Surface freshwater storage in the Amazon basin during the 2005 exceptional drought.

Frédéric Frappart (1), Fabrice Papa (2), Joecila Santos da Silva (3), Guillaume Ramillien (1), Catherine Prigent (4), Frédérique Seyler (5), Stéphane Calmant (2)

(1) Université de Toulouse, OMP-GET, 14 Avenue Edouard Belin, 31400 Toulouse, France

(2) Université de Toulouse, OMP-LEGOS, 14 Avenue Edouard Belin, 31400 Toulouse, France

(3) Universidade do Estado do Amazonas (UEA), Centro de Estudos do Trópico Úmido (CESTUAv). Djalma Batista, 3578, Flores, Manaus, Amazonas, Brasil

(4) CNRS-LERMA, Observatoire de Paris, Paris, France

(5) UMR 228 ESPACE-DEV (IRD,UAG,UM2,UR), Montpellier, France

Corresponding author email: frederic.frappart@get.obs-mip.fr

Supplementary Information

1. Datasets

1.1 The multisatellite inundation extent

This dataset quantifies at global scale the monthly distribution of surface water extent and its variations at ~25 km 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, 1993–2007, 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 (Prigent et al., 2001, 2007, 2012; Papa et al., 2006; 2008; 2010).

1.2 Envisat RA-2 radar altimeter-derived water level heights

Santos da Silva et al. (2012) build 543 time series of water levels derived from ENVISAT RA-2 ranges processed using the Ice-1 retracker over the Amazon basin (see Fig. 1a for their locations), for the period 2002-2010. The uncertainty associated with the water level height ranges between 5–25 cm for high water season to 12–40 cm during low water season (Frappart et al., 2006; Santos da Silva et al., 2010).

1.3 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 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., 2005; 2008; Schmitt et al., 2008) with an accuracy of ~1.5 cm of equivalent water thickness when averaged over surfaces of a few hundred square-kilometres. In this study, we used equivalently monthly GFZ, UTCSR and JPL solutions from February 2003 (data are missing for January 2003) to December 2007 in order to analyse the time variations of the water mass changes in the Amazon basin. Unfortunately, the GRACE solution suffer from the presence of an unrealistic high frequency noise corresponding to north-south striping that is caused by orbit resonance during the Stokes coefficients determination and aliasing of not well-modelled short-term phenomena. To attenuate the noise in the Level-2 GRACE solutions, we used the global solutions post-processing by an Independent Component Analysis (ICA) approach based on the combination of GFZ/UTCSR/JPL solutions of the same monthly period to isolate statistically independent components of the observed gravity field, and mainly the continental water storage contribution (Frappart et al., 2010; 2011a). These data can be downloaded at: http://grgs.obs-mip.fr.

1.4 TRMM 3B43 monthly rainfall

In this study, we used the 3B43 TRMM and other monthly rainfall data sources at a spatial resolution of 0.25° from January 2002 to December 2007. This dataset is obtained by combining satellite information from passive microwave imager (TMI) and precipitation radar (PR) onboard the Tropical Rainfall Measuring Mission (TRMM), a Japan-US satellite launched in November 1997, the Visible and InfraRed Scanner (VIRS) onboard the Special Sensor Microwave Imager (SSM/I), and rain gauge observations. It results from the merging of the 3B42 TRMM-adjusted merged infrared precipitation with the monthly accumulated Climate Assessment Monitoring System or Global Precipitation Climatology Center Rain Gauge analyses (3S45) (Huffman et al., 1995; 2007). Even if this product overestimates low rainfall, and underestimates large rainfall (Aragaõ et al., 2007) and precipitation over mountainous areas (Lavado et al., 2009; Condom et al., 2011), it has been frequently used for large-scale climatic studies over the Amazon basin (Saleska et al., 2007; Philipps et al., 2009; Lewis et al., 2011). It is available on the Goddard Earth Sciences Data and Information Services Center (GES DISC) website: http://daac.gscf.nasa.gov.

1.5 Monthly river discharges

Time series of surface water volume variations at monthly timescale were compared to monthly discharges estimated at the closest gauge to the mouth of the Amazon River and some of its largest western and southern tributaries (*i.e.*, the Solimões, the Madeira, and the Tapajosrivers) in Obidos (55.68°W, 1.92°S), Manacapuru (60.61°W, 3.31°S), Fazenda Vista Alegre (60.03°W, -4.90°S), and Itaituba (56.00°W, 4.29°S) respectively. Their records were downloaded from the Environmental Research Observatory (ORE) HYBAM website (http://www.ore-hybam.org/) over the period June 2002 – June 2008.

1.6 Masks of the sub-basin

Masks at 0.25° of spatial resolution of the largest sub-basins of the Amazon were built using the watershed delineation for the Amazon sub-basin systems based on GTOPO30 DEM and a drainage network extracted from JERS SAR images from Seyler et al. (2009). The Amazon drainage system was decomposed into 8 large drainage areas (larger than 400,000 km² to be compatible with the low spatial resolution of the GRACE data, see Frappart et al., under review): Andean encompassing Ucayali and Marañon flowing from the south, and the Japura and the Iça flowing from northwest, Solimoes, Mamoré, downstream Madeira, Negro, downstream Amazon, Tapajos, and Xingu basins.

2. Methods

Reliable estimates of water volume stored in the surface reservoir depend on an accurate elevation of the reference surface (*i.e.*, the topography or the elevation of the surface corresponding to the minimum water levels during the observation period). A map of minimum water levels was estimated for the entire observation period (2003-2007) using a hypsometric approach to take into account the difference of elevation in each cell area of the multisatellite inundation dataset corresponding to, for instance, the difference of elevation between the river and the floodplain (Fig. S1a). For each inundated pixel of coordinates (λ_j,φ_j), the minimum elevation h_{min} during the observation period ΔT for a percentage of inundation α is given as:

$$h_{\min}(\lambda_i,\varphi_i,\alpha,\Delta T) = \min(h(\lambda_i,\varphi_i,t))_{P(\lambda_i,\varphi_i,t)\leq\alpha;t\in\Delta T} \qquad \text{(S1)}$$

where α varies between 0 and 100 and t is a monthly observation during ΔT.

The minimum elevation H_{min} for a pixel of coordinates (λ_j,φ_j) during the observation period ΔT is hence:

$$H_{\min}(\lambda_i,\varphi_i,\Delta T)=\frac{1}{100}\sum_{\alpha=0}^{100}h_{\min}(\lambda_i,\varphi_i,\alpha,\Delta T)\Delta\alpha \qquad \text{(S2)}$$

where $\Delta\alpha$ is the increment in percentage of inundation (a step of 1% was chosen here).

An example of hypsometric curve is given in Fig. S1b corresponding to the pixels of coordinates (60°W, 0°) and (60°W, 1.25°N).

3. Results

The anomalies of surface water levels (see Maps of surface water levels in section Methods or Frappart et al., 2008 and 2011b for more details) averaged over two consecutive months during 2005 are compared with bi-monthly anomalies of rainfall from TRMM (with an advance of two months) and TWS from GRACE for the rainy season, from January to July 2005 (Fig. S2). A detailed analysis of these results can be found in the corresponding article.

4. Supplementary references

Aragão L E O, Malhi C Y, Roman-Cuesta R M, Saatchi S, Anderson L O and Shimabukuro Y E 2007 Spatial patterns and fire response of recent Amazonian droughts *Geophys. Res. Lett.* **34** L07701

Condom T, Rau P and Espinoza J C 2011 Correction of TRMM 3B43 monthly precipitation data over the mountainous areas of Peru during the period 1998–2007 *Hydrol. Process.* **2** 1924–1933

Frappart F**,** Calmant S, Cauhopé M, Seyler F and Cazenave A 2006 Preliminary results of ENVISAT RA-2 derived water levels validation over the Amazon basin *Remote Sens. Environ.* **100(2)** 252-264

Frappart F, Ramillien G, Maisongrande P and Bonnet M-P 2010 Denoising satellite gravity signals by Independent Component Analysis *IEEE Geosci. Remote Sens. Lett.* **7(3)** 421-425

Frappart F, Ramillien G, Leblanc M, Tweed S O, Bonnet M-P and Maisongrande P 2011a An independent Component Analysis approach for filtering continental hydrology in the GRACE gravity data *Remote Sens. Env.* **115(1)** 187-204

Frappart F, Papa F, Güntner A, Werth S, Santos da Silva J, Tomasella J, Seyler F, Prigent C, Rossow W B, Calmant S and Bonnet M-P 2011b Satellite-based estimates of groundwater storage variations in large drainage basins with extensive floodplains *Remote Sens. Env.* **115(6)** 1588-1594

Frappart F, Ramillien G and Ronchail J Terrestrial water storage variations over 2003-2010 using GRACE and TRMM observations *Int. J. Climato*. **Under revision**.

Huffmann G J, Adler R F, Rudolf B, Schneider U and Keehn P 1995 Global precipitation estimates based on a technique for combining satellite-based estimates, rain gauge analysis, and NWP model precipitation information *J. Clim.* ***8*** 1284-1295

Huffmann G J, Adler R F, Bolvin D T, Gu G, Nelkin E J, Bowman K P, Hong Y, Stocker E F and Wolf D B 2007 The TRMM multi-satellite precipitation analysis: quasi-global, multi-year, combined-sensor precipitation estimates at fine scale *J. Hydromet.* **8(1)** 38-55

Lavado W, Labat D, Guyot J-L, Ronchail J and Ordonez J 2009 TRMM rainfall data estimation over the Peruvian Amazon-Andes basin and its assimilation into a monthly water balance model *IAHS Pub.* **333** 245-252

Lewis S L, Brando P M, Phillips O L, van der Heijden M F and Nepstad D 2011 The 2010 Amazon drought *Science* **331** 554

Papa F, Prigent C, Durand F and Rossow W B 2006 Wetland dynamics using a suite of satellite observations: A case study of application and evaluation for the Indian Subcontinent *Geophys. Res. Lett*. **33** L08401

Papa F, Güntner A, Frappart F, Prigent C and Rossow W B 2008 Variations of surface water extent and water storage in large river basins: A comparison of different global data sources *Geophys. Res. Lett*. **35** L11401

Papa F, Prigent C, Aires F, Jimenez C, Rossow W B and Matthews E 2010 Interannual variability of surface water extent at global scale *J. Geophys. Res.* **115** D12111

Philips O L et al. 2009 Drought sensitivity of the Amazon rainforest *Science* **323** 1344-1347

Prigent C, Papa F, Aires F, Rossow W B and Matthews E 2007 Global inundation dynamics inferred from multiple satellite observations, 1993-2000 *J. Geophys. Res*. **112** D12107

Prigent C, Papa F, Aires F, Jiménez C, Rossow W B and Matthews E 2012 Changes in land surface water dynamics since the 1990s and relation to population pressure *Geophys. Res. Lett.* **39** L08403

Ramillien G, Frappart F, Cazenave A and Güntner A 2005 Time variations of land water storage from the inversion of 2-years of GRACE geoids *Earth Planet. Sci. Lett.* **235(1-2)** 283-301

Ramillien G, Famiglietti J S and Wahr J 2008 Detection of continental hydrology and glaciology signals from GRACE: a review *Surv. Geophys.* **29** 361-374 2008

Saleska S R, Didan K, Huete A R and da Rocha A R 2007 Amazon forests green-up during 2005 drought *Science* **318** 612

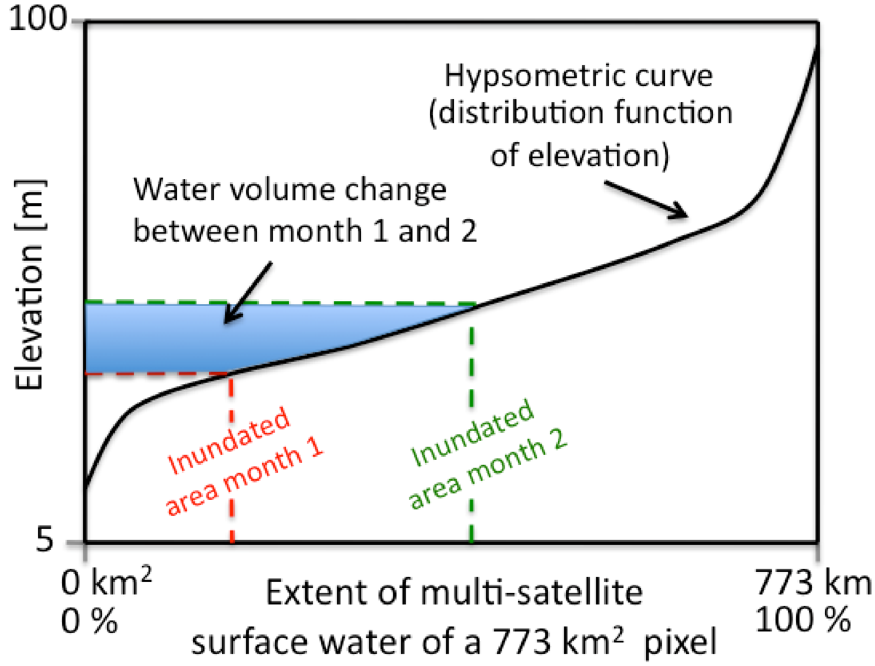
Santos da Silva J, Calmant S, Seyler F, Rottuno Filho O C, Cochonneau G, and Mansur W J 2010 Water levels in the Amazon basin derived from the ERS 2 and ENVISAT radar altimetry missions *Remote Sens. Env.* **114(10)** 2160-2181

Santos da Silva J, Seyler F, Calmant S, Corrêa Rotuno Filho O, Roux E, Magalhaes A A and Guyot J-L 2012 Water level dynamics of Amazon wetlands at the watershed scale by satellite altimetry. *Int. J. Remote Sensing* **33(11)** 200-206

Schmidt R, Flechtner F, Meyer U, Neumayer K H, Dahle C, Koenig R and Kusche J 2008 Hydrological Signals Observed by the GRACE Satellites *Surv. Geophys.* **29** 319–334

Seyler F, Muller F, Cochonneau G, Guimarães L and Guyot J-L 2009 Watershed delineation for the Amazon sub-basin system using GTOPO30 DEM and a drainage network extracted from JERS SAR images *Hydrol. Proc.* **23(22)** 3173-3185

Fig. S1: a) Hypsometric curve or distribution elevation function relating extent of surface water in a pixel with elevation. b) Two examples of hypsometric curves at pixel of coordinates (60°W,0°) and (60°W, 1.25°N).



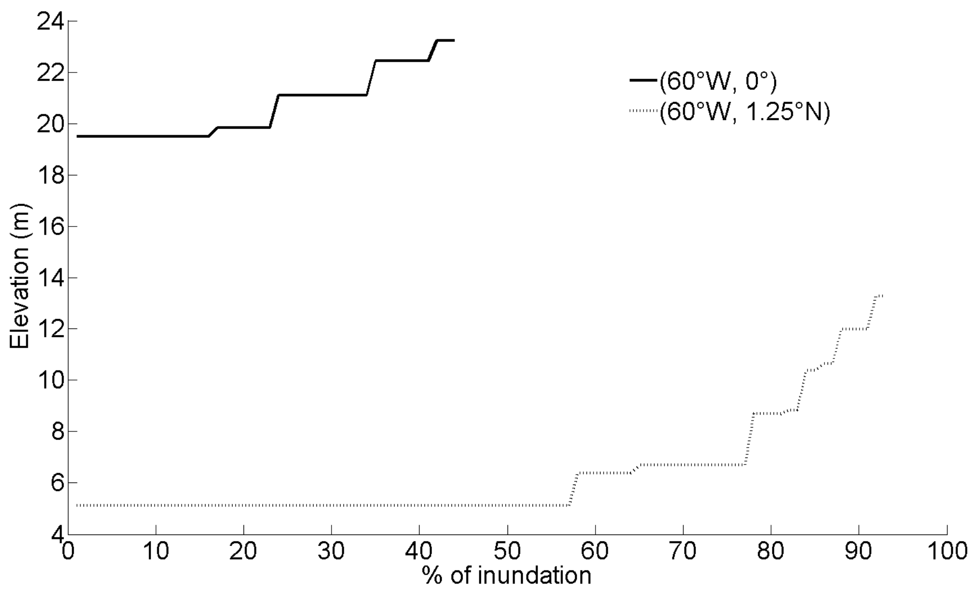


Fig. S2: Maps of anomaly of rainfall (mm) for November-December 2004, January-February 2005, and March-April 2005 (top), surface water level (m) for January-February, March-April, and May-June 2005 (centre), and TWS (mm) for January-February, March-April, and May-June 2005 (bottom).