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Interannual variability in water storage over 2003-2008 in the Amazon Basin from GRACE space gravimetry, in situ river level and precipitation data

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2 **Interannual variability in water storage over 2003-2007 in the Amazon Basin**
3 **from GRACE space gravimetry, in situ river level**
4 **and precipitation data**
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6

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26
27 **Abstract**
28 We investigate the interannual variability over 2003-2007 of different hydrological parameters in
29 the Amazon river basin: vertically-integrated water storage from the GRACE space gravimetry
30 mission, surface water level over the Amazon River and its tributaries from in situ gauges, and
31 precipitation. We analyze the spatio-temporal evolution of total water storage from GRACE and
32 in situ river level along the Amazon River and its main tributaries. We also perform an Empirical
33 Orthogonal Decomposition of the total water storage, river level and precipitation over the whole
34 basin. We find that this period is characterized by two major hydrological events: a temporary
35 drought that affected the western part of the basin during year 2005 and very wet conditions in
36 the eastern, northern and southern regions of the basin, peaking in mid-2006. Derivative of basin-
37 average water storage from GRACE is shown to be highly correlated to the Southern Oscillation
38 Index, indicating that the spatio-temporal change in hydrology of the Amazon basin is at least
39 partly driven by the ENSO (El Nino-Southern Oscillation) phenomenon, as noticed in previous
40 studies.

41

42 **Keywords:** GRACE, Hydrology, Climate Change, ENSO, South America.

43 **Introduction**

44 In most world river basins, information on the hydrological regime is mainly based on rainfall,
45 river stage (water level) and discharge data. However in many parts of the world, substantial
46 sections of river basins (if not the whole basin in some cases) are void of in situ data. Moreover,
47 some of the existing hydrological networks are deteriorating. Concerning precipitation, gridded
48 data sets and global reanalyses available since two decades have helped in solving in situ
49 coverage problems. But for studying water balance at a river basin scale, precipitation provides
50 insufficient information. In the recent years, remote sensing data (such as altimetry-based surface
51 water levels and total water storage from space gravimetry) have proved to be very helpful for
52 studying the water balance at sub-basin and basin scales. In particular total water storage, now
53 measured by the GRACE (Gravity Recovery and Climate Experiment) space gravimetry mission,
54 is a parameter which was not accessible from direct observations so far. The GRACE space
55 mission, launched in 2002, was developed by NASA (USA) and DLR (Germany) to measure
56 spatio-temporal change of the Earth gravity field at monthly interval, with a ground resolution of
57 300-400 km. On time scales ranging from months to decades, temporal gravity variations mainly
58 result from to surface redistribution of water inside and among outer fluid envelopes of the Earth
59 (Tapley et al., 2004, Wahr et al., 2004). Over land, GRACE provides measurement of vertically-
60 integrated water storage change in river basins, i.e., water storage in surface reservoirs, in upper
61 layers of soil and underground water reservoirs.

62 Several studies have demonstrated the usefulness of GRACE to study the water balance of large
63 river basins (e.g., Chen et al., 2005; Schmidt et al., 2006, 2008, Rodell et al., 2007, Syed et al.,
64 2008, Ramillien et al., 2008). Some of them concern the Amazon basin as a whole and focus on
65 the seasonal cycle (e.g., Syed et al., 2005, Crowley et al. 2007). Only few studies investigated
66 the interannual variability of Amazon hydrology (e.g., Chen et al., 2009 who focused on the 2005

67 drought reported in the central part of the Amazon basin by Zeng et al., 2008a).
68 In the present study, we concentrate on the interannual variability in land water storage using
69 GRACE solutions. But instead of considering the Amazon basin as a whole, we analyze the
70 spatial variability of the water storage signal along the main river, from upstream to downstream,
71 as well as along the main tributaries of the Amazon River (Negro, Madeira and Tapajos). We also
72 analyze other hydrological variables such as precipitation and in situ water levels. This allows us
73 investigating the coherence of the hydrological spatio-temporal variability and detecting
74 significant different behaviors at sub-basin scale.

75

76 **Hydrological regime of the Amazon River basin**

77 The Amazon river basin is the largest river basin of the world in terms of area ($6.2 \times 10^6 \text{ km}^2$)
78 and annual mean discharge to the Atlantic Ocean (6300 km^3 per year). The contour of the
79 Amazon basin is shown in Fig.1. Although the Amazon basin is not one of the most populated of
80 the world, its hydrological regime has been the object of several review studies (e.g., Costa and
81 Foley, 1999, Marengo and Nobre, 2001, Marengo, 2005,; just to quote a few) and numerous
82 detailed studies (see Marengo, 2005 and references herein). We briefly summarize the main
83 aspects of the hydrological cycle in the Amazon basin. In terms of annual average, precipitation
84 and runoff amount to $\sim 2100 \text{ mm/yr}$ and 1000 mm/yr respectively (mean of values given in Table
85 1 of Marengo, 2005). On the assumption that on long-term average, precipitation minus runoff
86 equates evapotranspiration, this gives for the latter a mean value of 1400 mm/yr .

87 The annual cycle of the water balance is very strong. Along the Amazon river, flow exhibits a
88 maximum in May-June, about 3 months after the peak (in February) of the mean precipitation
89 over the basin. This lag results from the time needed for the surface runoff to flow through the
90 basin. The annual amplitude of the main river water level ranges between 2 and 18 meters

91 depending on the location, the maxima being observed at the downstream parts of Jurus, Purus
92 and Madeira rivers (Guyot et al., 1999). Difference in hydrological regime is observed between
93 the northern and southern parts of the basin, especially for precipitation. The southern part
94 closely follows the mean regime in the northern part, precipitation peaks in April (Marengo 2005,
95 Espinoza Villar et al., 2008).

96 Significant interannual variability is observed in hydrological parameters. Analysis of rainfall
97 data over the last decades show clear fluctuations associated with El Nino and La Nina, the warm
98 and cold phases of ENSO (El Nino-Southern Oscillation) (e.g., Coe et al., 2002, Zeng, 1999).
99 According to Marengo (2005), reduced precipitation and runoff are found during El Nino years
100 on average over the Amazon basin while the inverse occurs during La Nina phases.

101 On longer time scales, analyses of rainfall data have detected a small decreasing trend over the
102 whole basin for 1929-1998 but such a trend has to be confirmed (Marengo, 2004). On the other
103 hand, important decadal fluctuations are also observed, with contrasting behaviors between
104 northern and southern Amazonia (Marengo, 2004, 2005). More detailed analysis indicates that
105 the northern Amazonia rainfall is dominated by ENSO-type fluctuations while southern
106 Amazonia exhibits essentially decadal variability.

107 Some studies have investigated the possible impacts of human activities (e.g., land surface
108 changes associated with deforestation, cultivation and road constructions; reservoirs building for
109 hydroelectric energy; generation of aerosols from biomass burning) on the hydrological regime of
110 the Amazon basin. All these factors affect the water and energy balance of the region. For
111 example, Costa et al. (2003) have detected increased mean and high-flow season discharge in
112 eastern Amazonia, even though rainfall has not increased. Callede et al. (2004) also suggested
113 increased mean discharge of the main river near Obidos and interpret this as a result of
114 deforestation, but Marengo (2004) attributes this to natural decadal variability. The effect of

115 deforestation has been investigated by coupled climate models (e.g., Zhang et al., 2001). Most
116 models indicate significant reduction in precipitation, evapotranspiration and runoff together with
117 increased air temperature. In most models, the dry season becomes longer. The models are able to
118 capture decadal fluctuations and ENSO-type variability.

119

120 **Data**

121 *Space gravimetry data from GRACE*

122 Raw GRACE data are processed by different groups from the GRACE project (CSR and JPL,
123 USA, and GFZ in Germany). GRACE data are also processed by other groups (GSFC/NASA,
124 USA; GRGS, France and DUT, The Netherlands). The GRACE products provided over land by
125 all groups are expressed in equivalent water height, either as spherical harmonic coefficients up
126 to a given degree and order or as gridded data. Successive GRACE products releases have been
127 produced by the GRACE project during the last few years. Here we use the latest release (RL04)
128 of the CSR solutions ($1^\circ \times 1^\circ$ global grids at monthly interval). This new data set (available at
129 <http://grace.jpl.nasa.gov/data/mass/>) includes an implementation of the carefully calibrated
130 combination of de-stripping and smoothing, with a 300 km half width Gaussian filter (Chambers
131 2006). (<http://grace.jpl.nasa.gov/data/mass/>). Compared to earlier products (contaminated by
132 north-south strips due to aliasing of high-frequency atmospheric perturbations by the GRACE
133 coverage), the latest release is much less noisy owing to the de-stripping procedure applied to the
134 data. The spatial resolution is consequently improved. The gridded time series used in this study
135 covers the time span from January 2003 through December 2007.

136

137 *Precipitation*

138 We use daily precipitation data from Global Precipitation Climatology Project (Huffman et al.,

139 2001). These data, which consist of global gridded time series with a spatial resolution of $1^{\circ} \times 1^{\circ}$,
140 are available at <http://www.precip.gsfc.nasa.gov/>.

141

142 *Water level data*

143 For the water level (or stage) time series over the main river (Amazon) and its tributaries, we
144 used data from the ANA network. The Brazilian water agency ANA (“Agencia Nacional de
145 Aguas”) is responsible for maintenance of the water resources database for Brazilian watersheds.
146 This database is composed of hundreds of gauge stations, each one covering different time spans.
147 Water level measurements are performed usually once or twice daily. Even if some efforts have
148 been done in order to improve data gathering and spatio-temporal coverage of the network, many
149 of these stations have records with long temporal gaps. Herein we only take into account about a
150 hundred gauge stations over the Amazon watershed with available records spanning the period of
151 2003-2007.

152

153 **Interannual variability in total water storage and surface water levels in the Amazon basin**

154 Interannual total water storage (TWS) from GRACE, from 2003 to 2007, has been computed in
155 successive $4^{\circ} \times 4^{\circ}$ pixels (approximately the GRACE resolution) along the Amazon River,
156 arranged from upstream to downstream. Fig.2a shows the pixel location while Fig.2b shows TWS
157 temporal evolution for each pixel. To compute TWS, $1^{\circ} \times 1^{\circ}$ gridded GRACE data have been
158 spatially averaged over the pixel area and the annual cycle has been removed by simply adjusting
159 a sinusoid of 12-month period. TWS is expressed in water volume by simply multiplying
160 GRACE equivalent water height by the pixel area. From Fig.2b, we note that TWS interannual
161 variability significantly evolves along the main river. Upstream curves (pixels 1 and 2) show a
162 large negative trend, of $7-8 \text{ km}^3$, during the first half 2005. The minimum is reached by mid-

163 2005, then a slow positive recovery up to mid-2007 is observed. The next two pixels show a
164 positive oscillation centered early 2005. Pixels 5 to 8 display a slight minimum in mid-2005 then
165 an increase, with a large maximum in TWS in mid-2006. In pixel 7 which includes the Obidos
166 station, the maximum amplitude, relatively to the 2003-2005 period, reaches nearly 2 km^3 . The
167 GRACE data show that in mid-2005, the upstream part of the river experienced dry conditions
168 around mid-2005 (as described by Chen et al., 2009) while the downstream region became very
169 wet during the second half of 2006.

170 On Fig.2b are also superimposed river water levels. For each pixel, we averaged all available
171 stage data. . The annual cycle has been removed to each pixel average. Comparing TWS and
172 surface water level curves, we note very similar co-variation in most zones, except near the river
173 mouth (pixels 7 and 8) where TWS and water level show some discrepancy.

174 In Fig.2b are also presented similar curves (TWS and river water level) for the Amazon sub-
175 basins. Pixels 9-13 cover the portions of the Jurua, Purus and Madeira tributaries. These pixels
176 are dominated by the signature of the mid-2005 drought. Pixels 14 and 15 cover the northern part
177 of the Negro sub-basin. In this region, the main feature seen in TWS and surface water level is
178 the positive anomaly extending from mid-2005 to the end of 2006. Wet maximum is reached by
179 mid-2006. Pixels 16-18 cover the Tapajos tributary. This region shows a small negative anomaly
180 in mid-2005 (the eastern extension of the 2005 drought), followed by a large positive anomaly
181 which maximum is reached in Fall 2006. In terms of water storage, this maximum amounts to
182 $\sim 15 \text{ km}^3$ above the 2004-2005 average. Surface water levels closely follow TWS variations in all
183 these regions.

184
185 **Empirical Orthogonal Function decomposition of total water storage, river stage and**
186 **precipitation over the Amazon basin**

187 In order to get a synoptic view of the spatio-temporal variations in Amazon hydrology, we
188 performed an Empirical Orthogonal Function (EOF) decomposition (e.g., Preisendorfer, 1988) of
189 three hydrological parameters over the 5-year time span (January 2003 through December 2007):
190 TWS, river water level and precipitation. This method expresses a function $F_0(x,y,t)$ as a sum of
191 combined $X_n(x, y)$ spatial modes and $e_n(t)$ principal components (where x, y are geographical
192 coordinates and t is time; n is mode order). It allows extracting the different modes of spatial and
193 temporal variability of a signal. The first modes (which contain the largest variance of the total
194 signal) represent the dominant spatio-temporal components of the signal.

195 All data sets have been filtered out from the annual cycle by a 12-month moving-average filter, in
196 order to focus on the interannual variability. In Table 1 are presented the explained variances of
197 the two leading modes for each parameter. The EOF decomposition was performed by means of
198 the algorithm developed by Toumazou and Crétaux (2001).

199 Fig.3a (left hand side, from top to bottom) shows the mode 1 spatial patterns of the EOF
200 decomposition of TWS, river stage and precipitation over the Amazon basin. Corresponding
201 temporal curves (or principal components) are displayed in Fig.3b (left hand side). Spatial
202 patterns of mode 2 are presented in the right hand side of Fig.3a (arranged as for mode 1) while
203 the temporal curves are displayed in Fig.3b (right hand side). Fig.3a shows that all three variables
204 present similar spatial patterns. Following these results, it can be realized that the Amazon basin
205 is clearly divided into two zones (west and east) with opposite behaviour. Mode 1 is dominated
206 by a strong positive signal affecting the downstream portion of river Amazon (after its confluence
207 with the Madeira river) and also the Negro subbasin, plus a small area in the southern part of the
208 basin. Following the respective principal components depicted at Figure 3b (left), this signal
209 corresponds to a positive trend whose maximum is reached during the first half of 2006.

210 Mode 1 temporal curves display a large maximum in mid 2006 for all three variables. A very
211 strong correlation is noticed between their spatio-temporal patterns, in particular between TWS
212 and river stage, confirming results presented above for individual pixels. We note however that
213 the rising branch of the precipitation and river stage principal components (from the beginning of
214 2005 to mid-2006) is ahead of the TWS one by about 3 months. We also note a lag of TWS
215 compared to precipitation during the descending phase. This behaviour is likely to be related to
216 the time needed to water to spread out into surface and underground stores.

217 Spatial patterns and principal components of mode 2 for the three variables are shown in Fig.3a,b
218 (right hand side). This mode is clearly dominated by the mid-2005 drought that affected the
219 western part of the basin. It was particularly strong over Solimoes and Madeira subbasins.
220 According to the temporal curves, dry conditions also affected these regions in early 2004, but
221 with less intensity than in 2005. We observe a lag of about 3 months between TWS and
222 precipitation.

223 Some discrepancy is noticed between rainfall and TWS mode 2 patterns on the Xingu subbasin
224 (see Figure 1 for location). In fact, in this subbasin the TWS behaviour is well correlated to that
225 of its neighbour, the Tocantins basin. A similar feature is noticed for the the Tapajos subbasin
226 (located between the Tapajos and Madeira subbasins). A more detailed analysis at the subbasin
227 scale (not presented herein) shows that the rainfall patterns on the Tapajos subbasin is correlated
228 to the Madeira one while its TWS behaviour is more related to the Xingu one. This apparently
229 anomalous behaviour could be due to groundwater behaviour in this subbasin, which seems to be
230 somehow linked to the Xingu subbasin. This remains to be verified by a specific in depth study.

231 These EOFs results provide another way of displaying the spatio-temporal variability of Amazon
232 hydrology. We see that during the time span of analysis, two major events occurred: a temporary
233 drought during year 2005 affecting essentially the western part of the basin and very wet

234 conditions over a broad area covering the southern, northern and eastern portions of the basin.
235 Wetness maximum occurred in mid-2006 and was particularly high over the main river portion
236 located between Manaus (Negro-Solimoes confluence) and the Amazon mouth.

237 As expected, the surface water temporal variability over the Amazon basin, expressed herein by
238 the river stage's principal components, follows closely to the precipitation with a lag of a few
239 months. The TWS variability is also well correlated with the two other variables, but presents a
240 larger lag with precipitation.

241

242 **Change in TWS and the Southern Oscillation Index**

243 Several studies have investigated the interannual variability on rainfall and river discharge in the
244 Amazon basin (e.g., Grim, 2003, 2004, Espinoza Villar et al., 2008, Robertson and Mechoso,
245 1998, Ronchail and Gallaire, 2006). For example, Espinosa Villar et al. (2008) showed a clear
246 link between ENSO effects and rainfall in the northern and northeastern regions of the basin. El
247 Nino phase correspond to rainfall deficit in these regions while La Nina phase correspond to
248 rainfall increase. In addition to rainfall and surface streamflow, it is also worth to see if TWS is
249 influenced by ENSO. For that purpose we have computed the derivative of GRACE-based total
250 water storage over the entire Amazon basin and compared its temporal evolution with the
251 Southern Oscillation Index (SOI), a proxy of ENSO. The reason to look at TWS derivative
252 instead of TWS is because it is the variable to consider in the water balance equation (as directly
253 related to precipitation). On Fig.3a it was shown that TWS increase occurred in 2006 and end of
254 2007. The latter increase corresponds to the recent strong La Nina event. In Fig.4, is shown TWS
255 derivative evolution (averaged over the whole Amazon basin). We note a very strong positive
256 signal, maximum in early 2006 and another positive signal at the end of 2007 (coincident with the

257 La Nina event). In Fig.4 is superimposed the SOI index. As it can be seen on Fig. 4, there is a
258 good correlation between these curves, especially beyond 2005

259

260 **Conclusion**

261 In this study, we have investigated the spatio-temporal evolution of the vertically-integrated
262 water storage over 2003-2007, as given by GRACE space gravimetry, over the Amazon basin,
263 focusing on the interannual variability. We have compared TWS over individual pixels of $4^{\circ} \times 4^{\circ}$
264 from upstream to downstream along the Amazon River, as well as over different portions of the
265 main tributaries. A clear difference is noticed between the western and northeastern/southeastern
266 parts of the basins. The 2005 drought reported by earlier studies affects TWS in the center of the
267 basin. The largest signal detected by this analysis is a strong positive TWS anomaly in 2006
268 affecting the eastern, northeastern and southern parts of the basin. Another positive anomaly is
269 also apparent by the end of 2007 that we can link to the recent La Nina event.

270 To study the spatio-temporal variability of the Amazon basin (as well as other large river basins
271 worldwide), the use of GRACE looks very promising because it provides an integrated
272 information of much broader scale than rainfall –which is highly variable spatially- and in situ
273 stages or discharges which are very local response to precipitation forcing. In addition, GRACE-
274 based TWS is a quantity that is directly comparable to hydrological model outputs. It is thus very
275 helpful when performing model comparisons. Among future research directions, assimilation of
276 GRACE products into the hydrological models is a key issue. Preliminary attempts are already in
277 progress.

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286

287

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365

366 **Figure captions**

367

368 Fig.1: Amazon river watershed with its main subbasins

369

370 Fig.2 : (a) location of the $4^{\circ} \times 4^{\circ}$ pixels in which terrestrial water storage (TWS) from GRACE
371 and average in situ river levels are computed. (b) Temporal evolution of TWS (black) and
372 average river level (red) for each pixel

373

374 Fig.3a : Spatial patterns of the EOF decomposition of precipitation, TWS and insitu river levels
375 (arranged from top to bottom). Mode 1 : left hand side panels. Mode 2 : right hand side panels.

376

377 Fig.3b: Temporal curves of the EOF decomposition. Black, red and green curves refer to
378 precipitation, TWS and river level respectively. Mode 1 : left hand side panels. Mode 2 : right
379 hand side panels.

380

381 Fig.4 : Time derivative of mean TWS over the Amazon basin (black curve) and SOI index (pink
382 curve)

383

384 **Table caption**

385 Table 1 – EOF leading modes: % of explained variance

386

Data	First EOF mode	Second EOF mode
Rainfall	61.54	19.33
GRACE	72.66	21.05
River stage	63.71	17.25

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Figure 1
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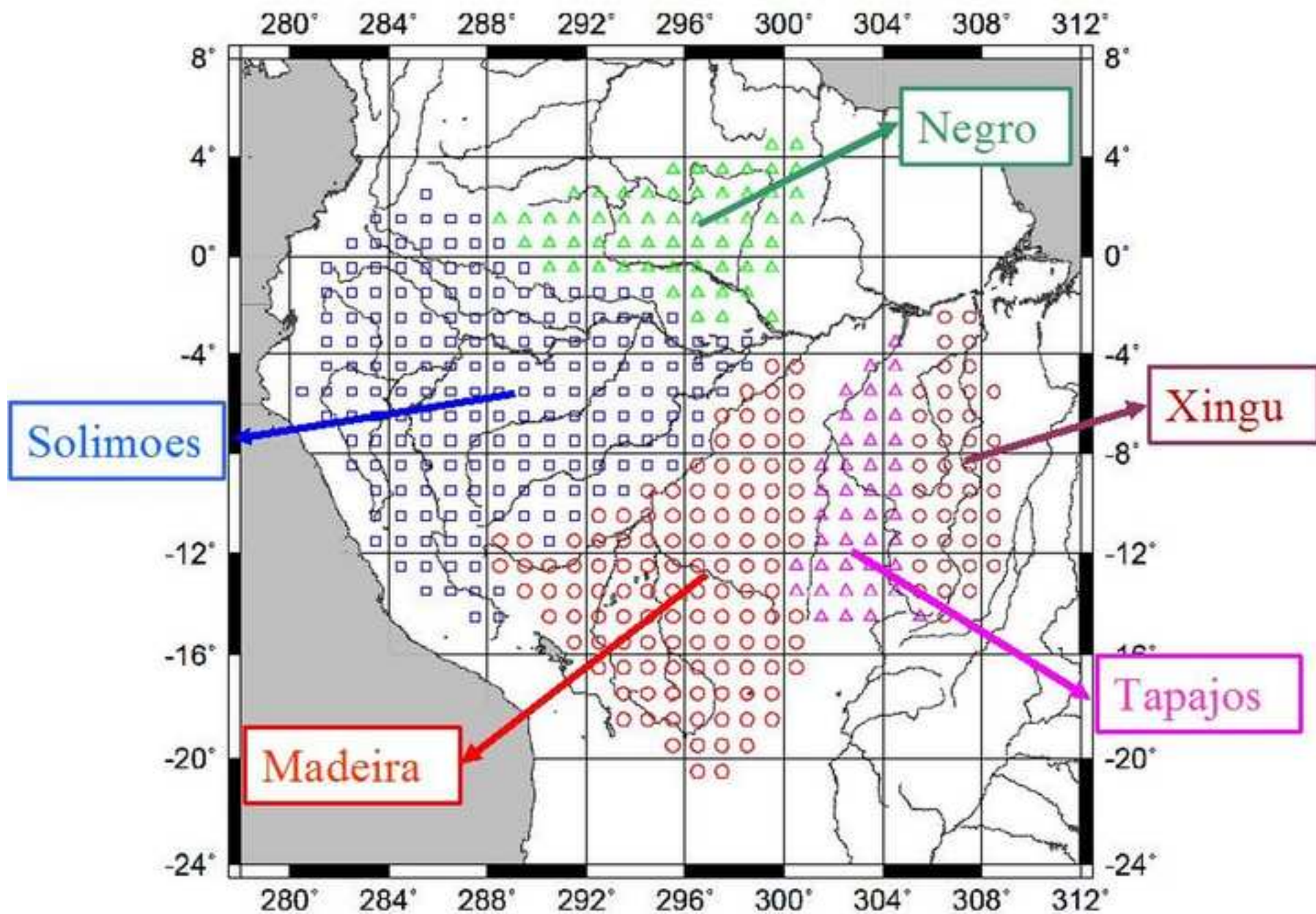


Figure 2a

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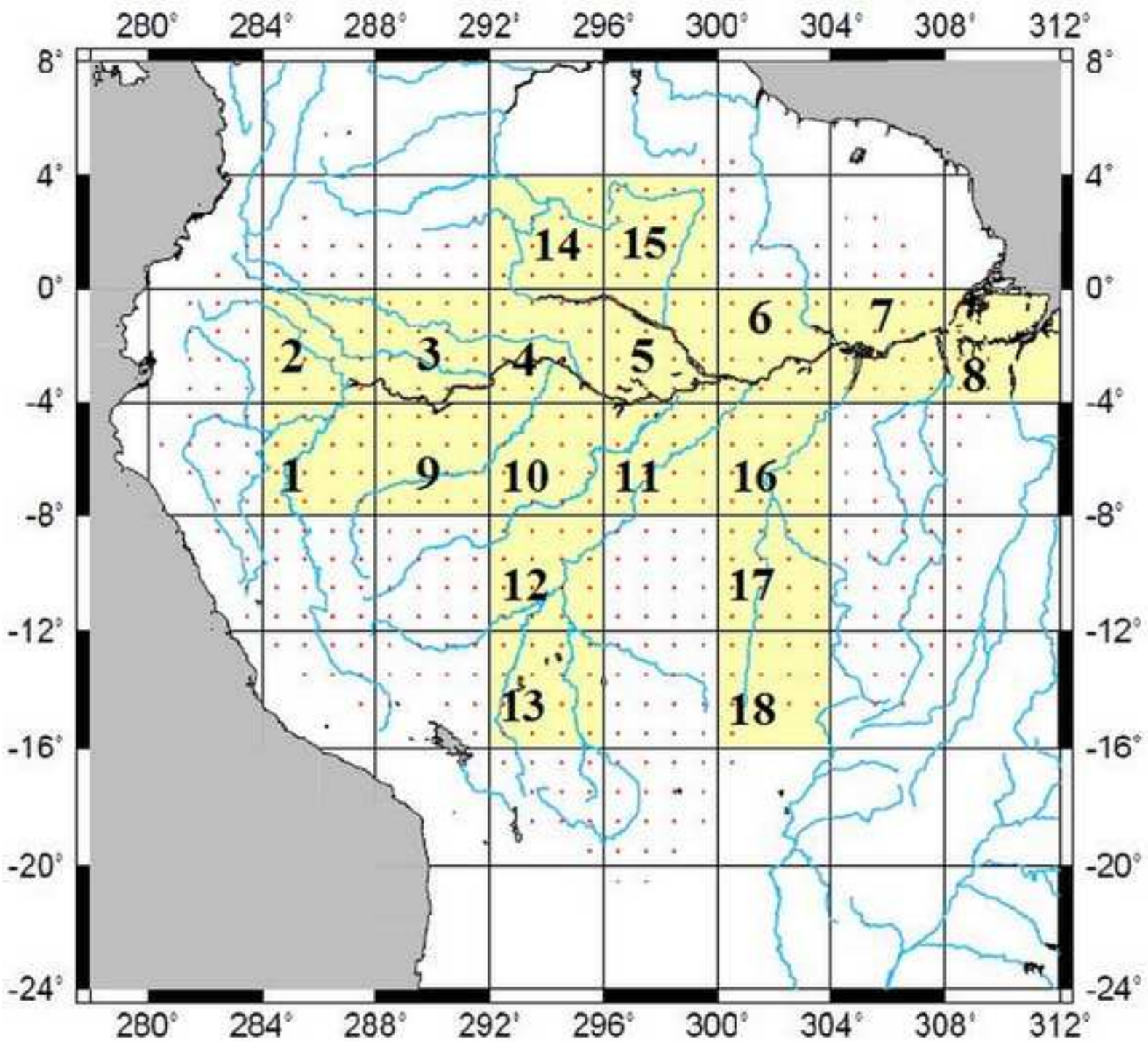


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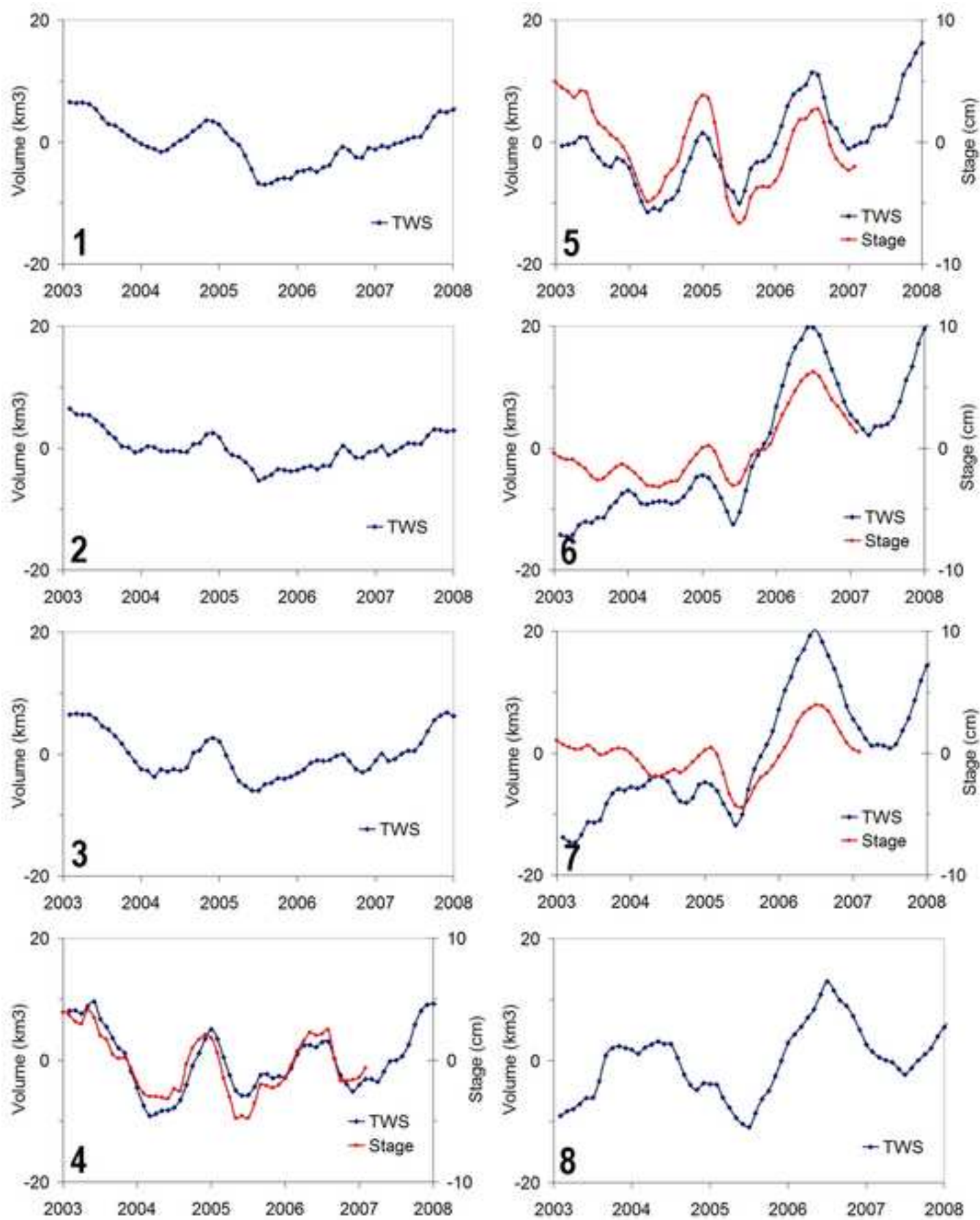


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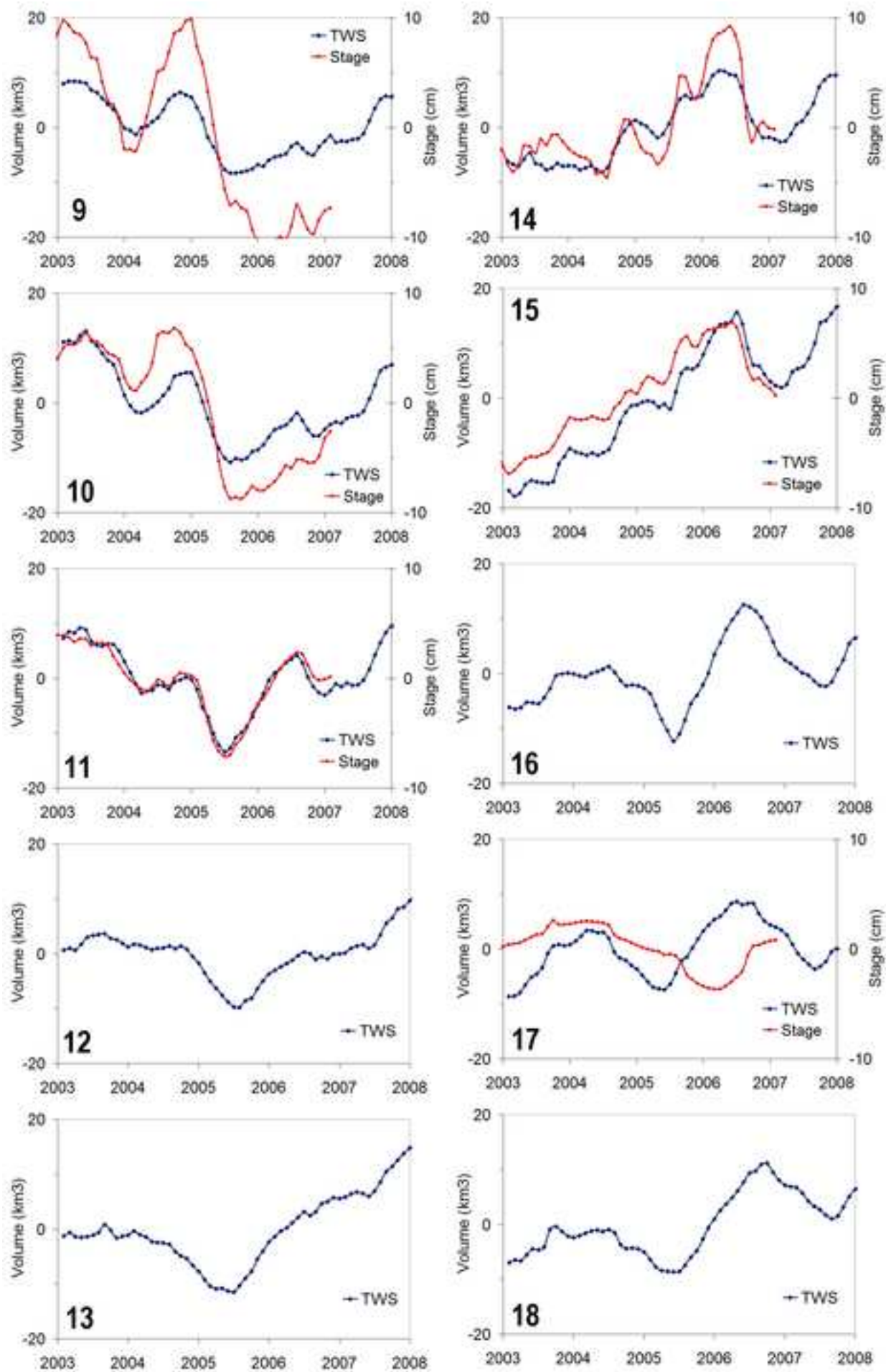


Figure 3a

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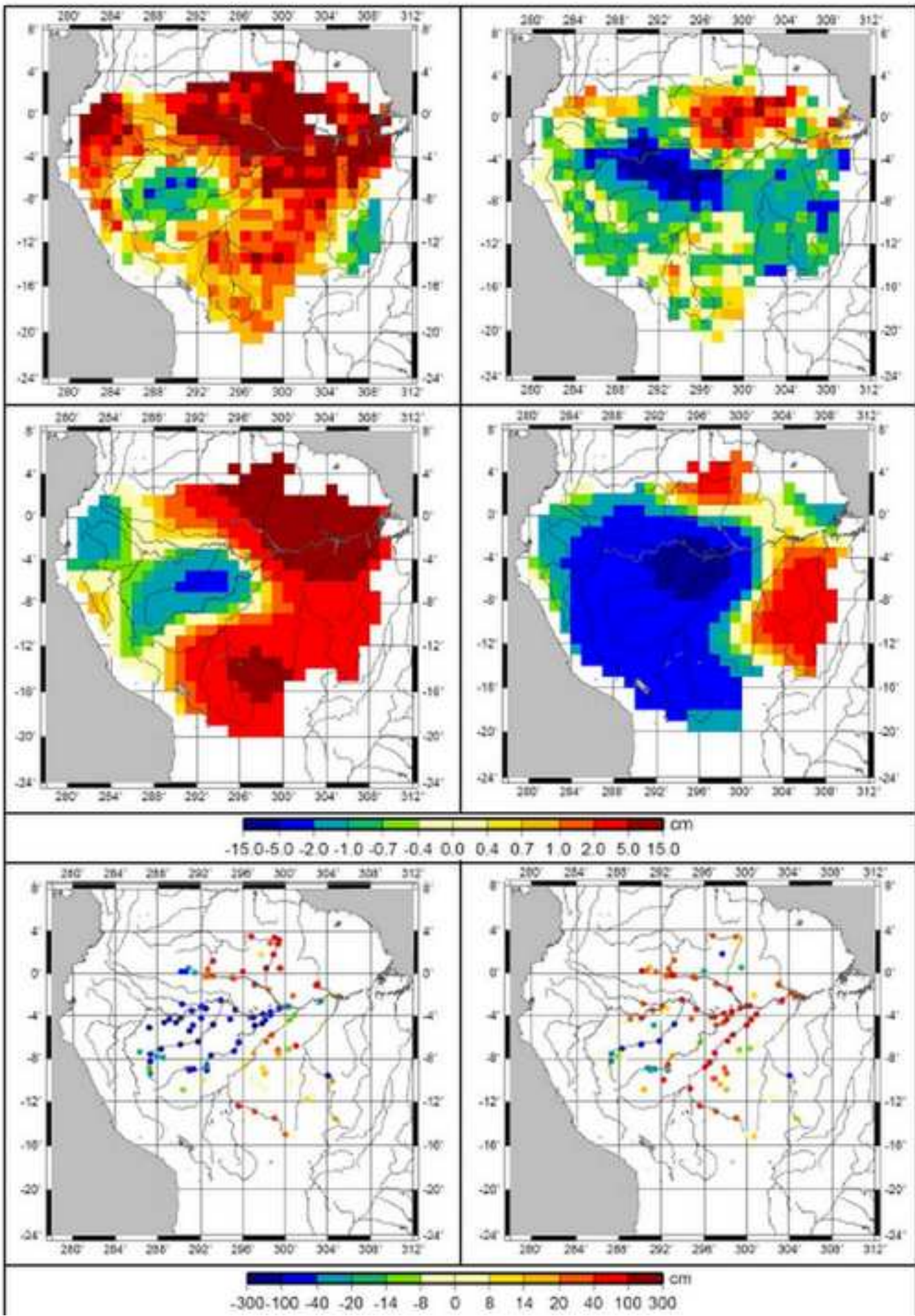


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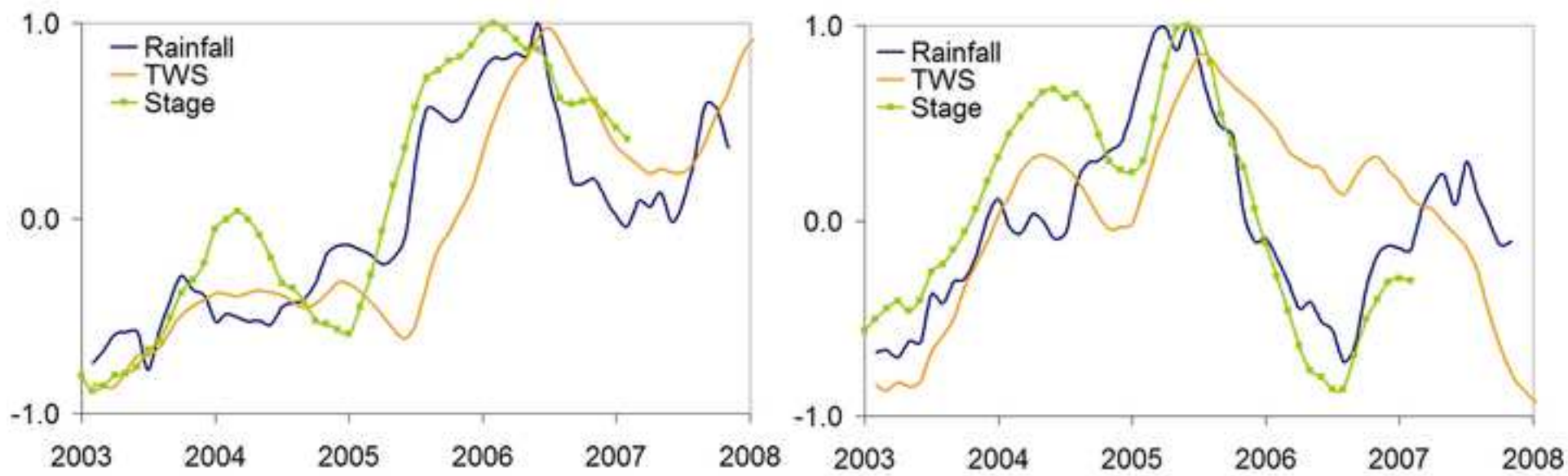


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