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

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14  
15 **Abstract**

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

## 28        **1. Introduction**

29    The amount of water stored and moving through the floodplains and wetlands of large river  
30    basins plays a major role in the global water cycle and is a critical parameter for water  
31    resources management. Covering more than 300,000 km<sup>2</sup> (5% of the surface of the entire  
32    basin) (Diegues, 1994; Junk, 1997), the Amazon extensive floodplains are particularly crucial  
33    to global climate and biodiversity but they remain still poorly monitored at large-scale,  
34    limiting our understanding of their role in flooding hazard, carbon production, sediment  
35    transport, nutrient exchange, and air-land interactions. The droughts that affected large areas  
36    of this basin in recent years are among the most severe ones in the past hundred years  
37    (Marengo *et al.*, 2008a) with the 2005- and 2010-events still considered as the most  
38    exceptional ones in the last 40 years. Mostly located in the Solimões, the Madeira, the  
39    Amazon Rivers (Fig. 1a) and its southwestern tributaries (Marengo *et al.*, 2008b; Tomasella *et*  
40    *al.*, 2011), the 2005 drought indeed affected an extensive area of  $1.9 \cdot 10^6$  km<sup>2</sup> for the dry  
41    season, to  $2.5 \cdot 10^6$  km<sup>2</sup> considering the maximum climatological water deficit (MCWD) based  
42    on satellite-derived rainfall anomalies (Lewis *et al.*, 2011). The impact on the Amazon  
43    rainforest was strong, with several studies reporting an increase in tree mortality and loss in  
44    biomass (Philips *et al.*, 2009), peaks of forest fires and burning of biomass (Aragão *et al.*,  
45    2007; Koren *et al.*, 2007; Bevan *et al.*, 2009) and highlighting its vulnerability to extreme  
46    drought conditions, with large potential impacts on regional biogeochemical and carbon  
47    cycles (Philips *et al.*, 2009). During the low water stage season of 2005, *in situ* observations  
48    reported historic minima of river water levels, up to several meters below their mean  
49    (Marengo *et al.*, 2008a; Zeng *et al.*, 2008; Tomasella *et al.*, 2011) with important  
50    consequences as well on human activities and economy.

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

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

64

## 65 **2. Methods**

### 66 *2.1 Maps of surface water levels*

67 Maps of water levels over the floodplains of the Amazon Basin were obtained by combining  
68 observations from a multisatellite inundation dataset and altimetry-based water levels at  
69 monthly time-scale over 2003-2007 where all the datasets overlap. Water levels, derived from  
70 ranges processed with Ice-1 algorithm to obtain more accurate estimates (Frappart *et al.*,  
71 2006), for 534 ENVISAT RA-2 altimetry stations (Santos da Silva *et al.*, 2012) were  
72 bilinearly interpolated over inundated surfaces estimated using multisatellite observations  
73 (Papa *et al.*, 2008; 2010; Prigent *et al.*, 2007; 2012). Each monthly map of surface water  
74 levels has a spatial resolution of  $0.25^\circ$  and is referenced to EGM2008 geoid. The error on  
75 these estimates is lower than 10% (Frappart *et al.*, 2008; 2011a). A map of minimum water  
76 levels was estimated for the entire observation period using a hypsometric approach to take

77 into account the difference of altitude between the river and the floodplain (see  
78 Supplementary Information).

79

## 80 2.2 Time series of water volume variations

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

$$83 \quad V_{SW}(t) = R_e^2 \sum_{j \in S} P(\lambda_j, \varphi_j, t) (h(\lambda_j, \varphi_j, t) - h_{\min}(\lambda_j, \varphi_j, P(\lambda_j, \varphi_j, t))) \cos(\varphi_j) \Delta \lambda \Delta \varphi \quad (1)$$

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

90 Accordingly, the time variations of volume of *TWS* anomalies from Level-2 GRACE  
91 solutions filtered using an Independent Component Analysis (ICA) approach (Frappart *et al.*,  
92 2011b) are computed following Ramillien *et al.* (2005):

$$93 \quad \Delta V_{TWS}(t) = R_e^2 \sum_{j \in S} \Delta h_{tot}(\lambda_j, \varphi_j, t) \cos(\varphi_j) \Delta \lambda \Delta \varphi \quad (2)$$

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

95

## 96 3. Results

97 For the very first time, a continuous mapping of surface water levels and surface water  
98 volumes, as well as their temporal dynamics at interannual time-scale, are presented for the  
99 Amazon River, the largest drainage basin on Earth. First, monthly surface water level maps  
100 are obtained by combining multisatellite-based wetland maps (Papa *et al.*, 2010; Prigent *et al.*,

101 2007; 2012) with 534 altimetry-derived water levels in the Amazon basin (Santos da Silva *et*  
102 *al.*, 2012) (see the location of ENVISAT RA-2 altimetry stations in Figure 1a) over the period  
103 2003-2007 at monthly time-scale (see Maps of surface water levels in section Methods or  
104 Frappart *et al.*, 2008; 2010 and 2011a for more details). Focusing on the signature of the 2005  
105 drought on Amazon surface water, the map of anomaly of minimum water levels for 2005  
106 (Figure 1b) shows that the whole wetland complex of the Central Amazon exhibits large  
107 negative values, with the greatest anomalies registered for the Purus (64.9°-61°W and 2°-  
108 4.5°S), Madeira (between 55.67°-59.9°W and 1.25°-5.25°S), and Mamiraua (between 64.67°-  
109 67.4°W and 1.4–3.1°S) wetlands. The large wetland complexes of Abanico of Pastaza River  
110 in Peru (between 74°-76.8°W and 3°-5°S), and Llanos de Mojos in Bolivia (between 63°-  
111 69°W and 11°-16°S) are also strongly affected in comparison to the northern part of the basin.  
112 These minima derived from radar altimetry are consistent with anomalies (computed on  
113 longer time periods) of levels estimated from *in situ* gauge records: -2.4 m at Tabatinga  
114 (69.9°W, 4.25°S) (Zeng *et al.*, 2008), -4.8 m in Iquitos (72.28°W, 3.43°S), between two and  
115 five meters on several locations along the Amazonas (Peru) and its major tributaries, and  
116 along the Solimões and its southern tributaries, -4 m at Manaus (60.04°W, 3.15°S) at the  
117 mouth of the Negro River (Marengo *et al.*, 2008a).

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

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

135 This very unique opportunity to monitor the changes of water level all along the hydrological  
136 cycle at monthly time-scale is illustrated in Figure 2 (along with Figure S2) for the drought of  
137 2005. The anomalies of surface water levels averaged over two consecutive months during  
138 2005 are compared with bi-monthly anomalies of rainfall from Tropical Rainfall Measuring  
139 Mission (TRMM, see Supplementary Information) (with an advance of two months) and TWS  
140 from GRACE (Figure 2 for the dry season, from July to December, and Figure S2 for the  
141 rainy season, from January to July). Rain deficits (upper panel) in the northern and western  
142 part of the basin in the heart of the rainy season (May-June), are responsible for anomalously  
143 low levels in the wetlands of the central corridor of the Amazon two months later (September-  
144 October), in good accordance with the TWS observations (lower panel). The spatial and  
145 temporal patterns in the anomalies of surface water (center panel) are consistent with both *in*  
146 *situ* measurements of water levels and discharges and satellite-derived observations of TWS  
147 (lower panel). For instance, in the central part of the Amazon (from Manacapuru ( $60.61^{\circ}\text{W}$ ,  
148  $3.31^{\circ}\text{S}$ ) to Obidos), the surface water maps present levels close or above the mean until May-  
149 June 2005 (Figure S2) that then started to drop until a minimum in September-October 2005  
150 (Figure 2) is reached, similarly to what was recorded by gauges (Tomasella *et al.*, 2011). In

151 the Madeira basin, the water levels between 10°S and 5°S were close to the mean until  
152 March-April 2005, and then below, with a minimum in September close to 5°S as observed in  
153 Fazenda Vista Alegre (60.03°W, -4.90°S). In the Negro basin, important contrast is observed  
154 between the upper (above the mean over the whole period) and the lower (above normal until  
155 June 2005 and then below the mean of several meters after July-August 2005) parts of the  
156 basin. These results are also in good agreement with what was observed at the gauges of  
157 Manaus (60.04°W, 3.15°S) and Serrinha (64.88°W, 0.48°N) (Marengo *et al.*, 2008a;  
158 Tomasella *et al.*, 2011). The lack of backwater effect (*i.e.*, the control of the water levels in  
159 the lower Negro by the stages of the Solimões (Meade *et al.*, 1991; Filizola *et al.*, 2009)) is  
160 clearly visible in September-October 2005 with anomalies of minimum of surface water  
161 reaching -3 m close to the mouth of the Negro River. These minima are not caused by deficit  
162 of rainfall but can be related to below normal water levels in the southwestern tributaries of  
163 the Solimões (Tomasella *et al.*, 2011). These maps of surface water levels permit to spatialize  
164 and quantify the water deficit between Serrinha and Manaus, confirming what has been  
165 coarsely detected by GRACE (Chen *et al.*, 2009 and Figure 2 lower panel).

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



176 These differences in time shift are consistent with what we know about the dynamics of  
177 surface in these sub-basins. The white waters (turbid with large amount of dissolved organic  
178 carbon) originating from the Andes loaded with sediments during their stay in the extensive  
179 floodplains distributed along the Solimões and most of the tributaries forming the Madeira  
180 have a longer residence time in the basin than the clear waters (transparent containing low  
181 content of dissolved organic carbon) of the Tapajos descending from the Brazilian shield  
182 through numerous waterfalls and rapids. The analysis of the 2005 annual cycle also reveals  
183 differences among these sub-basins. Volume of surface water in the Solimões basin was close  
184 to the mean or above during the rising period, peaking at a value greater than  $+\sigma$  in May, and  
185 declined rapidly with a minimum reached below  $+\sigma$  in October (Figure 3b). Similar behavior  
186 is found in the Tapajos (with a peak reached in April, one month earlier than usual, Figure 3f).  
187 Most of surface waters in the Tapajos are located in the large estuary formed by its encounter  
188 with the Amazon. At its mouth, its level is controlled by the stage of the Amazon. This can  
189 account for the similar temporal pattern found in Tapajos and Solimões 2005 annual cycle for  
190 surface waters. The lower agreement with discharge ( $R=0.71$ ) at interannual time-scale is  
191 more likely caused by the differences of hydrological regime between the upper and lower  
192 parts of the Tapajos (Figure 3f). On the contrary, the volume of surface water in the Madeira  
193 basin was below the mean until May, and then close to the mean (Figure 3d). These results are  
194 consistent with what was observed at *in situ* gauges (Marengo *et al.*, 2008a; Tomasella *et al.*,  
195 2011).

196 The impact of the 2005 drought was quantified for the surface water storage and the TWS for  
197 the whole Amazon basin (respectively 129 and 245 km<sup>3</sup> below the 2003-2007 average), and  
198 for the three sub-basins mentioned above for which different hydrological behaviors are  
199 observed during the 2005 drought (Table 1). The minimum volume of water stored in the  
200 Amazon was by 71% lower for the surface reservoir, under the assumption that the storage

201 below the minimum water level can be neglected, compared to the average during 2003-2007,  
202 and by 29% for the total hydrological reservoirs. If the 2005 drought strongly affected the  
203 four different western and southern tributaries, its impact on TWS also differs from one  
204 another, giving us information on the importance of the surface reservoir in the Amazon  
205 basin. Notice that surface water storage and TWS were much more affected by drought in the  
206 Solimões basin than in the three other tributaries. This coincides with areas of largest  
207 anomalies of MCWD and increase in tree mortality (Aragão *et al.*, 2007; Lewis *et al.*, 2011),  
208 and with regions with important fire activity in 2005 (Koren *et al.*, 2007).

209

#### 210 **4. Discussion and Conclusion**

211 Our results provide the first pluri-annual estimates of the variations of surface water storage in  
212 a large basin at monthly time-scale. They reveal that during 2003-2007, the variations of  
213 surface water reservoir vary from 800 to 1,000 km<sup>3</sup> per year, which represents 15-20% of the  
214 water volume that flew out of the Amazon basin and about half of the variations of the total  
215 amount of water in the Amazon basin as detected using GRACE data. This result is 3 to 4  
216 times greater than what was found by a previous study solving the water balance equation  
217 with gravimetric and imaging satellite methods (*i.e.*, GRACE, SRTM, GPCP and JERS-1) for  
218 six GRACE gridcells of 330 km of spatial resolution encompassing the floodplains along the  
219 Amazon mainstem (Alsdorf *et al.*, 2010). The major reason of this discrepancy must come  
220 from the leakage from other regions, due to the spherical harmonics representation of the  
221 GRACE data, which contaminate the signal at the GRACE gridcell resolution. Our estimates  
222 agree well with i) analysis of GRACE data and GLDAS/NOAH outputs which show that the  
223 TWS is equally partitioned between surface and sub-surface reservoirs, and soil water (Han *et*  
224 *al.*, 2009), and to ii) modeling results from ensemble hydrological simulations with river  
225 routing which found that surface water and shallow groundwater represents 73% of the TWS

226 in the Amazon basin (Kim *et al.*, 2009). In addition, the method presented here to derive  
227 water levels from multisatellite datasets over rivers and floodplains offers the first opportunity  
228 to continuously monitor the mass transport in the surface water reservoir before the launch of  
229 the NASA-CNES Surface Water and Ocean Topography (SWOT) mission in 2019. It makes  
230 possible to study the changes affecting the hydrological cycle in the large river basins covered  
231 with floodplains. It also helps better understand the complex dynamics of surface water in  
232 large drainage basins (*i.e.*, back water effects, Amazon flood-pulse linked to the strong  
233 seasonality of the rainfall, or time residence of water in the floodplains).

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

244

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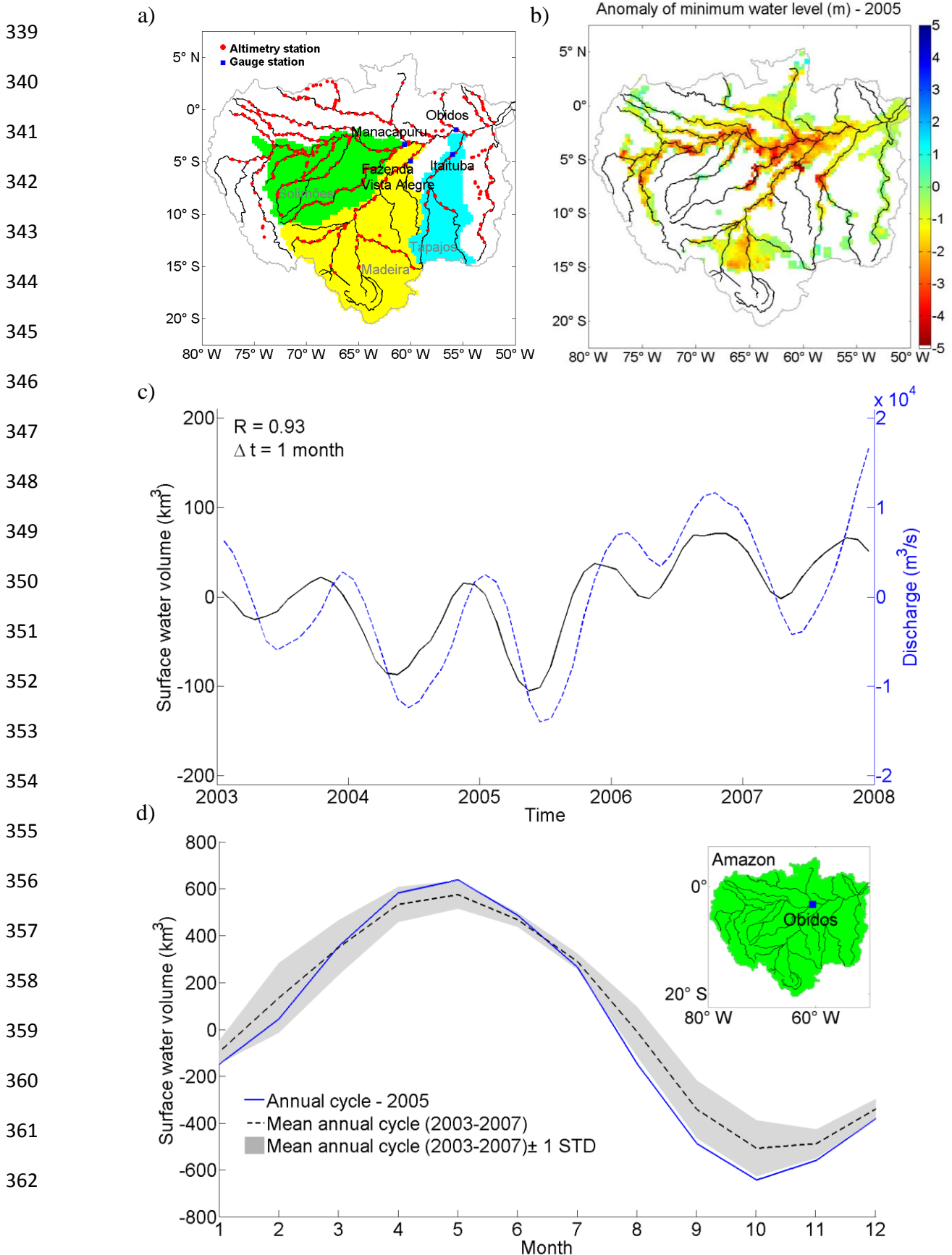
329 Table 1: Anomaly of minimum of water volume in 2005 (2003-2007 reference period) for the  
330 Amazon and some of its tributaries (km<sup>3</sup> and %).

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

<b>2005 Anomaly of minimum of water volume</b>	<b>Surface Water Storage* (km<sup>3</sup>)</b>	<b>(%)</b>	<b>Total Water Storage (km<sup>3</sup>)</b>	<b>(%)</b>
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

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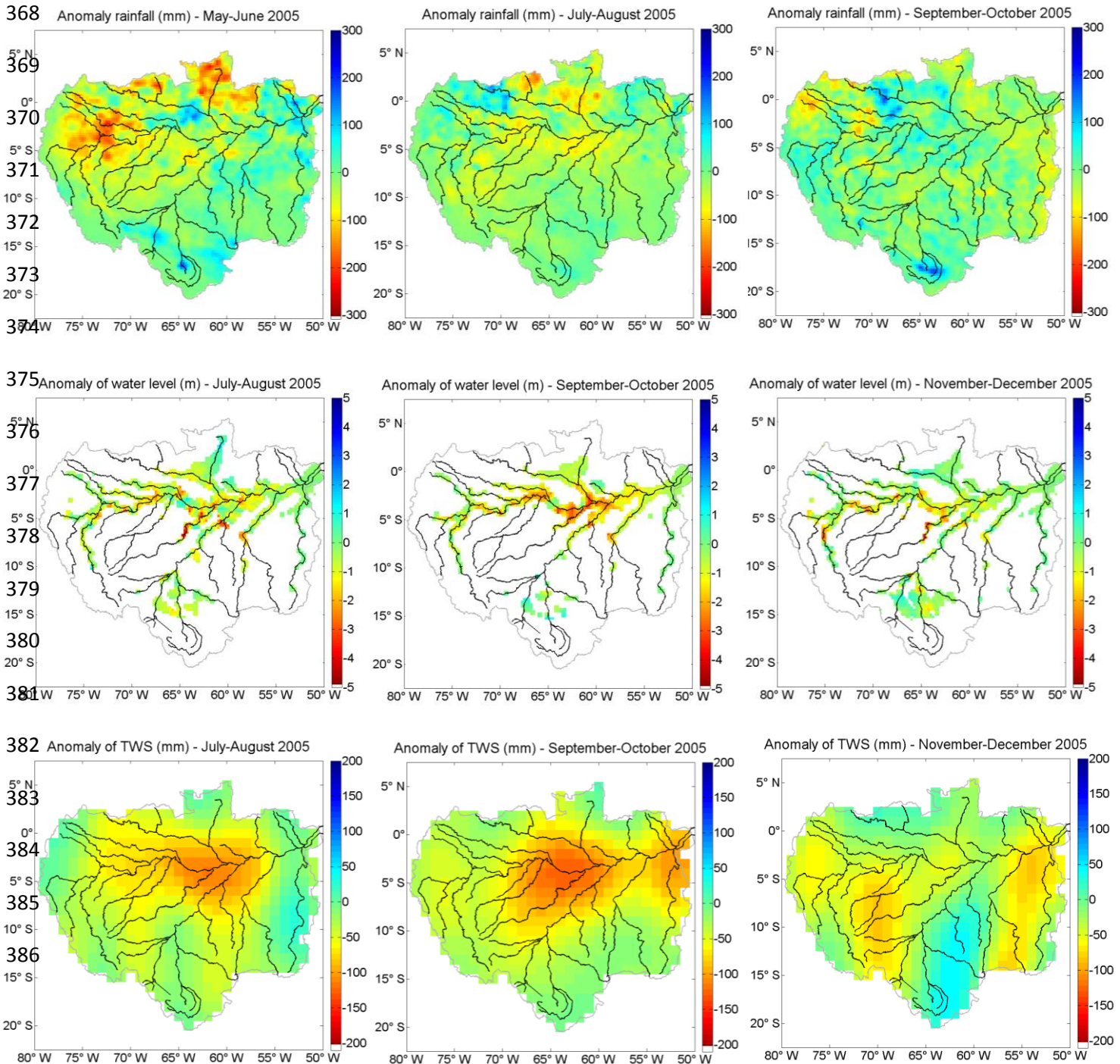
334 Figure 1: a) Map of the Amazon basin with locations of altimetry stations (red points) and *in*  
 335 *situ* discharge gauges (blue). b) Map of anomaly of water level for 2005 (2003-2007 reference  
 336 period). c) Interannual variations of surface water volume of the Amazon (black) and  
 337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





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



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

