-variable gravity fields with improved background geophysical models and data processing techniques were released [*Bettadpur*, 2007a]. RL04 shows significantly

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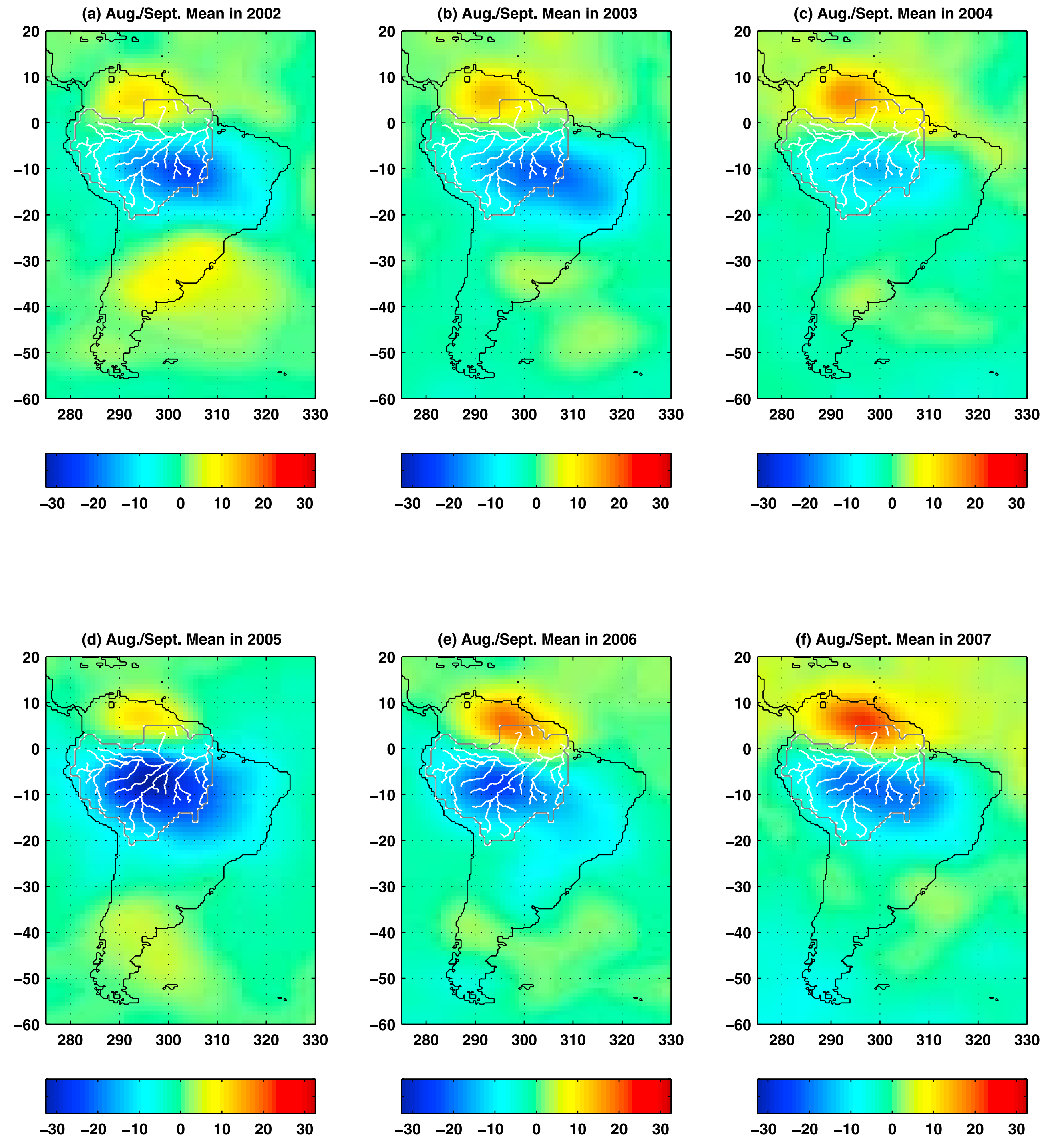

Figure 1. GRACE-averaged August and September water storage changes (in centimeters of water) in South America in (a) 2002, (b) 2003, (c) 2004, (d) 2005, (e) 2006, and (f) 2007. A 2-step filtering scheme (P4M6 and 500-km Gaussian smoothing) is applied, as described in the text.

improved data quality and spatial resolution, now better than 500 km [e.g., *Chen et al.*, 2007], enabling the study of a much wider class of problems than before. Improved quality and spatial resolution of RL04 and optimized data processing and filtering techniques [e.g., *Swenson and Wahr*, 2006] provide new opportunities for quantification of TWS changes, better monitoring of the global water cycle, and related understanding of droughts and floods.

[7] In this study, we examine TWS change in the Amazon basin using RL04 time-variable gravity fields and predictions from major climate and land surface models, including the National Oceanic and Atmospheric Administration (NOAA) National Centers for Environmental Prediction (NCEP) reanalysis II climate model and the global land data assimilation system (GLDAS) [*Rodell et al.*, 2004]. The goal is to demonstrate the capability of GRACE to

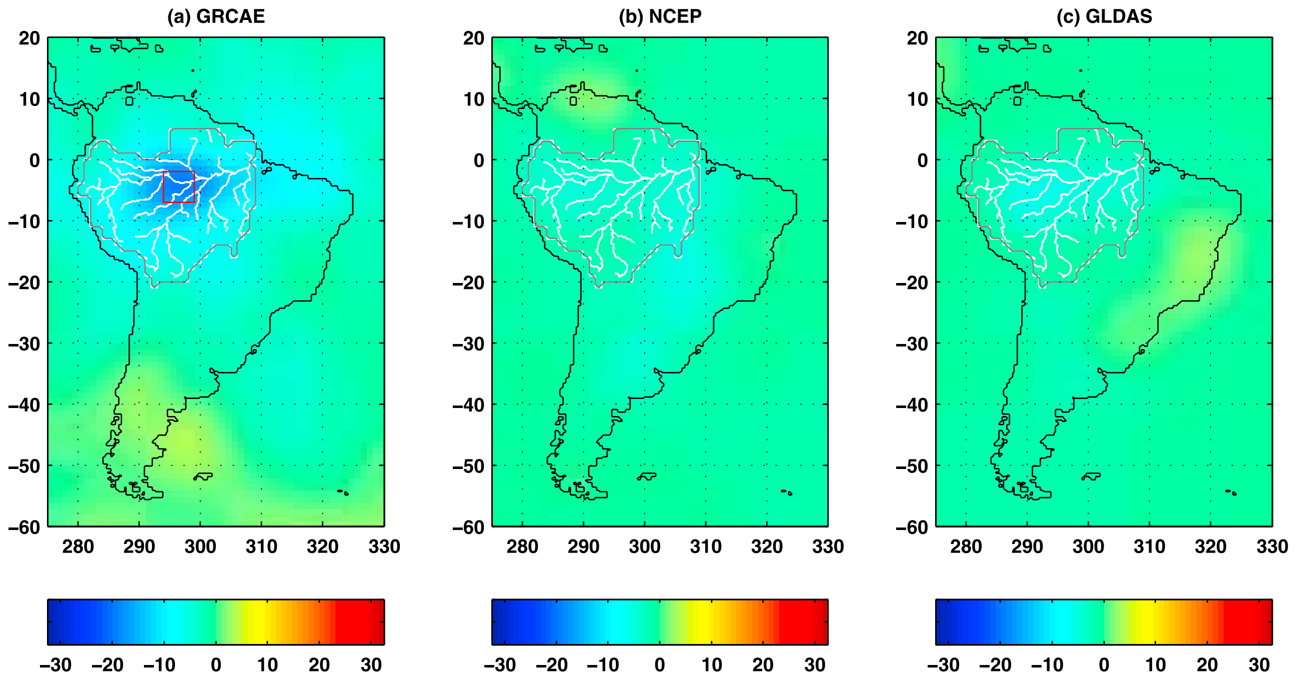

Figure 2. Differences of mean August/September TWS changes (in centimeters of water) in South America in 2005 relative to mean August/September TWS changes of other years in the period 2002–2007: (a) from GRACE, (b) from NCEP, and (c) from GLDAS. GRACE displays a strong 2005 TWS deficit, while NCEP and GLDAS do not.

observe and quantify the severe 2005 Amazon drought event, and to compare GRACE results with climate model descriptions of the same event.

2. Data Processing

2.1. TWS Changes From GRACE RL04

[8] Our GRACE time series includes 65 approximately monthly gravity solutions, for the period April 2002 to December 2007. Spherical harmonic (SH) coefficients (to degree and order 60) are used to compute monthly mass change fields on a $1^\circ \times 1^\circ$ grid. *Swenson and Wahr* [2006] showed that GRACE longitudinal stripe noise is associated with correlations among even or odd degree SH coefficients at a given order. Here we apply a two-step filter as in previous studies [*Chen et al.*, 2007]. The first step (called P4M6) removes this correlated noise by fitting and subtracting a fourth-order polynomial to even and odd coefficient pairs at SH orders 6 and above. The second step involves smoothing with a 500-km Gaussian filter [*Jekeli*, 1981]. After filtering, the mean of the 65-point time series at each grid point is removed to obtain a time series of gravity field variations, expressed as equivalent surface mass variations in cm of water.

[9] Atmospheric and oceanic mass changes have been largely removed from RL04 using numerical model predictions [*Bettadpur*, 2007b], so that variations over time scales of months to years should reflect primarily unmodeled effects such as TWS change, snow/ice mass changes (including polar ice sheets and mountain glaciers), plus other geophysical signals such as postglacial rebound (PGR) and coseismic and postseismic deformation. Over the Amazon basin, surface mass variations are expected to be dominantly due to near-surface water storage changes. Given this, the major errors in GRACE time series over the Amazon arise from spatial leakage associated with a finite range of SH terms, attenuation due to filtering, residual atmospheric signals, and GRACE measurement errors.

2.2. TWS Changes From Climate and Land Surface Models

2.2.1. NCEP Reanalysis II Model Estimates

[10] (NCEP/DOE AMIP) II Reanalysis-II was developed at NCEP and the Department of Energy (DOE) from the widely used NCEP/NCAR Reanalysis [*Kalnay et al.*, 1996]. NCEP reanalysis II (simply called NCEP in the subsequent discussion) improves upon earlier results by correcting errors and refining parameterizations of physical processes. Soil moisture (volume percentage) and snow fields (cm of water equivalent) are monthly averages from January 1948 to present, on a Gaussian grid (1.904°latitude by 1.875°longitude). Soil moisture is modeled for an upper layer of 10 cm and a lower layer of 190 cm thickness. Because NCEP does not model deeper ground water storage, TWS change at each grid point is the sum of two soil water layers plus snow water.

2.2.2. GLDAS Model Estimates

[11] GLDAS was developed jointly at the National Aeronautics and Space Administration Goddard Space Flight Center and NOAA NCEP [*Rodell et al.*, 2004]. GLDAS parameterizes, forces, and constrains sophisticated land surface models with ground and satellite products with the goal of estimating land surface states (e.g., soil moisture and temperature) and fluxes (e.g., evapotranspiration). In this particular simulation, GLDAS drove the Noah land surface model [*Ek et al.*, 2003], with observed precipitation

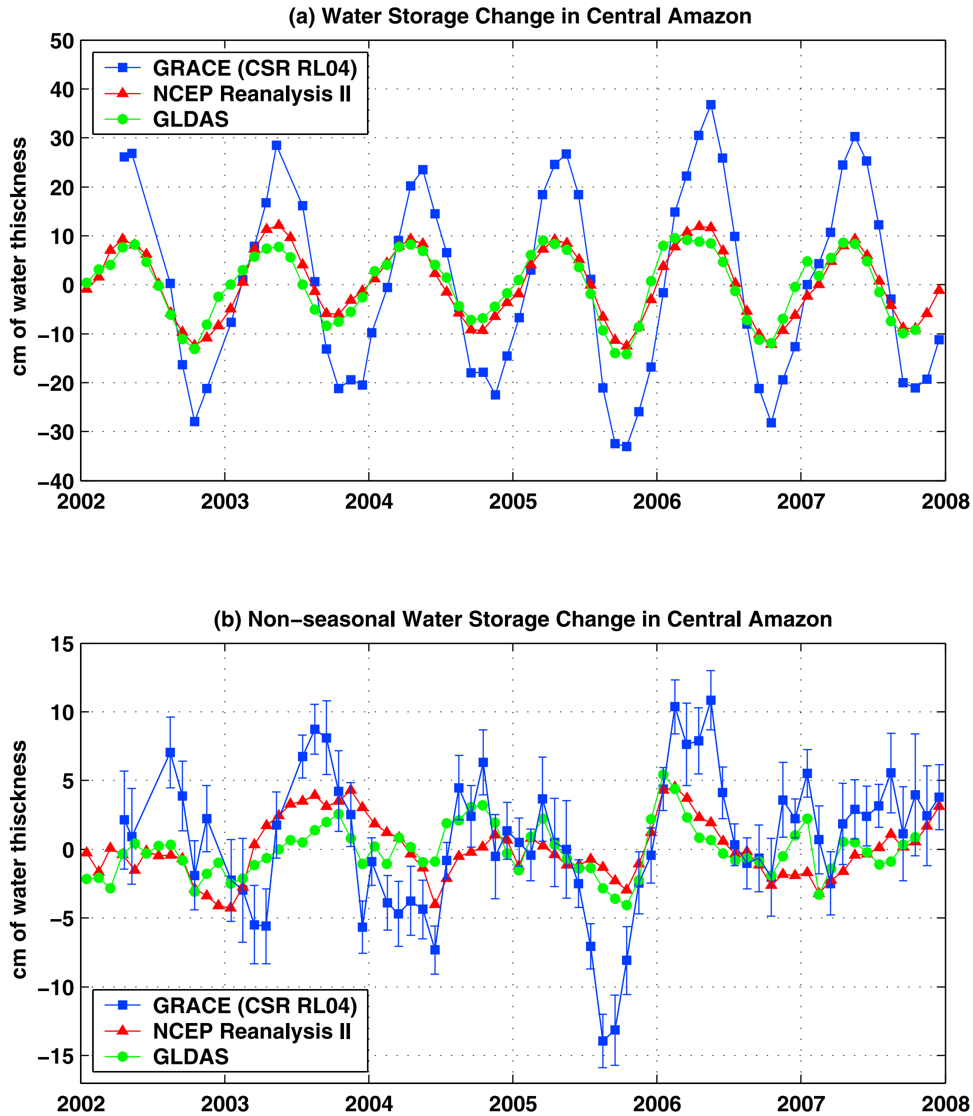

Figure 3. (a) Comparison of TWS changes in the central Amazon basin (average within the red box [2°S–7°S,294°E–299°E] marked in Figure 2a) from GRACE (blue curve), NCEP (red curve), and GLDAS (green curve). (b) Comparison of nonseasonal TWS changes in central Amazon basin from GRACE (blue curve), NCEP (red curve), and GLDAS (green curve).

and solar radiation included as inputs. Monthly averaged soil moisture (2 m column depth) and snow water equivalent are available from 1979 to present, and TWS variation at each grid point is the sum of soil and snow water. Greenland and Antarctica are excluded because the model omits ice sheet physics. Ground water is also not modeled by GLDAS.

2.2.3. TWS Changes From NCEP and GLDAS

[12] A fair comparison with GRACE observations requires that NCEP and GLDAS fields be spatially filtered in a similar way. To accomplish this, GLDAS and NCEP TWS gridded fields were represented in a SH expansion to degree and order 100, and the same two step filter described earlier (to remove correlated noise and smooth RL04) was applied. SH coefficients were truncated above degree and order 60, and additionally SH coefficients for degree 0 (imposing global mass conservation) and degree 1 (removing geocenter motion) were set to zero. Finally, GLDAS and NCEP SH representations were evaluated on a global 1° × 1° grid.

3. Results

3.1. GRACE and Climate Models Estimates

[13] Average August and September [(August + September)/2] TWS changes are used to measure the 2005 Amazon drought. The drought is at its maximum during these two months, and GRACE observations are available for August and September starting in 2002. Figure 1 shows GRACE (August/September) TWS change relative to the mean in South America for 2002 through 2007. In 2005 (Figure 1d), a minimum in TWS is evident (in the region circled by a gray curve). The Orinoco basin (to the north of the Amazon) shows a significantly wetter 2007 (Figure 1f).

[14] Figure 2a displays the difference between the 2005 (August/September) average and the mean (August/September)

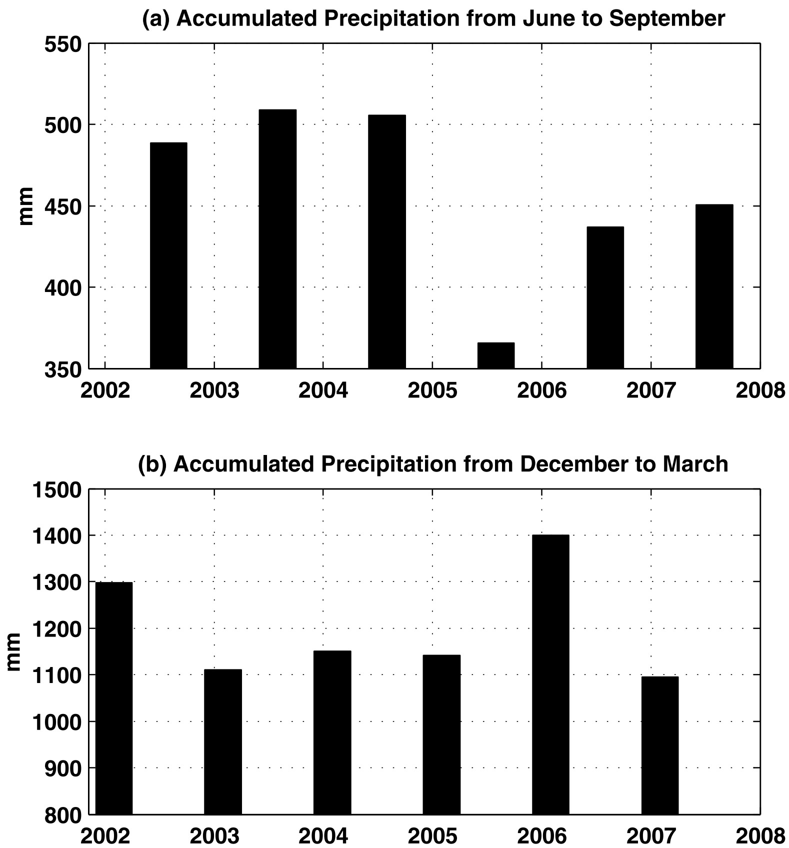

Figure 4. (a) Accumulated precipitation in the central Amazon region (marked by the red box in Figure 2a) during June to September based on GPCP data. (b) Accumulated precipitation in the central Amazon region during December to March based on GPCP data.

determined from the other 5 years. This indicates a GRACE-observed deficiency around 8–9 cm basin wide for 2005, or approximately $\sim$515 km^3 of water (integrated over the entire Amazon basin). Figures 2b and 2c show 2005 (August/September) anomalies relative to the other 5 years from NCEP and GLDAS, respectively. NCEP anomalies for 2005 are near zero, while those from GLDAS are larger, though smaller than the tens of cm seen in Figure 2a.

[15] We examine in more detail a $5^\circ \times 5^\circ$ region (Figure 2a, red box) near the center of the 2005 drought region evident in Figure 2a. Average TWS time series (average equivalent water height) for this entire region are calculated from GRACE, NCEP and GLDAS, and compared in Figure 3a. GRACE shows a strong seasonal signal with peak-to-peak amplitudes up to 70 cm, with additional nonseasonal variability. Near the end of 2005, GRACE TWS diminishes (relative to other years), indicating drought. Both NCEP and GLDAS show strong seasonal variation, but with magnitudes about one half of GRACE. Both show significantly less nonseasonal variability.

[16] Annual and semiannual sinusoids were fit by unweighted least squares and removed from each of the three time series, with results shown in Figure 3b. Additionally, we removed from the GRACE series a 161-day S2 tide alias [*Knudsen*, 2003] determined by least squares. The S2 alias amplitude (in this GRACE time series) is $\sim$1 cm, as compared to $\sim$25 cm for the annual component. In Figure 3b, GRACE shows a steady TWS decrease of about 14 cm, starting in March/April 2005 through August/September, marking a clear anomaly. NCEP and GLDAS series each show some TWS decrease in the same period, but the change does not appear unusual in the context of variations over the full 6 year time series.

[17] Estimates of GRACE noise (error bars in Figure 3b) are determined from root-mean-square (RMS) variability over tropical oceans (20°S–20°N), a region in which true mass variability (GRACE signal) is probably near zero, as barotropic ocean mass changes have been removed in GRACE dealiasing process [*Bettadpur*, 2007b]. Therefore residuals over the ocean could approximately represent residual errors of GRACE data (plus some unmodeled baroclinic ocean signals) [*Wahr et al.*, 2004]. Another estimate of GRACE error [*Wahr et al.*, 2006] is based on RMS residual of GRACE variability over land after subtracting seasonal sinusoids and smoothing, though this overestimates GRACE errors when there is significant nonseasonal (nonsinusoidal) variability, as evident in Figure 3b. However, after removing longer-period interannual variability from GRACE data, the two error bar estimates are similar (2.4 cm from ocean residuals versus 2.9 cm from land residuals).

3.2. Other Observational Evidences

[18] To validate GRACE-observed significant TWS decrease in during the 2005 Amazon drought, we analyze precipitation data from the Global Precipitation Climatology Project (GPCP) [*Adler et al.*, 2003], for the GRACE period.

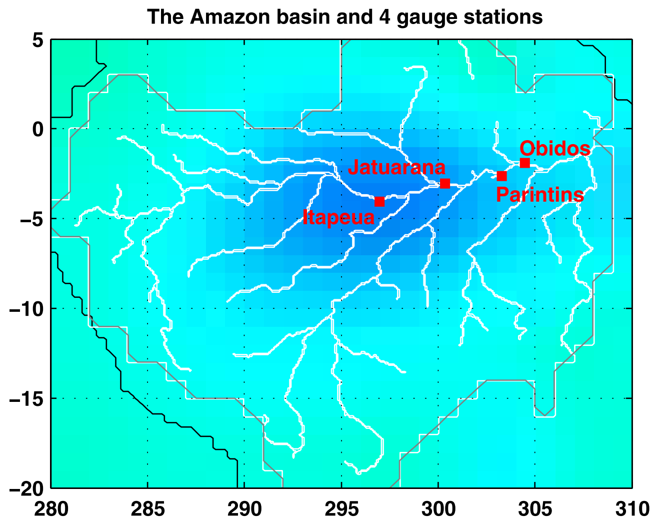

Figure 5. Location map of 4 river gauge stations (Itapeua, Jatuarana, Parintins, and Obidos) in the Amazon basin, superimposed by GRACE-observed TWS decrease in August/September 2005 (same as in Figure 2a).

We compute accumulated precipitation totals in the central Amazon region (Figure 2a, red box) in the 4 summer months (i.e., the sum of the 4 months' totals in June through September) for each of the 6 years from 2002 to 2007, and show the results in Figure 4a. The selection of summing June through September is based on the consideration that GRACE data show that the 2005 Amazon drought reached the peak (with minimum TWS) in August/September, and TWS change could reflect accumulated precipitation changes of a few months prior to the drought. The use of 4 months summation is arbitrary. We test the calculation in different cases (including using 3 and 6 months) and all show the least amount of accumulated precipitation in 2005, while the 4 months summation appears to show the most distinctive drop of accumulated summer precipitation in 2005. Similar 4-monthly totals for the same region, but for December to March are presented in Figure 4b. Clearly, in the summer 2005, the central Amazon region recorded significantly less precipitation (up to ~14 cm less) than any other year (during the period 2002 to 2008), consistent with GRACE observations, as well as reports of the 2005 drought severity cited earlier.

[19] GRACE time series (Figures 3a and 3b) indicate the 2005 drought had ended by the end of 2005 (or beginning of 2006), and the central Amazon region actually experienced a wetter (as compared to other years) winter season in early 2006. This is also consistent with GPCP precipitation data (Figure 4b), as the December–March precipitation total (in the central Amazon region) in 2005 is significantly less (up to 30 cm) than other years.

[20] To further verify GRACE measurements, we examine daily water-level data of 4 selected river gauges in the Amazon basin (see Figure 5). Among the 4 river gauge stations, Itapeua and Jatuarana are located close to the center of the TWS decrease observed by GRACE, and Parintins and Obidos are spread on the down stream side. To better focus on nonperiodic variations, we remove annual and semiannual variations from the 4 water-level time series (at the 4 gauges marked in Figure 5) using unweighted least squares fit, and show the nonseasonal water-level time series in Figure 6.

[21] Each of the 4 gauges show a clear drop of water level in the summer 2005, bottomed in around August and September, while Itapeua shows the largest water level decrease of up to ~4.8 m (with respect to the 6-year temporal mean). In situ water-level data at these 4 river gauge stations provide additional verification of the significant central Amazon TWS decrease in 2005 as observed by

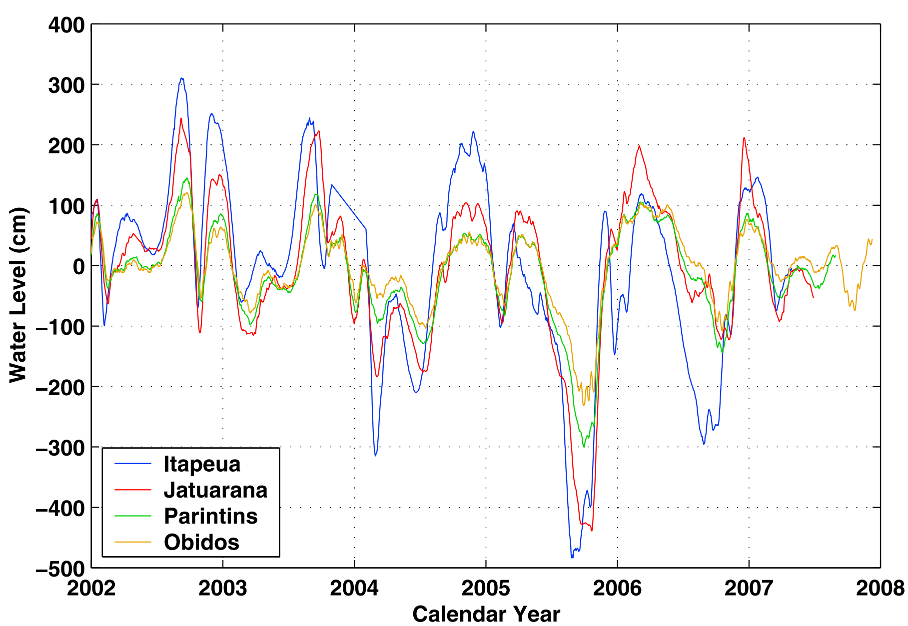

Figure 6. Nonseasonal daily water-level change at 4 selected river gauge stations marked in Figure 5. Annual and semiannual variations have been removed from these time series using unweighted least squares fit.

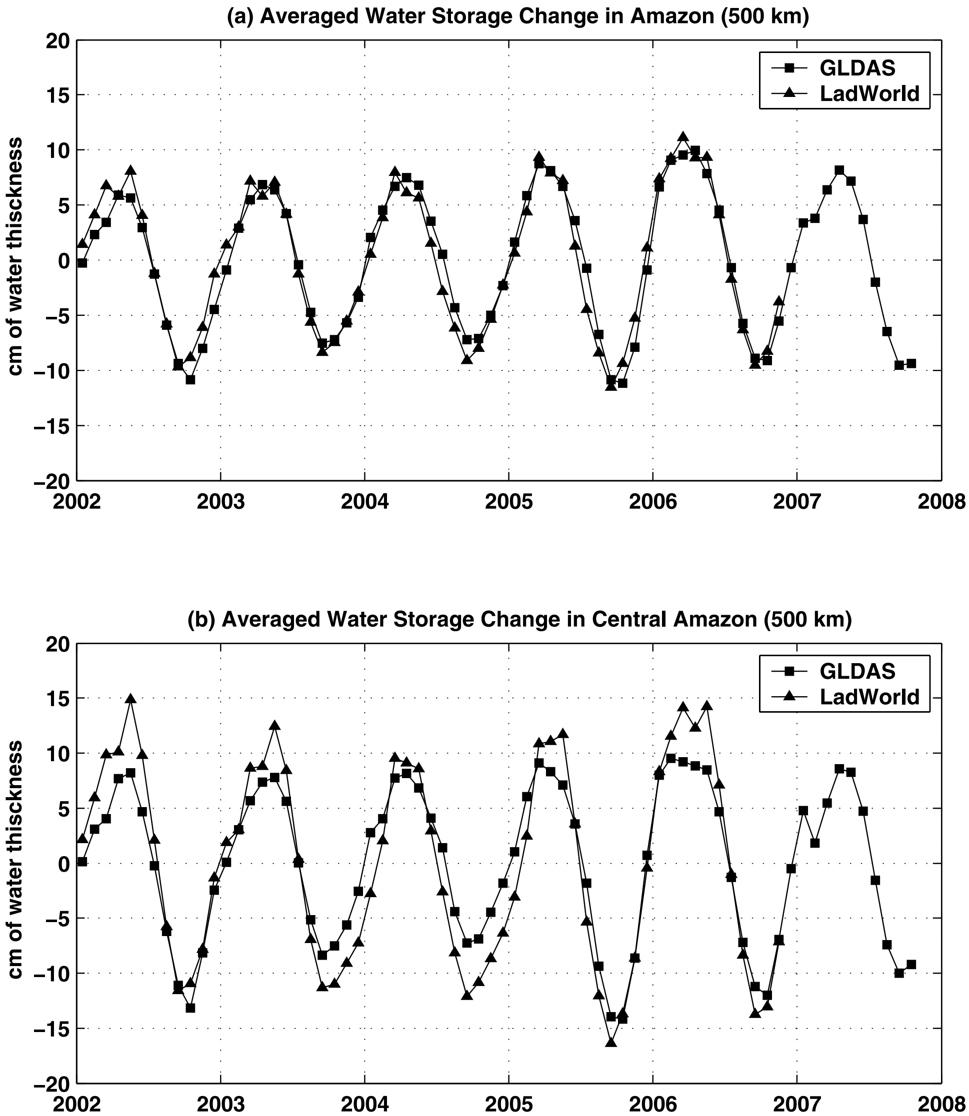

Figure 7. (a) Comparison of GLDAS and LadWorld estimated TWS changes in the Amazon basin (averaged over the entire basin). A 500-km Gaussian smoothing is applied to both data sets. (b) Comparison of GLDAS and LadWorld estimated TWS changes in the central Amazon area (average within the red box marked in Figure 2a).

GRACE, although quantitative comparisons (between GRACE and in situ river gauge data) are difficult because of different representations of the two different quantities. We see a gradual decease in magnitudes of the water-level drops among the 4 gauges, from ~4.8 m at Itapeua, ~4.4 m at Jatuarana, ~3 m at Parintins, to ~2 m at Obidos (Figure 6). This is consistent with the spatial TWS variation feature observed by GRACE (Figure 5). In situ water-level data also indicate that the 2005 Amazon drought had ended by the end of 2005 and by February or March 2006, the central Amazon region was actually wetter than normal (see Figure 6), also consistent with GRACE observations and GPCP precipitation data.

4. Discussion and Conclusions

[22] GRACE RL04 time series clearly indicate a significant TWS deficit accompanying the 2005 Amazon drought, on the order of 14 cm of water equivalent in the central Amazon. GRACE time series indicate the drought peaked in the period August to September 2005, and was relieved by the beginning of 2006, consistent with independent precipitation observations and in situ water-level measurements.

[23] NCEP and GLDAS land surface models significantly underestimate TWS change in the central Amazon relative to GRACE. These two models show only half the seasonal variability of GRACE observations, and both lack significantly diminished TWS associated with the 2005 drought. Unfortunately, there are no in situ TWS measurements to directly validate GRACE estimates. GPCP precipitation data are helpful for understanding TWS changes, but are not directly comparable to GRACE observations because they do not account for other elements affecting TWS. GPCP data do show diminished precipitation during the summer of 2005, consistent with GRACE time series.

Considering these limitations, this study demonstrates the unique strength of GRACE observations in monitoring droughts and floods via associated large spatial scale TWS changes. Additionally, GRACE observations provide independent measures of TWS for calibrating, evaluating, and improving climate and land surface models.

[24] Both the GRACE estimate of the 2005 TWS deficit (Figure 3b) and the discrepancy between GRACE and model estimates of seasonal variability (Figure 3a) greatly exceed estimated errors. Spatial leakage errors (due to filtering and limited SH range) are not likely causes of differences, given that similar filtering has been applied to all data sets. Lack of a ground water component in NCEP and GLDAS may partially account for differences between GRACE and model estimates, but is probably not a major cause [*Niu et al.*, 2007].

[25] To further prove this speculation, we show in Figure 7 the comparison of GLDAS TWS estimates and similar estimates from the LadWorld land surface model, which includes the groundwater component [*Milly and Shmakin*, 2002]. LadWorld TWS data (from the Fraser version, see information at http://www.gfdl.noaa.gov/~pcm/project/ladworld.htm for details) represent the sum of soil (of the top 6 m), water equivalent snow, and groundwater, and follow the same data processing (e.g., smoothing and truncation) as used in GLDAS data. For Amazon basin-wide average, GLDAS and LadWorld show very similar TWS estimates, even though groundwater is modeled in LadWorld. However, in the central Amazon area (marked in Figure 2a), LadWorld indeed show notably larger TWS variability than GLDAS (and the differences are considerably larger when no smoothing is applied). The increased TWS variability of LadWorld estimates is still significantly smaller than GRACE observations (at both seasonal and nonseasonal time scales), suggesting that groundwater is important but may not be the major contributor to models' underestimation of TWS changes in Amazon.

[26] A recent study [*Zeng et al.*, 2008b] has compared GRACE estimated TWS change in the Amazon basin with a few models' estimates and some other estimates based on water conservation equation using modeled moisture convergence minus observed runoff (MCR) or using observed precipitation minus observed runoff and modeled evapotranspiration (PER), and indicates that the PER estimate shows significantly larger seasonal variability (in the Amazon basin) than both models and MCR estimates and agrees well with GRACE data. This appears to indicate that, given the parameterizations of current land surface models, the more 'traditional' PER method can better depict TWS changes, at least in the Amazon basin.

[27] Model and GRACE estimates are more similar in other major basins than in the Amazon (e.g., the La Plata to the south), although model TWS changes are consistently smaller than GRACE estimates in the La Plata as well. Because the Amazon is the largest river basin in the world, estimated TWS is likely to be least affected by GRACE's spatial resolution limitations. On the other hand, neither model appears to do a good job of describing TWS variability in this basin. One reason may be that most macrohydrological models (including NCEP, GLDAS, and LadWorld) do not consider horizontal transport of water, implying instantaneous runoff. In very large basins, such as the Amazon, precipitation may actually be retained for some time (in lakes, wet lands, and shallow reservoirs), leading to underestimation of TWS change. This suggests that proper modeling of the terrestrial water cycle within the Amazon will likely require additional consideration of complexity of its river systems, vegetation, soils, and floodplains.

[28] **Acknowledgments.** The authors are grateful to Anny Cazenave and an anonymous reviewer for their insightful comments, which led to improved presentation of the results. This research was supported by NASA's Solid Earth and Natural Hazards and GRACE Science Program (NNG04GF10G, NNG04G060G, NNG04GF22G, and NNG04GP70). The authors would like to thank Flavio Vaz for providing the river gauges water-level data.

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