Remote Sensing of Environment 115 (2011) 1588–1594

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Satellite-based estimates of groundwater storage variations in large drainage basins with extensive floodplains

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A R T I C L E   I N F O

Article history:
Received 29 July 2010
Received in revised form 17 January 2011
Accepted 1 February 2011
Available online 5 March 2011

Keywords:
Groundwater
Remote sensing
Hydrological modeling

A B S T R A C T

This study presents monthly estimates of groundwater anomalies in a large river basin dominated by extensive floodplains, the Negro River Basin, based on the synergistic analysis using multisatellite observations and hydrological models. For the period 2003–2004, changes in water stored in the aquifer is isolated from the total water storage measured by GRACE by removing contributions of both the surface reservoir, derived from satellite imagery and radar altimetry, and the root zone reservoir simulated by WGHM and LaD hydrological models. The groundwater anomalies show a realistic spatial pattern compared with the hydrogeological map of the basin, and similar temporal variations to local *in situ* groundwater observations and altimetry-derived level height measurements. Results highlight the potential of combining multiple satellite techniques with hydrological modeling to estimate the evolution of groundwater storage.

1. Introduction

The water cycle of large tropical river basins is strongly influenced by seasonal and interannual variability of rainfall and streamflow, affecting all the components of the water balance (Marengo, 2009; Ronchail et al., 2002). The Terrestrial Water Storage (TWS), which represents an integrated measurement of the water stored in the different hydrological reservoirs and is the sum of the surface water, root zone soil water, snowpack and groundwater, is a good indicator of the changes that occur in hydrological conditions globally and at basin scales. Nevertheless, TWS is difficult to measure due to the lack of *in situ* observations of the terrestrial hydrological compartments.

The Gravity Recovery And Climate Experiment (GRACE) mission, launched in 2002, detects tiny changes in the Earth's gravity field which can be related to spatio-temporal variations of TWS at monthly or sub-monthly time-scales (Tapley et al., 2004). Previous studies provide important information on changes in TWS over the Amazon (Chen et al., 2009; Crowley et al., 2008). Variations in groundwater storage can be separated from the TWS anomalies measured by GRACE using external information on the other hydrological reservoirs such as *in situ* observations (Yeh et al., 2006), model outputs (Roddel et al., 2009), or both (Leblanc et al., 2009). No similar studies have been undertaken yet for large river basins characterized by extensive wetlands or floodplains.

Although wetlands and floodplains cover only 6% of the Earth surface, they have a substantial impact on flood flow alteration, sediment stabilization, water quality, groundwater recharge and discharge (Bullock & Acreman, 2003; Maltby, 1991). Moreover, floodplain inundation is an important regulator of river hydrology owing to storage effects along channel reaches. Reliable and timely information about the extent, spatial distribution, and temporal variation of wetlands and floods as well as the amount of water stored is crucial to better understand their relationship with river discharges, and also their influence on regional hydrology and climate. Remote sensing techniques are a unique mean for monitoring large drainage basins climate and hydrology where *in situ* information is lacking (as, for instance, over floodplains and wetlands or for groundwater monitoring).

In this study, a new technique is proposed to derive the spatio-temporal variations of water volume anomalies in the aquifer of the Negro River Basin, a large tropical basin dominated by extensive floodplains (see Fig. 1a and b for its location). The Negro River Basin,

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doi:10.1016/j.rse.2011.02.003

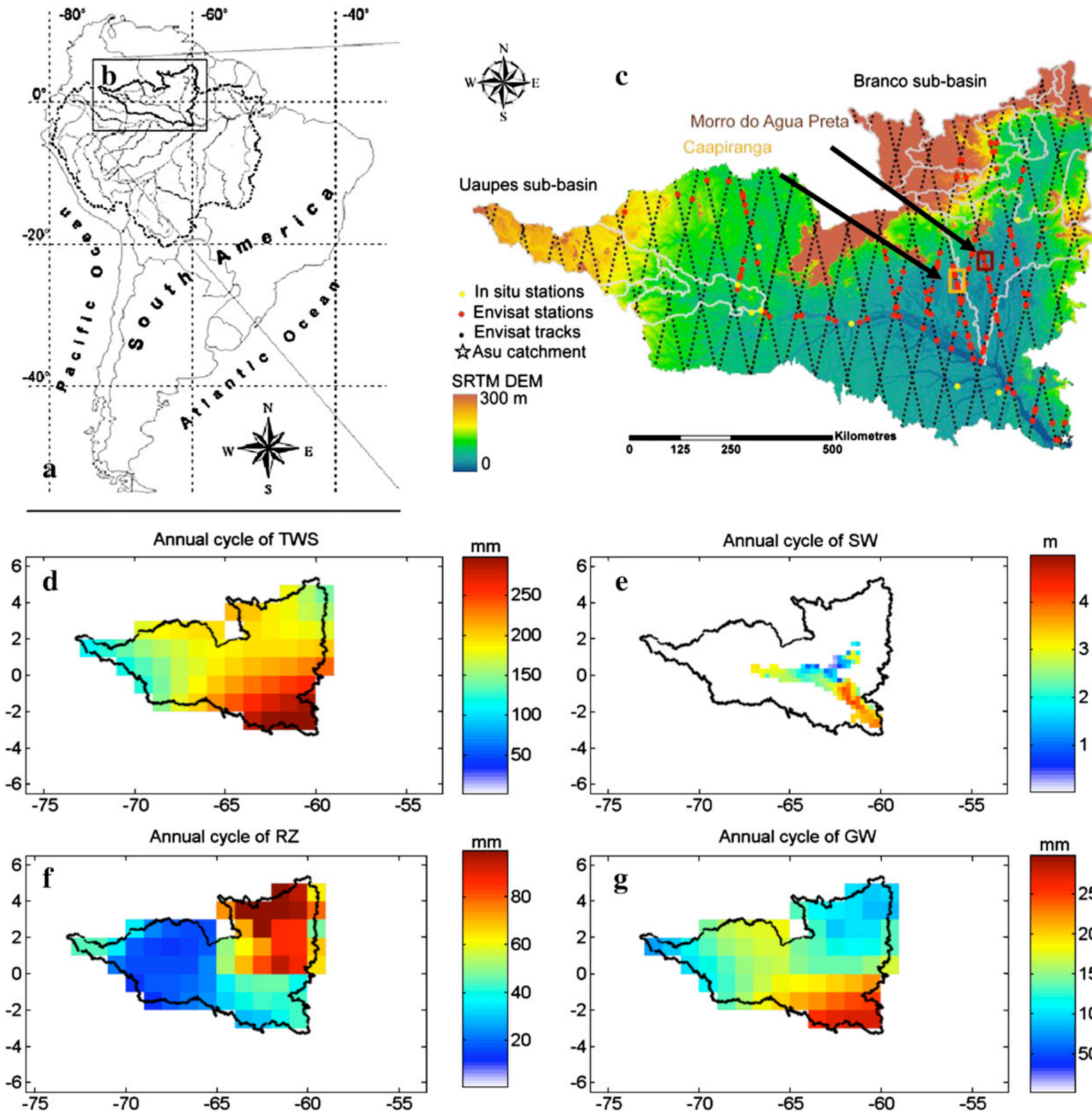

Fig. 1. a) Overview map of South America with the location of the Negro River Basin (b). c) Map of the Negro River sub-basin extracted from SRTM DEM. Each thin line of black dots represents an ENVISAT track. Yellow dots represent *in situ* gauge stations, and red dots represent altimetry stations. d), e), f) and g) Maps of amplitude of the annual cycle for TWS, SW, RZ and GW respectively.

with a drainage area of 700,000 km^2, is indeed the second largest tributary to the Amazon River, covering 12% of the Amazon basin, with a mean annual discharge of 28.400 $m^3 \cdot s^{-1}$ (Molinier, 1992; Richey et al., 1989). The method is based on the combination of multisatellite-derived hydrological products and outputs from global hydrology models. Water storage anomalies in the different hydrological reservoirs are removed from the TWS anomalies measured by GRACE to isolate the groundwater anomaly storage over 2003–2004. Results are both evaluated and validated using a hydrogeological map of Brazil, *in situ* measurements of groundwater level variations in a micro-catchment, and altimetry-derived water stages for zones where the aquifers reach the land surface.

2. Datasets

2.1. GRACE-derived land water mass solutions

The Gravity Recovery And Climate Experiment (GRACE) mission, launched in March 2002, provides measurements of the spatio-temporal changes in the Earth's gravity field. Several recent studies have shown that GRACE data over the continents can be used to derive the monthly changes of the total land water storage (Ramillien et al., 2008, 2005; Schmidt et al., 2008) with an accuracy of ~1.5 cm of equivalent water thickness when averaged over surfaces of a few hundred square-kilometers. We used the Level-2 land water solutions (RL04) produced by GFZ, JPL (for these two first products, January 2003, June 2003 and January 2004 are missing), and CSR (June 2003 and January 2004 are missing) with a spatial resolution of ~333 km, destriped and smoothed by Swenson and Wahr (2006) with an accuracy of 15–20 mm of water thickness. They are available at ftp://podaac.jpl.nasa.gov/tellus/grace/monthly.

2.2. The multisatellite inundation extent

This dataset quantifies at global scale the monthly distribution of surface water extent and its variations at ~25 km of resolution. The methodology which captures the extent (with an accuracy of ~10%) of episodic and seasonal inundations, wetlands, rivers, lakes, and irrigated agriculture over more than a decade, 1993–2004, is based on a clustering analysis of a suite of complementary satellites observations, including passive (SSM/I) and active (ERS) microwaves, and visible and near-IR (AVHRR) observations (Papa et al., 2008, 2010, 2006; Prigent et al., 2007).

2.3. Envisat RA-2 radar altimeter-derived water level heights over rivers and wetlands

Santos da Silva et al. (in press) build 140 time series of water levels derived from RA-2 ranges processed using the Ice-1 retracker over the Negro River drainage basin (see Fig. 1c for their locations), for the period 2002–2008, as suggested by Frappart et al. (2006a). The uncertainty associated with the water level height ranges between 5–25 cm for high water season and 12–40 cm during low water season (Frappart et al., 2006a; Santos da Silva et al., 2010).

2.4. In situ surface water levels

We used daily measurements of water stage from eight leveled *in situ* gauge stations from the Brazilian Water Agency (Agência Nacional de Águas or ANA — http://www.ana.gov.br), see Fig. 1c for their location.

2.5. In situ groundwater levels

The Asu micro-catchment, with a drainage area of 6.58 km^2, ~90 km north-northwest of Manaus, was instrumented with dipwells in 2001 (see (Tomasella et al., 2008) for a complete description of the catchment instrumentation). We used the well measurements to evaluate our estimates of the groundwater storage variations at that location.

2.6. Root zone water storage outputs from hydrological models

Hydrological model outputs are widely used to analyze spatio-temporal variations of water storage content at basin and global scales. We used water storage in the root zone from the Land Dynamics (LaD) model (Milly & Shmakin, 2002) outputs and from the latest version (Hunger & Döll, 2007) of the WaterGAP Global Hydrology Model (WGHM) (Döll et al., 2003).

2.7. Precipitation estimates from the Global Precipitation Climatology Project (GPCP)

These data quantify the distribution of precipitation over the global land surface (Adler et al., 2003). We used the monthly Satellite-Gauge Combined Precipitation Data product Version 2 data, available from January 1997 to present with a spatial resolution of 1° of latitude and longitude. Over land surfaces, uncertainty in rate estimates from GPCP is generally less than over the oceans due to the *in situ* gauge input (in addition to satellite) from the GPCC (Global Precipitation Climatology Center). Over land, validation experiments have been conducted in a variety of locations worldwide and suggest that while there are known problems in regions of persistent convective precipitation, non precipitating cirrus or regions of complex terrain, the uncertainty estimates range from 10 to 30% (Adler et al., 2003).

2.8. Hydrogeological map of Brazil

We used a hydrogeological map from the Brazilian Department of Mineral Production (DNPM, 1983) which provides the boundaries and the hydrogeological importance of the aquifers of the whole Brazil. This map, holdings of ISRIC, is made available by the European Commission — Joint Research Centre through the European Digital Archive of Soil Maps (EuDASM) (Selvaradjou et al., 2005): http://eusoils.jrc.ec.europa.eu/esdb_archive/EuDASM/EUDASM.htm.

3. Methods

3.1. Monthly water level maps

Monthly maps of water level over the floodplains of the Negro River Basin have been determined by combining the observations from a multi-satellite inundation dataset, RA-2 derived water levels, and the *in situ* hydrographic stations for the water levels over rivers and floodplains (see Fig. 1c for the location of altimetry-based and *in situ* stations). For a given month during the flood season, water levels were linearly interpolated over the flooded zones of the Negro River Basin. A pixel of 25 km × 25 km is considered inundated when its percentage of inundated area is greater than 0. The elevation of each pixel of the water level maps is given with reference to its minimum computed over the 2003–2004 period. This minimum elevation represents either the land surface or very low water stage of the floodplain. More details about the methodology used here can be found in Frappart et al. (2006b, 2005, 2008, 2010).

3.2. GRACE leveling and time-shift

An optimum filter method was developed by analyzing the correspondence of GRACE basin-average water storage to the ensemble mean of hydrological models (WGHM, LaD) and by analyzing the error budgets (satellite/leakage errors) and amplitude and phase biases for the different filter types. For the Negro River Basin, the destriped filter with 300 km smoothing radius provides the best results among six different filtering methods and different parameters (see Werth et al. (2009) for the filters employed and the values of the parameters that define the degree of smoothing used). Only a very small bias in the seasonal phase of storage changes resulted due to filtering. The GRACE products have been rescaled with a factor of 1.061 to account for amplitude smoothing due to filtering determined from smoothed and unsmoothed basin-average model ensemble time series of water storage.

3.3. Groundwater storage estimates

The time variations of the TWS expressed as anomalies are the sum of the contributions of the different reservoirs present in a drainage basin:

$$\Delta \mathrm{TWS} = \Delta \mathrm{SW} + \Delta \mathrm{RZ} + \Delta \mathrm{GW} \quad (1)$$

where SW represents the total surface water storage including lakes, reservoirs, in-channel and floodplains water; RZ is the water contained in the root zone of the soil (representing a depth of 1 or 2 m), GW is the total groundwater storage in the aquifers. These terms are generally expressed in volume (km^3) or mm of equivalent water height.

The GW anomaly over 2003–2004 is obtained in Eq. (1) by calculating the difference between the TWS anomaly estimated by GRACE and the SW level anomaly maps previously derived from remote sensing and the RZ anomaly derived from hydrological models outputs. The TWS and RZ monthly anomalies are the average anomalies of respectively the Level-2 GRACE CSR, GFZ and JPL destriped and smoothed solutions at 300 km of averaging radius, and the outputs from LaD and WGHM, respectively.

3.4. Water volume variations

For a given month t, the regional water volume of TWS, SW, RZ or GW storage $\delta V(t)$ in a basin with surface area S, is simply computed from the water heights δh_j, with $j = 1, 2, \ldots$ (expressed in mm of equivalent water height) inside S, and the elementary surface $R_e^2 \sin\theta_j \delta\lambda\delta\theta$ (and the percentage of inundation P_j for SW):

$$\delta V(t) = R_e^2 \sum_{j \in S} P_j \delta h_j \left(\theta_j, \lambda_j, t\right) \sin\theta j \delta\lambda\delta\theta \quad (2)$$

where λ_j and θ_j are co-latitude and longitude, $\delta\lambda$ and $\delta\theta$ are the grid steps in longitude and latitude (generally $\delta\lambda = \delta\theta$), and R_e the mean radius of the Earth (6378 km). The surface and total water volume variations are expressed in km^3.

Error on anomalies of surface water volumes were computed in the Negro Basin using Eq. (3):

$$dV = \sum_{i=1}^{n} \left(S_i d\delta h_i + dS_i \delta h_i\right) \quad (3)$$

where dV is the error on the monthly water volume anomaly (V), S_i the ith elementary surface, δh_i the ith elementary water level variation between two consecutive months, dS_i the error on the ith elementary surface, and $d\delta h_i$ the error on the ith elementary water level variation between two consecutive months.

The error sources include misclassifications, altimetry measurements and the linear interpolation method. The maximum error on the volume variation is monthly estimated as:

$$\Delta V_{max} \leq \Delta S_{max} \delta h_{max} + S_{max} \Delta(\delta h_{max}) \quad (4)$$

where: $\Delta V_{\max}$ is the maximum error on the water monthly volume anomaly, $S_{\max}$ is the maximum monthly flooded surface, $\delta h_{\max}$ is the maximum water level variation between two consecutive months, $\Delta S_{\max}$ is the maximum error for the flooded surface, and $\Delta(\delta h_{\max})$ is the maximum error for the water level between two consecutive months.

4. Results and discussion

Monthly estimates of water storage in the different hydrological reservoirs are computed for 2 years (2003–2004) for which the different datasets overlap in time. Maps of annual amplitudes of TWS,

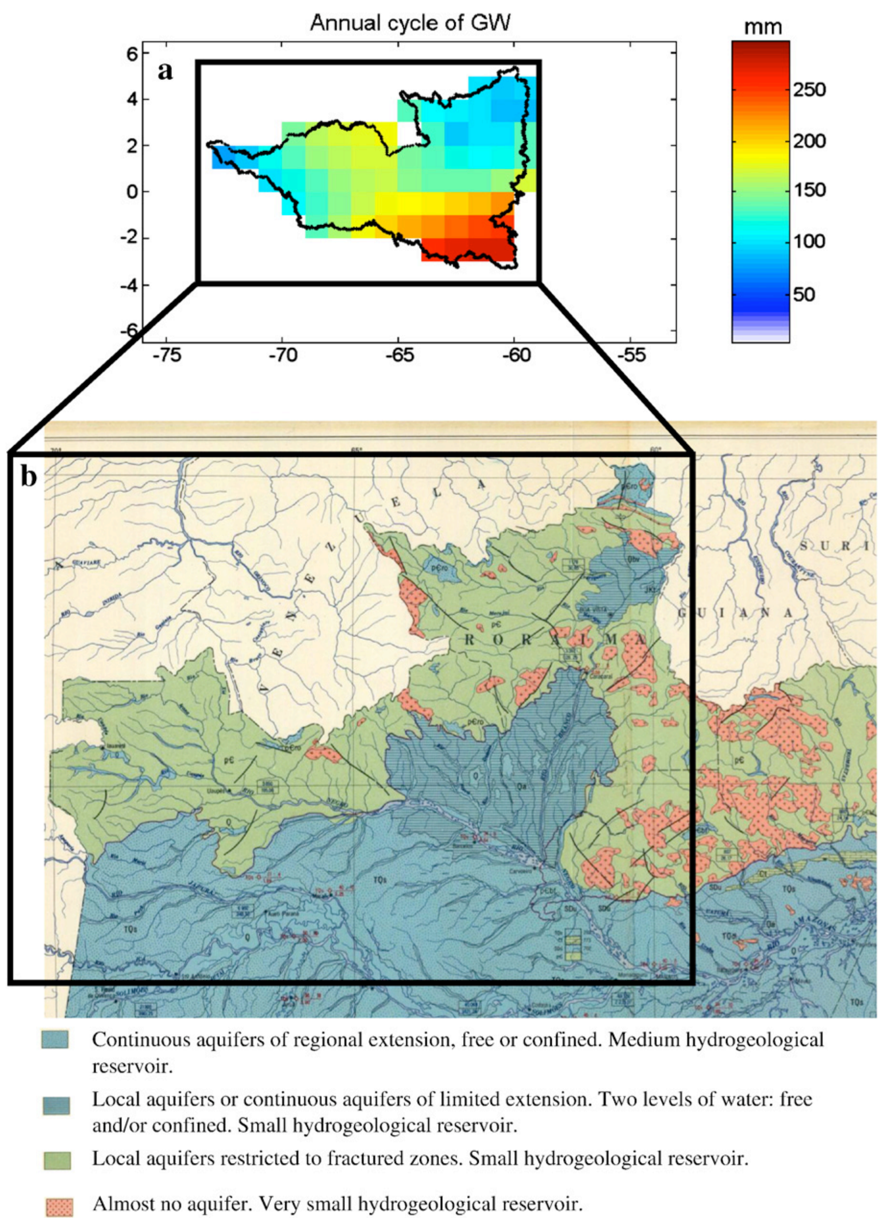

Fig. 2. a) Map of annual amplitude of GW in the Negro River Basin. b) Hydrogeological map of Brazil from DNPM (1983).

SW, RZ and GW are respectively presented in Fig. 1d–g. They were obtained by fitting simultaneously the temporal trend, the amplitudes of the annual and semi-annual cycles by least-square adjustment at each grid point. The amplitude of the annual cycle for TWS is maximum along the Negro River, and the downstream part of the Branco River, and also over the non flooded areas in the northwest of the Branco River (see Frappart et al. (2005) for a classification of the vegetation and flood extent in the Negro River Basin), reaching 300 mm in the downstream part (Fig. 1d). This area corresponds also to the maximum of amplitude of the SW (Fig. 1e), clearly related to substantial backwater effects produced at the Negro–Solimões confluence (Filizola et al., 2009). The amplitude of the annual cycle for RZ (Fig. 1f) is small except in the upstream part of the Branco River sub-basin, where large precipitation occurred without significant flood events. The largest amplitudes of the annual cycle for the GW (Fig. 1g) were observed along the Negro River stream, peaking at 250 mm, *i.e.*, ~72% of the TWS, in the downstream part of the basin. In contrast, small amplitudes were obtained in the Branco and Uaupes Basins. The pattern of GW storage variations observed in Fig. 2a tends to be similar to the hydrogeological structures of the Negro River Basin (Fig. 2b). For important aquifers, higher yield, recharge and drainage volumes and thus larger seasonal storage variations can be expected than for local and unimportant aquifers with low porosity. According to the hydrogeological map of Brazil (DNPM, 1983), the lower part of the basin (longitude $\geq -67°$ and latitude $\leq 0°$), where the amplitude of the GRACE-based GW seasonal cycle is the largest, is characterized by continuous aquifers of medium hydrogeological importance. The Uaupes Basin, which only contains local aquifers of relatively small importance, and the Branco Basin, which presents a mixture of local aquifers and small continuous aquifers of relatively small importance, and zones with almost no aquifers, correspond to the smallest amplitudes of the GW seasonal cycle. Note that a secondary maximum of the amplitude of the GW seasonal cycle (66°W, 2°N) can be observed in the upper part of the Negro River which is in good agreement with the presence of two small aquifers of medium importance (DNPM, 1983).

Fig. 3a shows the time variations (and deviation at each time step) of the water storage anomalies in the TWS, SW, RZ and GW reservoirs for 2003 and 2004. The deviations correspond to the extrema values for the different water reservoirs and obtained as the monthly range of variations of the GRACE-derived TWS from CSR, GFZ and JPL, of RZ from LaD and WGHM outputs, the mean surface water volume variations more or less the error computed using Eq. (4), the GW extrema by difference of the formers. The TWS signal is dominated during high waters (May to July) by SW variations. The RZ varies in phase with both TWS and SW and the amplitude of its variations represents a third of the amplitude of TWS variations, which is similar to what was obtained by Kim et al. (2009) for the whole Amazon basin. The resulting GW variations exhibit a more complex profile with two peaks. Its time variations follow the bimodal distribution of the precipitation resulting from the geographical location of the basin in both hemispheres (Fig. 3b). A large variability, reaching several months, is observed in the timing the extrema across the basin: GW storage is maximum (minimum) in July–August (December–March) in the western part (Uaupes and west of the Negro), in June–July (February to April) in the center of the basin and the downstream of the Branco, in August–September in the upper part of the Branco, and in May–June (October to December) for the downstream part of the Negro Basin. These results are consistent with *in situ* measurements from sites located in the downstream part of the Negro Basin (Do Nascimento et al., 2008; Tomasella et al., 2008) and closely related to the timing of GW recharge and soil thickness. In Manaus, the time-lag between the maxima of rainfall and GW is 3 months, which is similar to what is observed with *in situ* measurements.

Fig. 4 compares *in situ* measurements of GW levels from the Asu catchment and water levels from the Caapiranga and Morro da Água Preta swamps with the estimated anomalies of GW.

The GW levels in the Asu micro-catchment (below 2 m) were converted into GW storage using a specific yield of 0.17 as in

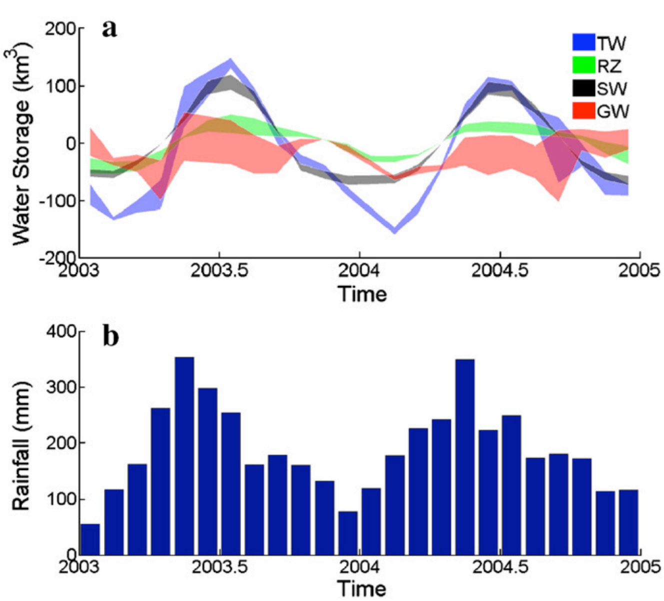

Fig. 3. a) Time variations of the water storage contained in the different hydrological reservoirs: TWS (blue), RZ (green), SW (black), GW (red). b) Monthly distribution of the rainfall (GPCP).

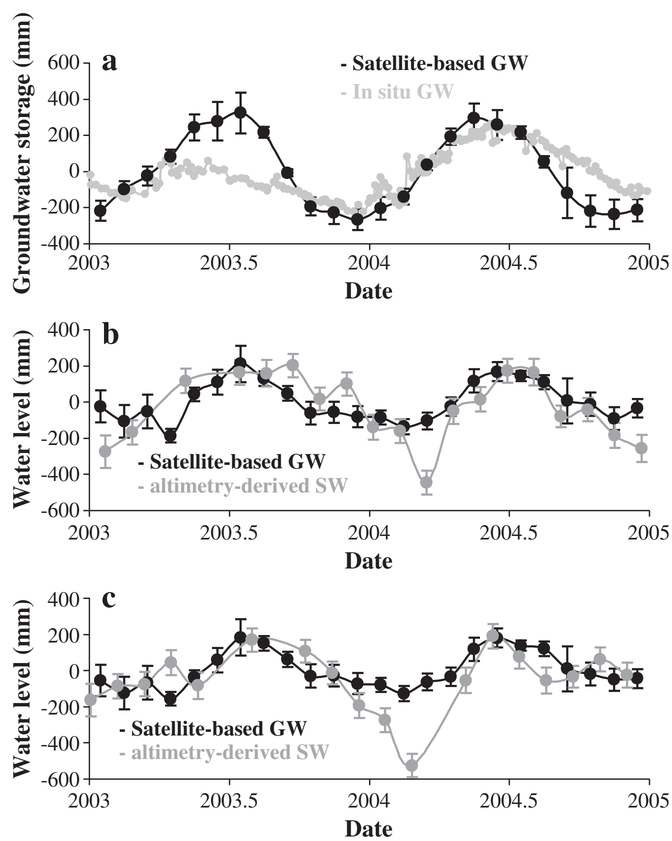

Fig. 4. a) Time variations of the GW storage in the Asu catchment (*in situ* — gray) and in the corresponding GRACE gridcell (satellite-based — black). b) and c) Time variations of the surface water levels (altimetry-derived — gray) and the groundwater for the corresponding GRACE gridcell (satellite-based — black) in the swamps of Caapiranga and Morro da Água Preta respectively.

Tomasella et al. (2008). Fig. 4a shows the 2003–2004 time variations of the GW storage of the Asu catchment and the encompassing GRACE gridcell. They show similar temporal variations. Very good agreement is found between mid 2003 and 2004. Nevertheless, the increase in GW starts later in 2003 for the *in situ* measurements and the maximum value is three times lower. A less pronounced decrease can also be observed for 2004. Two main factors can account for these differences: the respective sizes (7 km^2 against 10,000 km^2), and the fact that the Asu catchment is not directly connected to the Negro River, so the recharge processes may be different.

The groundwater table permanently reaches the surface in several parts of the Negro River Basin. Two of these regions, the Caapiranga and Morro da Água Preta swamps (Fig. 1c), are flooded and can be monitored using radar altimetry. In these cases, we expect GW to have similar time variations as surface water levels. Time series of SW and corresponding GW anomalies over 2003–2004 are presented in Fig. 4b and c for Caapiranga and Morro da Água Preta respectively. Except for February 2004, where the SW derived from radar altimetry present an abnormally low level (larger errors on altimetry-derived stages during the low water season), due to the presence of dry land or vegetation in the satellite field of view have also been reported by other studies, see for instance Frappart et al. (2006a) or Santos da Silva et al. (2010), both time series agree well ($R = 0.76$ for Caapiranga and 0.73 for Morro da Água Preta) and exhibit similar temporal patterns and amplitudes. The comparisons in Fig. 4 give confidence in the groundwater variations derived by the approach presented here.

5. Conclusion

This study presents the first attempt to estimate time variations of GW anomalies using GRACE-based TWS in combination with other remote sensing measurements and model outputs for a large river basin characterized by extensive inundation. Both spatial and temporal patterns of ground water storage anomalies exhibit realistic behavior. Comparisons with scarce *in situ* and satellite information show good agreement, in spite of the difference in spatial scales. This promising study will be soon extended to the entire Amazon basin and for more years as all datasets will soon be available over a longer period of time (2002 to present). Extending this method to characterize the evolution of water storage in other large river basins, especially in semi-arid regions, is also important as it will provide regional estimates of groundwater variations, a key variable for water resource management.

Acknowledgements

This work was partly supported by the Foundation STAE in the framework of the CYMENT project and the ANR CARBAMA. Two authors (F. Papa and W.B. Rossow) are supported by NASA Grant NNXD7AO90G. The authors would like to thank the Centre de Topographie des Océans et de l'Hydrosphère (CTOH) at Laboratoire d'Etudes en Géophysique et Oceanographie Spatiales (LEGOS), Observatoire Midi-Pyrénées (OMP), Toulouse, France, for the provision of the ENVISAT RA-2 GDR dataset. They wish to thank an anonymous reviewer for helping us in editing the manuscript to improve its quality.

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