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ORIGINAL ARTICLE

Annual variations in water storage and precipitation in the Amazon Basin

Bounding sink terms in the terrestrial hydrological balance using GRACE satellite gravity data

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Abstract We combine satellite gravity data from the gravity recovery and climate experiment (GRACE) and precipitation measurements from the National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Center's (CPC) Merged Analysis of Precipitation (CMAP) and the Tropical Rainfall Measuring Mission (TRMM), over the period from mid-2002 to mid-2006, to investigate the relative importance of sink (runoff and evaporation) and source (precipitation) terms in the hydrological balance of the Amazon Basin. When linear and quadratic terms are removed, the time-series of land water storage variations estimated from GRACE exhibits a dominant annual signal of 250 mm peak-to-peak, which is equivalent to a water volume change of $\sim$1,800 km^3. A comparison of this trend with accumulated (i.e., integrated) precipitation shows excellent agreement and no evidence of basin saturation. The agreement indicates that the net runoff and evaporation contributes significantly less than precipitation to the annual hydrological mass balance. Indeed, raw residuals between the de-trended water storage and precipitation anomalies range from $\pm$40 mm. This range is consistent with stream-flow measurements from the region, although the latter are characterized by a stronger annual signal than our residuals, suggesting that runoff and evaporation may act to partially cancel each other.

Keywords Gravity recovery and climate experiment (GRACE) · Tropical rainfall measuring mission (TRMM) · CPC merged analysis of precipitation (CMAP) · Hydrological balance · Amazon Basin · Land water storage

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1 Introduction and background

Attempts to understand the details of the global hydrological cycle challenge our ability to accurately monitor the movement of deep ground water, the complex flow of surface waters, and the coupling of land, ocean and atmosphere through evaporation and precipitation. However, relatively new space-based measurements, such as the Gravity Recovery and Climate Experiment (GRACE) and the Tropical Rainfall Measuring Mission (TRMM), are yielding unprecedented constraints on both global and regional hydrological mass balances.

The twin GRACE satellites, launched in March 2002, have generated monthly maps ($\sim$30 days) of the Earth's gravitational field that allow one to infer surface mass anomalies (Swenson and Wahr 2002) and constrain continental hydrology (e.g., Rodell et al. 2004; Tapley et al. 2004; Wahr et al. 2004). GRACE has recently been used to estimate ground water variations in several major river basins including the Mississippi River basin (Rodell et al. 2004), the

Yangtze River basin (Hu et al. 2006), the Zambezi River basin (Winsemius et al. 2006), the Congo Basin (Crowley et al. 2006) and the Amazon Basin (Tapley et al. 2004; Syed et al. 2005). In particular, Tapley et al. (2004) estimated a large seasonal trend in water storage over South America and, moreover, they were able to distinguish the Amazon Basin from smaller river systems to the north. More recently, there have been a variety of efforts to bring other data sets to bear so as to constrain source (precipitation) and sink (runoff and evaporation) terms in the mass balance.

Syed et al. (2005) estimated Amazon Basin runoff by combining GRACE data (September 2002 to July 2004) with precipitable water and vapor flux divergence data from the European Centre for Medium-Range Forecasts (ECMWF) within the framework of a full (both land and atmosphere) hydrological mass balance. A comparison of their estimates with discharge data from the Obidos river (Brazil) gauging station showed reasonable qualitative agreement, though this discharge would only account for a portion of the total surface runoff.

Liu et al. (2006) analyzed GRACE and TRMM data, as well as ocean surface wind vectors measured by QuikSCAT and precipitable water measured by the Special Sensor Microwave/Imager (SSM/I), to consider the annual water balance in South America over the same time-period as Syed et al. (2005). The various estimated components of the hydrological cycle (mass change rate, moisture influx, river discharge) were found to satisfy the expected terrestrial balance. Furthermore, the annual rate of change of water storage in South America was in phase with the variation in rainfall. According to Liu et al. (2006, p. 2), this correlation is to be expected, since in '... large geographic regions, where the variation of (evaporation) E and surface/groundwater outflow are small, (precipitation) P should dominate the annual variation of water storage...'.

In this paper, we use a longer time-series of GRACE data (April 2002 to May 2006), together with precipitation data (from both TRMM and the Climate Prediction Center's (CPC) Merged Analysis of Precipitation, CMAP), to quantify the extent to which precipitation dominates the annual water storage variation. To put it another way, our goal is to bound the importance of sink terms (runoff, evaporation) in the annual hydrological balance within the Amazon Basin over the GRACE time-window.

2 Background theory: the terrestrial hydrological water balance

The governing equation for the terrestrial hydrological cycle may be written as

$$\frac{dW(t)}{dt} = P(t) - R(t) - E(t), \tag{1}$$

where W is the total land (surface and ground) water storage, P is the precipitation, R is the runoff, and E is the evaporation. The individual terms on the right-hand side (RHS) of Eq. (1) can be decomposed into constant, linear and residual (i.e., other time-variable) terms (Crowley et al. 2006).

For example, we may write for precipitation

$$P(t) = P_\circ + P_1 t + P^*(t). \tag{2}$$

If we adopt a similar symbolism for R and E, then integrating and rearranging terms in Eq. (1) yields

$$W(t) - (P_\circ - R_\circ - E_\circ)t - \frac{1}{2}(P_1 - R_1 - E_1)t^2 + C = \int_0^t [P^*(t') - R^*(t') - E^*(t')]\, dt', \tag{3}$$

where C is a constant of integration.

The left-hand side (LHS) of Eq. (3) may be represented as a single time-dependent function,

$$W^*(t) = W(t) - (P_\circ - R_\circ - E_\circ)t - \frac{1}{2}(P_1 - R_1 - E_1)t^2 + C, \tag{4}$$

which can be numerically determined by removing the linear and quadratic trends from a time-series of GRACE-derived monthly measurements of land water storage, $W(t)$. The total de-trended anomalous monthly output from the Amazon Basin can then be determined by substituting Eq. (4) into Eq. (3) and rearranging the terms to yield

$$\int_0^t [R^*(t') + E^*(t')]\, dt' = \int_0^t [P^*(t')]\, dt' - W^*(t), \tag{5}$$

where the de-trended precipitation time-series $P^*(t)$ in Eq. (5) (and Eq. 2) is derived from either the TRMM or CMAP database.

Thus, while total runoff and, in particular, evaporation are difficult to measure accurately, an estimate of their combined contributions to the terrestrial hydrological cycle within the Amazon Basin (LHS, Eq. 5) can be made by combining GRACE gravity data with CMAP or TRMM precipitation data.

Equation (5) does not solely represent an annual hydrological balance, since the terms denoted by an asterisk can include a spectrum of time variability (e.g., annual, semi-annual, etc.) An advantage of retaining all such terms is that the balance between water storage and integrated precipitation may vary across intra-annual frequencies. As an example, Crowley et al. (2006) have shown, using a similar analysis of the Congo Basin, that periods of anomalously large precipitation lead to basin saturation and a pulse of water outflow. Nevertheless, the residual defined by the

RHS of Eq. (5) can be further decomposed to isolate the contribution from annual trends alone.

3 Results

We have analyzed 42 gravity field solutions from the GRACE database (University of Texas at Austin, Center for Space Research, RL01 unconstrained solutions, available at http://podaac.jpl.nasa.gov/grace/daac/data/L2/csr/RL01/) that span the period April 2002 to May 2006. These solutions are represented in terms of fully normalised spherical harmonic decompositions. While most of the monthly data sets are truncated at spherical harmonic degree and order 120, several only include harmonics up to degree 70 due to GRACE passing through resonances (cf. Wagner et al. 2006). For the sake of consistency, and since signals above degree 70 are subject to increasingly large errors, a cut-off at degree 70 was adopted. As in Velicogna and Wahr (2005), the uncertain GRACE derived C_{20} coefficient time-series is replaced by the values derived from satellite laser ranging (SLR) (Cheng and Tapley 2004).

As an initial step in the analysis, we computed a monthly geoid ‘anomaly’ by removing the mean value of the 42 solutions from each of the individual datasets. These anomalies were then converted to equivalent surface mass anomalies using a mapping based on elastic Love number theory (Swenson and Wahr 2002). As an example of this procedure, the calculated surface mass anomalies for the months of April 2005 and October 2005 are shown in Fig. 1.

A regional average of the surface mass anomalies was computed by defining a mask with perimeter shown by the solid line in Fig. 2. (The geometry of the mask is taken from Eltahir et al. 2004.) To reduce errors associated with the higher degree components of the GRACE solutions, a Gaussian smoothing was applied to the mask. In this regard, we adopted a standard half-width for the averaging kernel of 600 km; the resulting averaging mask is shown in Fig. 2 [See Swenson and Wahr (2002) for details on the averaging function].

Figure 3 (red circles with error bars) shows the GRACE-derived time-series of land water storage after removal of the constant, linear and quadratic trends (i.e., the term $W^*(t)$ on the RHS of Eq. 5). The error bars on each of the monthly values were computed using Eq. (4) of Wahr et al. (2006) and the error files for the GRACE Stokes coefficients. The water storage shows a dominant annual signal with a peak-to-peak range equal to ~250 mm of equivalent water thickness. The Amazon Basin covers approximately 7 million km^2, and this annual variation thus represents a volume change of ~1,800 km^3 of water.

Next, we turn to the two precipitation data sets, TRMM and CMAP, which differ in their spatial resolution and coverage. TRMM is a grid covering the tropics and has a spatial resolution of 0.25°. In contrast, CMAP involves a global grid with a 2.5° resolution. To be consistent with the GRACE data analysis, spatial averages of the precipitation values were computed using the mask shown by the color contours in Fig. 2. We have adopted the CMAP and TRMM data sets to generate estimates of the integral of the de-trended precipitation time-series, i.e., the first term on the RHS of Eq. (5), for a period extending from November 2001 to March 2006. Both of these time-series are also shown in Fig. 3 (solid and dashed blue lines for CMAP and TRMM data, respectively).

The two precipitation results are consistent and a comparison between either time-series and the GRACE-derived water storage estimates indicates a high level of agreement. As suggested by Liu et al. (2006) on the basis of data up to mid-2004, the land water storage and integrated precipitation are strongly in-phase. Moreover, we find that the amplitudes are in close accord, indicating that the annual variation of the water storage within the Amazon Basin is strongly dominated by precipitation; that is, the net annual signal from the sink terms, runoff and evaporation, appears to be a significantly smaller contributor to the hydrological mass balance.

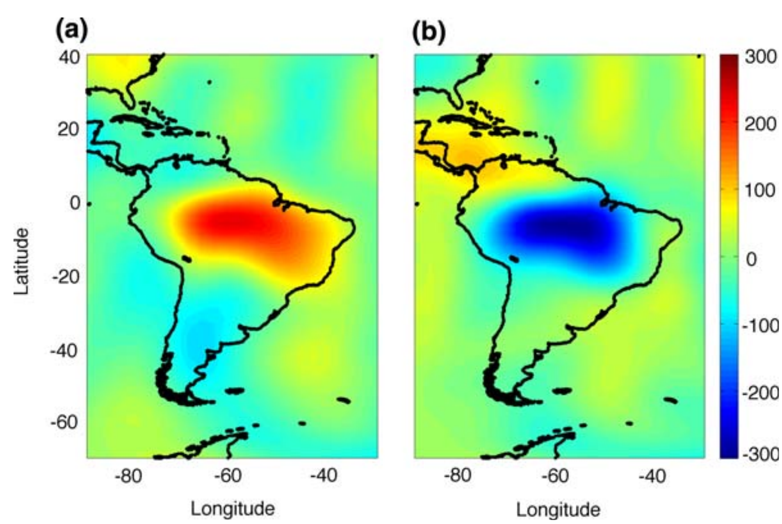

Fig. 1 Total surface mass anomaly, in units of mm of equivalent water thickness, over South America for the month of **a** April 2005, and **b** October 2005 (after Gaussian smoothing of the GRACE data with an averaging kernel half-width of 600 km)

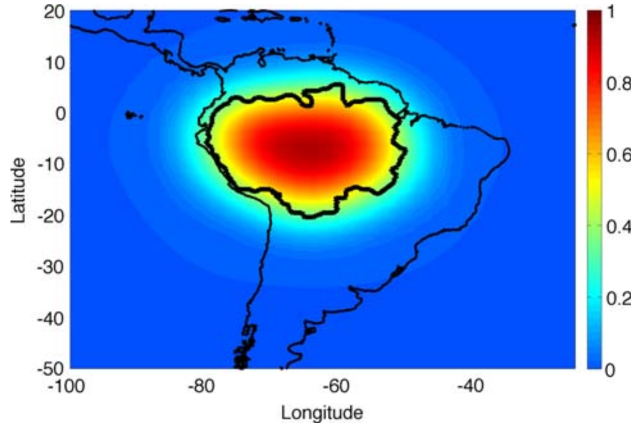

Fig. 2 Geographic mask adopted for the Amazon Basin analysis. The *solid line* is the perimeter of the Amazon Basin watershed. The *color contours* represent the averaging function associated with this region after Gaussian smoothing using an averaging kernel half-width of 600 km

To quantify this argument, Fig. 4 shows the residual between the integrated (CMAP) precipitation curve and the land water curve (i.e., the RHS of Eq. 5), as well as the best-fitting annual component for this residual. This residual, which varies from ∼±40 mm, provides an estimate of the combined contribution of (integrated) runoff plus evaporation to the de-trended hydrological balance. In this regard, the estimated best-fitting annual trend has a peak-to-peak amplitude of ∼20 mm.

Stream-flow data for the Amazon Basin (see, e.g., Syed et al. 2005; Liu et al. 2006) indicate annual magnitudes of 60–120 mm peak-to-peak for the integrated run-off over a 2-year period beginning September, 2002. This range is consistent with the total variation in the residuals in Fig. 4. However, the stream-flow data are characterized by a dominant annual variation, and in this sense the trends are larger (by a factor of three) than the annual component shown in Fig. 4. It is likely that a partial cancellation between the time-varying components of evaporation and runoff account for this discrepancy, and this warrants future investigation.

In contrast to our analysis of the Congo Basin in Africa (Crowley et al. 2006), there is no indication from the 4-year time variation in Figs. 3 and 4 that the water storage becomes saturated due to precipitation influx.

4 Conclusion

We have used gravity measurements from the GRACE satellite mission and precipitation data obtained from TRMM and CMAP to estimate annual and intra-annual variations in water storage and precipitation within the Amazon Basin from mid-2002 to mid-2006. Specifically, we have compared integrated precipitation data to water storage estimates from GRACE, where the monthly time-series have had best-fitting constant, linear and quadratic terms removed (see Eqs. 4, 5).

This comparison shows excellent agreement throughout the 4-year time-series and no evidence of basin saturation. The residuals between the two de-trended time-series range between ±40 mm, while the peak-to-peak range in the individual time series is ∼250 mm of equivalent water thickness.

We conclude that the annual and intra-annual mass balance within the Amazon Basin primarily involves water storage and precipitation, while the net contribution from runoff and evaporation is relatively smaller. The most likely explanation for the latter is that runoff and evaporation act to at least partially cancel one another, though we cannot rule out that both terms are small on the basis of the data considered herein.

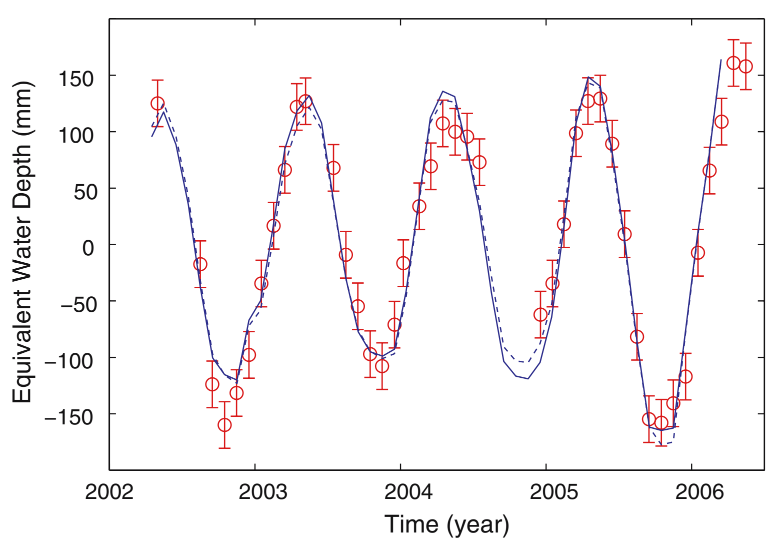

Fig. 3 Water storage anomalies for April 2002 to May 2006, with linear and quadratic terms removed, estimated from GRACE satellite gravity data over the Amazon basin (red circles; second term, RHS of Eq. 5) and integrated de-trended monthly precipitation for the Amazon Basin, calculated from CMAP and TRMM (*solid* and *dashed blue lines*, respectively; first term, RHS of Eq. 5)

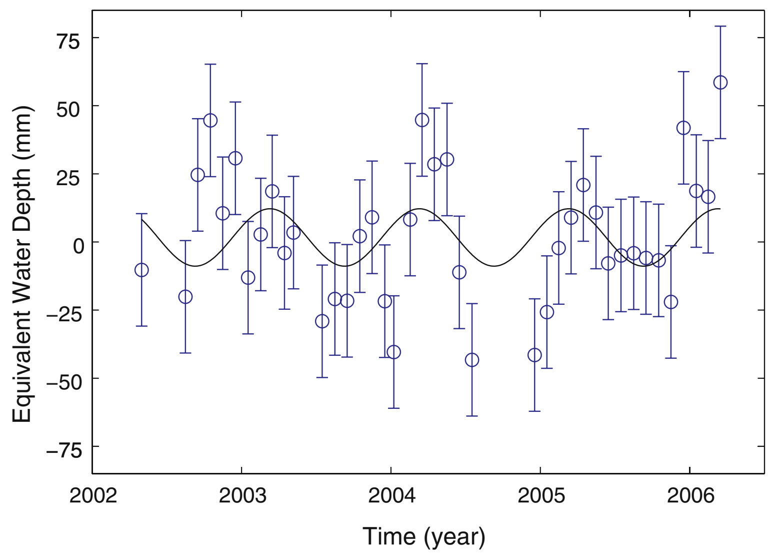

Fig. 4 Difference between the integrated (CMAP) precipitation and the GRACE-estimated land water storage time-series in Fig. 3 (*blue circles* with error bars; these errors are based on uncertainties in the water storage estimates, i.e., errors in the precipitation are not included), as well as the best-fitting annual trend to the residual (*solid black line*)

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