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Total basin discharge for the Amazon and Mississippi River basins from GRACE and a land-atmosphere water balance

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[1] Freshwater discharge along continental margins is a key Earth system variable that is not well monitored globally. Here we propose a method for estimating monthly river basin outflows based on the use of new GRACE satellite estimates of terrestrial water storage changes in a coupled land-atmosphere water balance. Using GRACE land water storage changes (which include changes in groundwater storage) in the water balance method results in more holistic estimates of basin discharge, which we call total basin discharge, that include not only streamflow, but the net of surface, groundwater and tidal inflows and outflows. The method was tested on the Amazon and Mississippi river basins, and could ultimately be applied to the major drainage regions and river basins of the globe. Estimated Amazon total basin discharge was well correlated with observed streamflow, but with a phase lag and underestimation of low flows. Estimated total basin discharge in the Mississippi river basin had a greater annual amplitude than observed streamflow, but showed good temporal covariance. Results for both basins highlight important differences between estimated total basin discharge and observed streamflow, at least part of which can be attributed to groundwater storage changes. Atmospheric moisture data and methods of GRACE data processing also contributed to the differences. **Citation:** Syed, T. H., J. S. Famiglietti, J. Chen, M. Rodell, S. I. Seneviratne, P. Viterbo, and C. R. Wilson (2005), Total basin discharge for the Amazon and Mississippi River basins from GRACE and a land-atmosphere water balance, *Geophys. Res. Lett.*, *32*, L24404, doi:10.1029/2005GL024851.

1. Introduction and Background

[2] Freshwater discharge from the continents is central to understanding a wide range of climatic, geomorphic, hydrologic and ecologic processes in the Earth system [*Famiglietti*, 2004]. Despite the importance of monitoring this critical flux, no comprehensive global discharge observing network for the world's major continental watersheds currently exists [*Alsdorf and Lettenmaier*, 2003]. Consequently, a consistent global picture of continental freshwater outflows remains elusive [*Famiglietti*, 2004].

[3] Here we define total basin discharge as the net surface and groundwater outflow from a watershed. While closely related to streamflow (channel) discharge in many regions of the world, it may differ considerably where floodplain and wetland flows are significant, where groundwater inflows and outflows are large, and in coastal watersheds, where submarine groundwater discharge and surface and groundwater inflows (e.g. tidal inflows, storm surges and salt water intrusion) can all play an important role in the water balance. Hence characterizing total basin discharge is an important step towards understanding the spatial-temporal dynamics of freshwater exchange at the land-ocean margin.

[4] Traditional stream gauging provides important information on the in-channel component of streamflow, but cannot measure groundwater discharge nor surface flow in braided channels or in inundated floodplains. Remote sensing of surface waters (i.e. lakes, reservoirs, rivers, wetlands, floodplains) offers a viable and potentially global-scale alternative to in situ gauge networks [*Smith*, 1997]. *Alsdorf and Lettenmaier* [2003] outline a plan for a hydrology-specific interferometric altimetry mission [*Rodriguez and Moller*, 2004] to measure surface water elevations, their derivatives in space and time, and its lateral extent. While this mission would primarily monitor terrestrial freshwater storage changes every 8 days, global river discharge (including both in-channel and overbank flow) would be a key derived product.

[5] In contrast, groundwater flow rates through large, continental river basin systems are largely unmonitored. In selected coastal regions, submarine groundwater discharge studies have shown that this flux can be as great as 40% of streamflow [e.g., *Cable et al.*, 1996; *Moore*, 1996]. *Zekster and Loaiciga* [1993] estimate that submarine groundwater discharge is about 6% of global annual discharge and can be significantly higher in some parts of the world. More generally, the magnitude and spatial-temporal variability of groundwater discharge in both interior and coastal basins remains an important unknown in the global water cycle.

[6] In this paper we present a method for estimating total basin discharge. Monthly estimates are produced by solving a combined land-atmosphere water balance equation [e.g., *Seneviratne et al.*, 2004]. The main contribution of the present work is the use of Gravity Recovery and Climate Experiment (GRACE) [*Tapley et al.*, 2004] satellite-based estimates of basin-scale terrestrial water storage change

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[*Chen et al.*, 2005; *Rodell et al.*, 2004; *Wahr et al.*, 2004] in the combined water balance equation. The GRACE mission is providing the first direct observations of monthly water mass changes for large river basins (which include groundwater storage changes): previous water balance studies to estimate discharge were forced to assume that basin-scale storage changes were equal to zero and consequently were restricted to long-term (annual mean) applications [*Dai and Trenberth*, 2002; *Oki et al.*, 1995; *Seneviratne et al.*, 2004].

[7] Given the constraints of the GRACE water storage change estimates to large river basins and monthly and longer time scales, we apply the water balance approach to two of the world's largest watersheds, the Amazon and the Mississippi River basins, to explore the potential of this method for estimating monthly total basin discharge. Results are compared to streamflow measurements in each of the basins with implications for the contributions of surface and groundwater flows beyond in-channel discharge. While the water balance method using GRACE observations of terrestrial water storage changes cannot approach the temporal (near weekly) and spatial (tens of meters) resolution of a future interferometric altimetry mission for surface water discharge, it has the potential to complement such data by immediately providing an integrated measure of surface and groundwater outflows on monthly and longer-term time scales for the world's major drainage regions [*Graham et al.*, 1999] and river basins. The work described here also demonstrates the potential for future, higher-resolution gravity missions for providing critical hydrologic information (snow, surface and groundwater storage changes; evapotranspiration and total basin discharge fluxes) at smaller spatial scales than are possible with the current GRACE mission.

2. Methods and Data

2.1. Combined Land-Atmosphere Water Balance

[8] The basin-scale terrestrial water balance equation is

$$\frac{\partial S}{\partial t} = P - ET - R \tag{1}$$

where S represents land water storage, and P and ET are the basin-wide totals of precipitation and evapotranspiration. Here we take R to represent total basin discharge, or the net surface and groundwater outflow. The time period ∂t is taken as one month for consistency with our GRACE land water storage estimates (see below).

[9] Similarly a monthly water balance for the atmospheric branch of the hydrologic cycle is given by

$$\frac{\partial W}{\partial t} = ET - P - div\mathbf{Q} \tag{2}$$

$$W = \int_{p_T}^{p_S} q \frac{dp}{g} \tag{3}$$

$$\mathbf{Q} = \int_{p_T}^{p_S} q\mathbf{V} \frac{dp}{g} \tag{4}$$

where W is the vertically-integrated precipitable water, div**Q** is the divergence of the vertically-integrated average atmospheric moisture flux vector, p_s and p_T are the pressure at the surface and the top of the atmosphere, q is the specific humidity, g is gravitational acceleration and **V** is the horizontal wind vector.

[10] Equation (1) could be solved directly for R. However, high uncertainties of ET [*Rodell et al.*, 2004] limit the utility of estimating R using (1) alone. An alternative approach is to combine (1) and (2), eliminating the P and uncertain ET terms. Solving for R, the combined land-atmosphere water balance equation is

$$R = -\frac{\partial S}{\partial t} - \frac{\partial W}{\partial t} - div\mathbf{Q} \tag{5}$$

[11] In this work we applied equation (5) to the Amazon and Mississippi river basins. Basin masks were prepared for each watershed and the land water storage, precipitable water and vapor divergence terms were prepared as described below.

2.2. Data

2.2.1. Land Water Storage Changes From GRACE

[12] Since its launch in March 2002, GRACE has been mapping Earth's temporal gravity field with a high degree of accuracy at monthly time scales [*Tapley et al.*, 2004; *Wahr et al.*, 2004]. To date the GRACE project has released 22 gravity field solutions as sets of Stokes coefficients up to degree and order 120, at irregularly spaced ~30 day periods, through July 2004.

[13] Global fields of monthly water storage changes were computed following *Wahr et al.* [1998] and using Gaussian smoothing with averaging kernel half-width of 1000 km. From these global fields water storage changes for the Amazon and Mississippi basins were extracted. *Chen et al.* [2005] provides additional detail on the processing used to extract basin-scale water storage changes. In general, GRACE estimates of basin-scale water storage changes agree well with global land hydrological models [*Chen et al.*, 2005; *Rodell et al.*, 2004; *Wahr et al.*, 2004] and observations [*Rodell et al.*, 2004].

[14] In this study, only consecutive months of GRACE data were used (18 total), including Sept., Oct., Nov. 2002; Mar., Apr., May, Aug., Sept., Oct., Nov., Dec. 2003; and Jan., Feb., Mar., Apr., May, Jun., Jul. 2004. For consistency with the timing of GRACE data collection, storage changes are considered to have occurred between the mid-point (nominally day 15) of each month.

2.2.2. Precipitable Water and Vapor Flux Divergence From ECMWF

[15] Daily estimates of div**Q** and W were computed from European Centre for Medium-Range Forecasts (ECMWF) operational forecast analyses http://www.ecmwf.int/research/ifsdocs/CY25r1/index.html;http://www.ecmwf.int/products/data/operational_system/evolution/index.html]. The monthly $\partial W/\partial t$ term was taken as the difference between the basin-average values on day 15 of each month. The monthly *div***Q** was computed by summing the daily

basin-average values. *Rodell et al.* [2004] and *Swenson and Wahr* [2005] used alternative methods for summing daily hydrologic fluxes that are also consistent with the timing of GRACE data collection. The impact of the different summation methods on estimated R was not explored here and warrants further attention.

2.2.3. River Discharge Data

[16] Daily streamflow discharge observations for the Amazon basin were obtained for the Obidos (Brazil) gauging station from Agência Nacional de Águas (M. C. R. Cordeiro, personal communication, 2005). Similar measurements for the Mississippi basin at the Vicksburg, Mississippi (USA) station were obtained from the U.S Army Corps of Engineers (M. Richter, personal communication, 2005). Monthly discharge for each basin was computed as the sum of the daily discharge.

2.3. Uncertainties

[17] Following *Rodell et al.* [2004] we computed the relative uncertainty in a monthly estimate of R, υ_R, as

$$\upsilon_R = \frac{\sqrt{\upsilon^2_{\frac{\partial S}{\partial t}}\left(\frac{\partial S}{\partial t}\right)^2 + \upsilon^2_{\frac{\partial W}{\partial t}}\left(\frac{\partial W}{\partial t}\right)^2 + \upsilon^2_{div\mathbf{Q}}(div\mathbf{Q})^2}}{-\frac{\partial S}{\partial t} - \frac{\partial W}{\partial t} - div\mathbf{Q}} \tag{6}$$

where $\upsilon^2_{\frac{\partial S}{\partial t}}$, $\upsilon^2_{\frac{\partial W}{\partial t}}$, and $\upsilon^2_{div\mathbf{Q}}$ are the relative uncertainties in the monthly GRACE land water storage change, precipitable water storage change and net divergence terms. The 95% confidence limits on estimated R were computed as R± υ_RR.

[18] The term $\upsilon\frac{\partial S}{\partial t}$ represents the absolute error of a GRACE estimate of monthly water storage change. *Wahr et al.* [2004] found that the error in monthly storage anomalies for the Amazon, Mississippi and Bay of Bengal basins ranged between 1.0 cm and 1.5 cm. We use a value of 1.25 cm here and multiply by $\sqrt{2}$ to account for month-to-month changes. Relative uncertainties of the monthly precipitable water and divergence terms are not well characterized at present. We assume values of 10%, although larger values may be more accurate (see Mississippi basin results below). The relative error in observed Amazon and Mississippi streamflow is assumed equal to 15% (M. C. R. Cordeiro and M. Richter, personal communication, 2005).

3. Results and Discussion

[19] Figure 1 shows that estimated total basin discharge and observed streamflow are in general agreement for the Amazon (mean observed streamflow, 9.86 cm; mean estimated R, 7.54 cm; RMSE, 3.85 cm). However, while the peak flows are similar in magnitude, the annual cycles appear out of phase. Additionally, estimated low flows are lower than those observed. There are several possible reasons for these discrepancies. Perhaps most importantly, estimated total basin discharge, as discussed previously, is a fundamentally different quantity than in-channel streamflow measured at a gauging station. We will return to this point at the end of this section.

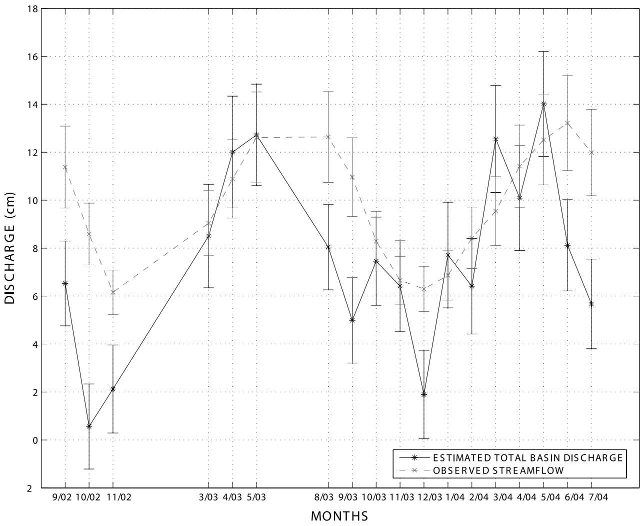

Figure 1. Monthly estimated Amazon total basin discharge (solid), streamflow (dashed) and uncertainties at Obidos, Brazil.

[20] Another important contribution to the difference seen in Figure 1 is that processing GRACE basin-scale water storage changes is a new and active area of research. For example, our ongoing research shows that as the length of the Gaussian smoothing radius increases, the phase of the GRACE water storage change signal shifts and its amplitude attenuates. After correcting for these effects, the phase of the "restored" water storage change signal is shifted forward by approximately one month. Accounting for both of these effects could explain much of the difference seen in Figure 1. A more complete understanding of GRACE data processing on these results will evolve as methods for estimating minimally-biased water storage changes mature. The contribution of the atmospheric moisture terms towards these differences is discussed below in the context of the Mississippi basin.

[21] Figure 2 shows that for the Mississippi, variability in estimated R often exceeds that shown by in-situ streamflow measurements (mean observed streamflow, 1.66 cm; mean estimated R, 1.21 cm; RMSE, 2.33 cm). The magnitude of the annual amplitude is roughly 2.5 cm for estimated R while only approximately 0.6 cm for observed streamflow. While a portion of this difference may be due to the difference between total basin discharge and streamflow, the overestimation of peak discharge and the negative low flow estimates are also consistent with previous studies that point to the atmospheric moisture data as an important source of errors in Mississippi basin water balance studies [*Roads and Betts*, 2000; *Seneviratne et al.*, 2004]. Exploration of the $\partial S/\partial t$, $\partial W/\partial t$ and $div\mathbf{Q}$ terms in (5) (not shown) reveals that for much of the time series, variations in estimated R closely follow those of $div\mathbf{Q}$. However, variations in both $div\mathbf{Q}$ and GRACE $\partial S/\partial t$ estimates are responsible for the variations in estimated R from April-July 2004. As in the case of the Amazon basin, use of the restored water storage change signals could also decrease the difference between estimated R and observed streamflow shown in Figure 2.

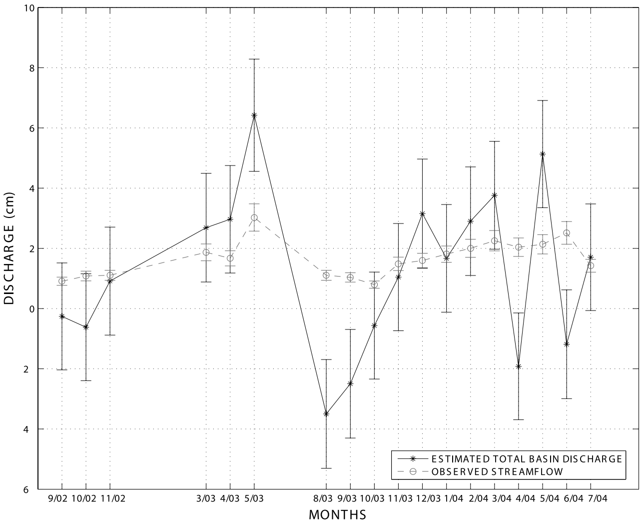

Figure 2. Monthly estimated Mississippi total basin discharge (solid), streamflow (dashed) and uncertainties at Vicksburg, Mississippi.

[22] However, since GRACE monitors changes in total water storage, it is observing both surface and groundwater storage changes, including groundwater inflows, outflows, and tidal inflows, none of which are modeled or accurately monitored by groundwater wells or stream gauging stations. As such, estimated total basin discharge R represents the true outflow from a watershed in a more holistic manner than a simple streamflow measurement at a particular channel cross-section. Consequently, important discrepancies in Figures 1 and 2 may also be related to unmonitored surface and groundwater inflows and outflows. The higher estimated peak flows in the Mississippi may well include true and unmeasured groundwater outflows. The average difference between estimated total basin discharge and observed streamflow (37% of average streamflow for the Mississippi; 31% for the Amazon) is within the range of the groundwater discharges reported by *Cable et al.* [1996], *Moore* [1996] and *Zekster and Loaiciga* [1993]. The underestimates of low flows in both basins may reflect real, unrecorded groundwater and surface water inflows. It is likely that for the first time, GRACE is monitoring, albeit with an integrated signal, the many difficult-to-measure surface and groundwater fluxes that we have included in R in (1), but that hydrologists have previously been forced to ignore.

4. Summary

[23] We presented estimates of Amazon and Mississippi total basin discharge using GRACE-derived terrestrial water storage changes in a combined land-atmosphere water balance. The method has the potential to provide an integrated monthly measure of both surface and groundwater outflows for large watersheds, and to complement current and future altimetry-based methods for monitoring surface water flows.

[24] The method was tested on the Amazon and Mississippi basins with promising results. Estimated Amazon total basin discharge was well correlated with observed streamflow, but with a phase lag and underestimation of low flows. Estimated basin discharge in the Mississippi river basin had a much greater annual amplitude than that observed, but showed good temporal covariance. Because we estimated basin discharge and not streamflow, we believe that the over (under) estimates of the peak (low) flows may in part represent unmonitored surface and groundwater fluxes that the GRACE mission may helping to identify. GRACE is providing new information on both surface and groundwater storage changes, which when combined, are larger than previous model-based estimates that do not include groundwater dynamics. When applied as in this study, the new GRACE data results in a more holistic measure of total basin discharge that includes not only streamflow, but other surface, groundwater and tidal inflows and outflows. Both atmospheric moisture and GRACE data also contributed to the differences in estimated total basin discharge and observed streamflow. Results suggest that further exploration of the method is warranted for other large drainage regions and basins around the globe, and to better characterize the factors responsible for the differences between estimated total basin discharge and observed streamflow.

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