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Surface freshwater storage and dynamics in the Amazon basin during the 2005 exceptional drought

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Abstract

The Amazon River basin was recently affected by extreme climatic events, such as the exceptional drought of 2005, with significant impacts on human activities and ecosystems. In spite of the importance to monitor freshwater stored and moving in such large river basins, only scarce measurements of river stages and discharges are available and the signatures of extreme drought conditions on surface freshwater dynamic at basin-scale are still poorly known. Here we use continuous multisatellite observations of inundation extent and water levels between 2003 and 2007 to monitor monthly variations of surface water storage at basin-scale. During the 2005 drought, the amount of water stored in the river and floodplains of the Amazon basin was ~130 km^3 (~70%) below its 2003-2007 average. This represents almost a half of the anomaly of minimum terrestrial water stored in the basin as estimated using the Gravity Recovery and Climate Experiment (GRACE) data.

1. Introduction

The amount of water stored and moving through the floodplains and wetlands of large river basins plays a major role in the global water cycle and is a critical parameter for water resources management. Covering more than 300,000 km² (5% of the surface of the entire basin) (Diegues, 1994; Junk, 1997), the Amazon extensive floodplains are particularly crucial to global climate and biodiversity but they remain still poorly monitored at large-scale, limiting our understanding of their role in flooding hazard, carbon production, sediment transport, nutrient exchange, and air-land interactions. The droughts that affected large areas of this basin in recent years are among the most severe ones in the past hundred years (Marengo *et al.*, 2008a) with the 2005- and 2010-events still considered as the most exceptional ones in the last 40 years. Mostly located in the Solimões, the Madeira, the Amazon Rivers (Fig. 1a) and its southwestern tributaries (Marengo *et al.*, 2008b; Tomasella *et al.*, 2011), the 2005 drought indeed affected an extensive area of 1.9 10^6 km² for the dry season, to 2.5 10^6 km² considering the maximum climatological water deficit (MCWD) based on satellite-derived rainfall anomalies (Lewis *et al.*, 2011). The impact on the Amazon rainforest was strong, with several studies reporting an increase in tree mortality and loss in biomass (Philips *et al.*, 2009), peaks of forest fires and burning of biomass (Aragão *et al.*, 2007; Koren *et al.*, 2007; Bevan *et al.*, 2009) and highlighting its vulnerability to extreme drought conditions, with large potential impacts on regional biogeochemical and carbon cycles (Philips *et al.*, 2009). During the low water stage season of 2005, *in situ* observations reported historic minima of river water levels, up to several meters below their mean (Marengo *et al.*, 2008a; Zeng *et al.*, 2008; Tomasella *et al.*, 2011) with important consequences as well on human activities and economy.

Despite the advent of hydrology-oriented Earth observation satellite missions, the spatial and temporal dynamics of surface freshwater storage are still poorly known (Alsdorf and

Lettenmaier, 2003; Alsdorf *et al.*, 2007). So the signatures of extreme climatic events such the drought of 2005 on the dynamic of surface freshwater volumes can only be inferred indirectly from satellite-based estimates of rainfall (Zeng *et al.*, 2008), from gridded measurements of rainfall (Marengo *et al.*, 2008a; 2008b) or from observations of integrated Terrestrial Water Storage (TWS) variations as measured by the Gravity Recovery and Climate Experiment mission (Chen *et al.*, 2009). In spite of being the largest component of freshwater in the watershed at seasonal time-scale, but also one of the major factors controlling surface processes and basin-wide hydrology, the surface freshwater stored in the Amazon is still not measured at proper space and time scales, leaving major questions opened: what is the seasonal amount of water in and out the Amazon floodplain, its interannual variability and its behavior during exceptional drought events?

2. Methods

2.1 Maps of surface water levels

Maps of water levels over the floodplains of the Amazon Basin were obtained by combining observations from a multisatellite inundation dataset and altimetry-based water levels at monthly time-scale over 2003-2007 where all the datasets overlap. Water levels, derived from ranges processed with Ice-1 algorithm to obtain more accurate estimates (Frappart *et al.*, 2006), for 534 ENVISAT RA-2 altimetry stations (Santos da Silva *et al.*, 2012) were bilinearly interpolated over inundated surfaces estimated using multisatellite observations (Papa *et al.*, 2008; 2010; Prigent *et al.*, 2007; 2012). Each monthly map of surface water levels has a spatial resolution of 0.25° and is referenced to EGM2008 geoid. The error on these estimates is lower than 10% (Frappart *et al.*, 2008; 2011a). A map of minimum water levels was estimated for the entire observation period using a hypsometric approach to take into account the difference of altitude between the river and the floodplain (see Supplementary Information).

2.2 Time series of water volume variations

At basin scale, the time-variations of surface water volume is simply computed as (Frappart *et al.*, 2011a):

$$V_{SW}(t) = R_e^2 \sum_{j \in S} P(\lambda_j, \varphi_j, t)\big(h(\lambda_j, \varphi_j, t) - h_{\min}(\lambda_j, \varphi_j, P(\lambda_j, \varphi_j, t))\big)\cos(\varphi_j)\Delta\lambda\Delta\varphi \qquad (1)$$

where V_{SW} is the volume of surface water, R_e the radius of the Earth equals 6378 km, $P(\lambda_j,\varphi_j,t)$, $h(\lambda_j,\varphi_j,t)$, $h_{min}(\lambda_j,\varphi_j)$ are respectively the percentage of inundation, and the water level at time t, the minimum of water level of the pixel of coordinates (λ_j,φ_j), $\Delta\lambda$ and $\Delta\varphi$ are respectively the grid steps in longitude and latitude. This minimum of water level is estimated through a hypsometric approach relating the percentage of inundation of a pixel to its elevation (see Supplementary Information for more details).

Accordingly, the time variations of volume of *TWS* anomalies from Level-2 GRACE solutions filtered using an Independent Component Analysis (ICA) approach (Frappart *et al.*, 2011b) are computed following Ramillien *et al.* (2005):

$$\Delta V_{TWS}(t) = R_e^2 \sum_{j \in S} \Delta h_{tot}(\lambda_j, \varphi_j, t)\cos(\varphi_j)\Delta\lambda\Delta\varphi \qquad (2)$$

where $h_{tot}(\lambda_j,\varphi_j,t)$ is the anomaly of *TWS* at time t of the pixel of coordinates (λ_j,φ_j).

3. Results

For the very first time, a continuous mapping of surface water levels and surface water volumes, as well as their temporal dynamics at interannual time-scale, are presented for the Amazon River, the largest drainage basin on Earth. First, monthly surface water level maps are obtained by combining multisatellite-based wetland maps (Papa *et al.*, 2010; Prigent *et al.*, 2007; 2012) with 534 altimetry-derived water levels in the Amazon basin (Santos da Silva *et al.*, 2012) (see the location of ENVISAT RA-2 altimetry stations in Figure 1a) over the period 2003-2007 at monthly time-scale (see Maps of surface water levels in section Methods or Frappart *et al.*, 2008; 2010 and 2011a for more details). Focusing on the signature of the 2005 drought on Amazon surface water, the map of anomaly of minimum water levels for 2005 (Figure 1b) shows that the whole wetland complex of the Central Amazon exhibits large negative values, with the greatest anomalies registered for the Purus (64.9°-61°W and 2°-4.5°S), Madeira (between 55.67°-59.9°W and 1.25°-5.25°S), and Mamiraua (between 64.67°-67.4°W and 1.4–3.1°S) wetlands. The large wetland complexes of Abanico of Pastaza River in Peru (between 74°-76.8°W and 3°-5°S), and Llanos de Mojos in Bolivia (between 63°-69°W and 11°-16°S) are also strongly affected in comparison to the northern part of the basin. These minima derived from radar altimetry are consistent with anomalies (computed on longer time periods) of levels estimated from *in situ* gauge records: -2.4 m at Tabatinga (69.9°W, 4.25°S) (Zeng *et al.*, 2008), -4.8 m in Iquitos (72.28°W, 3.43°S), between two and five meters on several locations along the Amazonas (Peru) and its major tributaries, and along the Solimões and its southern tributaries, -4 m at Manaus (60.04°W, 3.15°S) at the mouth of the Negro River (Marengo *et al.*, 2008a).

Second, surface water volume variations for the Amazon River are also estimated using surface water levels maps (see Maps of Time-series water volume variations in section Methods or Frappart *et al.*, 2008; 2010 and 2011a for more details). The time series of surface water volume over 2003-2007 for the Amazon basin was decomposed into interannual (Figure 1c) and annual (represented for 2005 in Figure 1d) terms using a 13-month sliding average and compared to river discharge for the whole Amazon basin. The surface water volume leads the interannual variations of the river discharge in Obidos (55.68°W, 1.92°S), the last station along the Amazon mainstem where discharge is estimated (data obtained from

Environmental Research Observatory (ORE) HYBAM (see Supplementary information)), (R=0.93 with R the linear correlation coefficient) with one-month lag. The reduction of rainfall over Southern Amazonia since 2002 (Marengo *et al.*, 2008a) caused a decrease of the water stored in the floodplains up to the minimum of 2005, also observed on streamflow (Zeng *et al.*, 2008). The annual cycle of surface water storage for 2005 was close to or above the mean from February to June 2005, peaking in May with a value around +σ (one standard deviation or STD). Then, it became significantly below the mean (values lower than -σ) from July to December (Figure 1d). These results are also in good agreement with what was observed on river discharge in Obidos (Tomasella *et al.*, 2011).

This very unique opportunity to monitor the changes of water level all along the hydrological cycle at monthly time-scale is illustrated in Figure 2 (along with Figure S2) for the drought of 2005. The anomalies of surface water levels averaged over two consecutive months during 2005 are compared with bi-monthly anomalies of rainfall from Tropical Rainfall Measuring Mission (TRMM, see Supplementary Information) (with an advance of two months) and TWS from GRACE (Figure 2 for the dry season, from July to December, and Figure S2 for the rainy season, from January to July). Rain deficits (upper panel) in the northern and western part of the basin in the heart of the rainy season (May-June), are responsible for anomalously low levels in the wetlands of the central corridor of the Amazon two months later (September-October), in good accordance with the TWS observations (lower panel). The spatial and temporal patterns in the anomalies of surface water (center panel) are consistent with both *in situ* measurements of water levels and discharges and satellite-derived observations of TWS (lower panel). For instance, in the central part of the Amazon (from Manacapuru (60.61°W, 3.31°S) to Obidos), the surface water maps present levels close or above the mean until May-June 2005 (Figure S2) that then started to drop until a minimum in September-October 2005 (Figure 2) is reached, similarly to what was recorded by gauges (Tomasella *et al.*, 2011). In the Madeira basin, the water levels between 10°S and 5°S were close to the mean until March-April 2005, and then below, with a minimum in September close to 5°S as observed in Fazenda Vista Alegre (60.03°W, -4.90°S). In the Negro basin, important contrast is observed between the upper (above the mean over the whole period) and the lower (above normal until June 2005 and then below the mean of several meters after July-August 2005) parts of the basin. These results are also in good agreement with what was observed at the gauges of Manaus (60.04°W, 3.15°S) and Serrinha (64.88°W, 0.48°N) (Marengo *et al.*, 2008a; Tomasella *et al.*, 2011). The lack of backwater effect (*i.e.*, the control of the water levels in the lower Negro by the stages of the Solimões (Meade *et al.*, 1991; Filizola *et al.*, 2009)) is clearly visible in September-October 2005 with anomalies of minimum of surface water reaching -3 m close to the mouth of the Negro River. These minima are not caused by deficit of rainfall but can be related to below normal water levels in the southwestern tributaries of the Solimões (Tomasella *et al.*, 2011). These maps of surface water levels permit to spatialize and quantify the water deficit between Serrinha and Manaus, confirming what has been coarsely detected by GRACE (Chen *et al.*, 2009 and Figure 2 lower panel).

Time variations of surface water volume over 2003-2007 were analyzed in the major western and southern tributaries of the Amazon. The most important contributions come from the Solimões and the Madeira basins (~30% and ~25% respectively) whereas the contribution from the Tapajos represents less than 6% of the water stored in the surface reservoir of the Amazon basin. The interannual variations of surface water generally precedes the interannual variations of discharge by one month in the Solimões (R=0.94) and the Madeira (R=0.84) basins (Figure 3a and c). Good but lower agreement can be observed between interannual variations of surface water storage and discharge for the Tapajos (R=0.71, $\Delta t=0$, where Δt is the time shift between the two time-series to be compared, Figure 3e). The discharge values for the four stations were obtained from ORE HYBAM (see Supplementary information).

These differences in time shift are consistent with what we know about the dynamics of surface in these sub-basins. The white waters (turbid with large amount of dissolved organic carbon) originating from the Andes loaded with sediments during their stay in the extensive floodplains distributed along the Solimões and most of the tributaries forming the Madeira have a longer residence time in the basin than the clear waters (transparent containing low content of dissolved organic carbon) of the Tapajos descending from the Brazilian shield through numerous waterfalls and rapids. The analysis of the 2005 annual cycle also reveals differences among these sub-basins. Volume of surface water in the Solimões basin was close to the mean or above during the rising period, peaking at a value greater than +σ in May, and declined rapidly with a minimum reached below +σ in October (Figure 3b). Similar behavior is found in the Tapajos (with a peak reached in April, one month earlier than usual, Figure 3f). Most of surface waters in the Tapajos are located in the large estuary formed by its encounter with the Amazon. At its mouth, its level is controlled by the stage of the Amazon. This can account for the similar temporal pattern found in Tapajos and Solimões 2005 annual cycle for surface waters. The lower agreement with discharge (R=0.71) at interannual time-scale is more likely caused by the differences of hydrological regime between the upper and lower parts of the Tapajos (Figure 3f). On the contrary, the volume of surface water in the Madeira basin was below the mean until May, and then close to the mean (Figure 3d). These results are consistent with what was observed at *in situ* gauges (Marengo *et al.*, 2008a; Tomasella *et al.*, 2011).

The impact of the 2005 drought was quantified for the surface water storage and the TWS for the whole Amazon basin (respectively 129 and 245 km^3 below the 2003-2007 average), and for the three sub-basins mentioned above for which different hydrological behaviors are observed during the 2005 drought (Table 1). The minimum volume of water stored in the Amazon was by 71% lower for the surface reservoir, under the assumption that the storage below the minimum water level can be neglected, compared to the average during 2003-2007, and by 29% for the total hydrological reservoirs. If the 2005 drought strongly affected the four different western and southern tributaries, its impact on TWS also differs from one another, giving us information on the importance of the surface reservoir in the Amazon basin. Notice that surface water storage and TWS were much more affected by drought in the Solimões basin than in the three other tributaries. This coincides with areas of largest anomalies of MCWD and increase in tree mortality (Aragão *et al.*, 2007; Lewis *et al.*, 2011), and with regions with important fire activity in 2005 (Koren *et al.*, 2007).

4. Discussion and Conclusion

Our results provide the first pluri-annual estimates of the variations of surface water storage in a large basin at monthly time-scale. They reveal that during 2003-2007, the variations of surface water reservoir vary from 800 to 1,000 km^3 per year, which represents 15-20% of the water volume that flew out of the Amazon basin and about half of the variations of the total amount of water in the Amazon basin as detected using GRACE data. This result is 3 to 4 times greater than what was found by a previous study solving the water balance equation with gravimetric and imaging satellite methods (*i.e.*, GRACE, SRTM, GPCP and JERS-1) for six GRACE gridcells of 330 km of spatial resolution encompassing the floodplains along the Amazon mainstem (Alsdorf *et al.*, 2010). The major reason of this discrepancy must come from the leakage from other regions, due to the spherical harmonics representation of the GRACE data, which contaminate the signal at the GRACE gridcell resolution. Our estimates agree well with i) analysis of GRACE data and GLDAS/NOAH outputs which show that the TWS is equally partitioned between surface and sub-surface reservoirs, and soil water (Han *et al.*, 2009), and to ii) modeling results from ensemble hydrological simulations with river routing which found that surface water and shallow groundwater represents 73% of the TWS in the Amazon basin (Kim *et al.*, 2009). In addition, the method presented here to derive water levels from multisatellite datasets over rivers and floodplains offers the first opportunity to continuously monitor the mass transport in the surface water reservoir before the launch of the NASA-CNES Surface Water and Ocean Topography (SWOT) mission in 2019. It makes possible to study the changes affecting the hydrological cycle in the large river basins covered with floodplains. It also helps better understand the complex dynamics of surface water in large drainage basins (*i.e.*, back water effects, Amazon flood-pulse linked to the strong seasonality of the rainfall, or time residence of water in the floodplains).

The surface water level maps give a unique and valuable spatial information on the time evolution of floodplains reservoir during the hydrological cycle in response to rainfall forcing caused by interannual and longterm variability of both the tropical Pacific and northern Atlantic Tropical Oceans. They permit to directly identify the regions most severely affected by exceptionally low stages during the extreme drought of 2005 (the volume of surface water in the Amazon basin during the 2005 low stage period was 71% below its 2003-2007 average according to our results). The estimated spatial and temporal patterns of surface water storage are in good agreement with *in situ* gauge records, satellite-derived hydrological variables, and ecological parameters. Removed from GRACE-derived TWS, they will permit a direct estimate of the soil water and groundwater storages in the Amazon basin.

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Table 1: Anomaly of minimum of water volume in 2005 (2003-2007 reference period) for the Amazon and some of its tributaries (km^3 and %).

* It is assumed that the storage below the minimum water level can be neglected compared to the surface water storage estimated with our methodology.

2005 Anomaly of minimum of water volume	**Surface Water Storage***		**Total Water Storage**	
	(km^3)	**(%)**	**(km^3)**	**(%)**
Amazon	-129.4	-71.0	-244.6	-29.1
Solimões	-36.7	-85.8	-78.3	-40.0
Madeira	-11.5	-70.1	-17.9	-17.6
Tapajos	-3.6	-66.7	-47.7	-20.7

Figure 1: a) Map of the Amazon basin with locations of altimetry stations (red points) and *in situ* discharge gauges (blue). b) Map of anomaly of water level for 2005 (2003-2007 reference period). c) Interannual variations of surface water volume of the Amazon (black) and discharge at Obidos (dotted blue) between 2003 and 2007. d) Annual cycle of surface water volume of the Amazon for 2005 (blue) and average (dotted black) ± std (grey area).

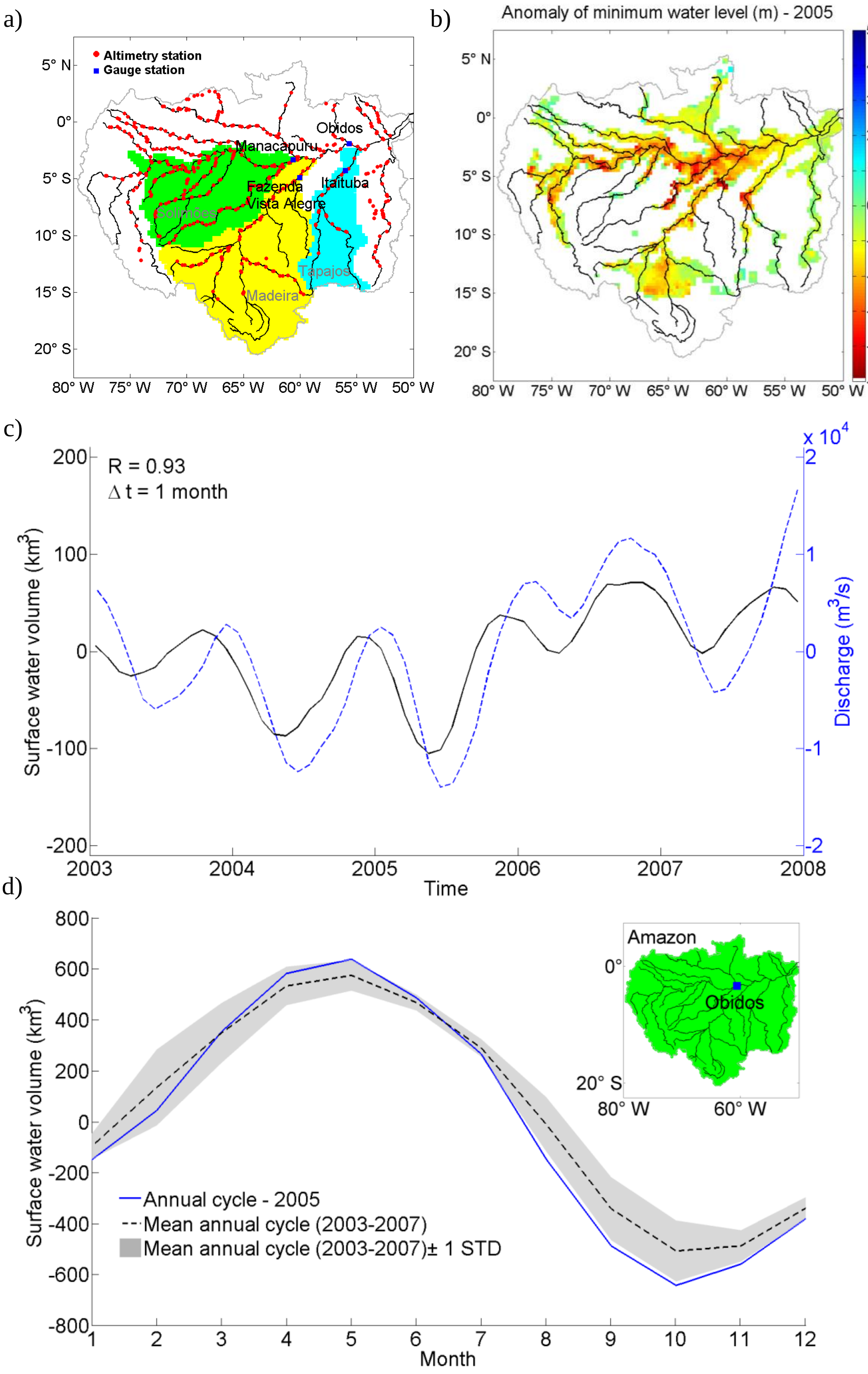

Figure 2: Maps of anomaly of rainfall (mm) for May-June, July-August, and September-October 2005 (top), surface water level (m) for July-August, September-October, and November-December 2005 (centre), and TWS (mm) for July-August, September-October, and November-December 2005 (bottom).

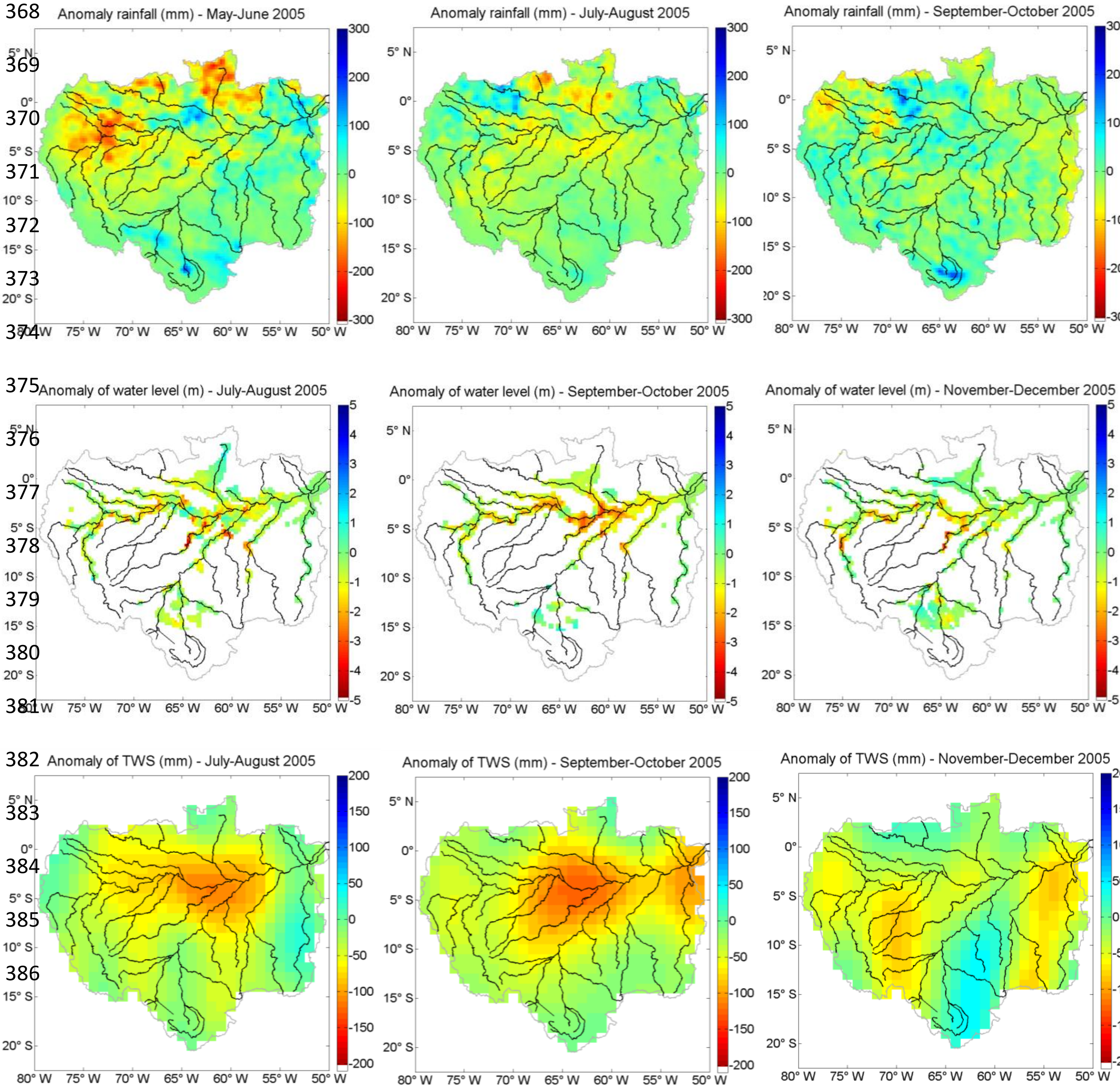

Figure 3: Interannual variations of surface water volume (black) and discharge (dotted blue) between 2003 and 2007 (left) and annual cycle of surface water volume of the Amazon (blue) and average (dotted black) ± std (grey area) (right) at a) Manacapuru (Solimões), b) Fazenda Vista Alegre (Madeira), c) Itaituba (Tapajos).