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Abstract

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

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

Introduction

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

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

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

Hydrological regime of the Amazon River basin

The Amazon river basin is the largest river basin of the world in terms of area (6.2 x 106 km_2) and annual mean discharge to the Atlantic Ocean (6300 km^3 per year). The contour of the Amazon basin is shown in Fig.1. Although the Amazon basin is not one of the most populated of the world, its hydrological regime has been the object of several review studies (e.g., Costa and Foley, 1999, Marengo and Nobre, 2001, Marengo, 2005,; just to quote a few) and numerous detailed studies (see Marengo, 2005 and references herein). We briefly summarize the main aspects of the hydrological cycle in the Amazon basin. In terms of annual average, precipitation and runoff amount to ~2100 mm/yr and 1000 mm/yr respectively (mean of values given in Table 1 of Marengo, 2005). On the assumption that on long–term average, precipitation minus runoff equates evapotranspiration, this gives for the latter a mean value of 1400 mm/yr.

The annual cycle of the water balance is very strong. Along the Amazon river, flow exhibits a maximum in May-June, about 3 months after the peak (in February) of the mean precipitation over the basin. This lag results from the time needed for the surface runoff to flow through the basin. The annual amplitude of the main river water level ranges between 2 and 18 meters depending on the location, the maxima being observed at the downstream parts of Jurus, Purus and Madeira rivers (Guyot et al., 1999). Difference in hydrological regime is observed between the northern and southern parts of the basin, especially for precipitation. The southern part closely follows the mean regime in the northern part, precipitation peaks in April (Marengo 2005, Espinoza Villar et al., 2008).

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

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

Some studies have investigated the possible impacts of human activities (e.g., land surface changes associated with deforestation, cultivation and road constructions; reservoirs building for hydroelectric energy; generation of aerosols from biomass burning) on the hydrological regime of the Amazon basin. All these factors affect the water and energy balance of the region. For example, Costa et al. (2003) have detected increased mean and high-flow season discharge in eastern Amazonia, even though rainfall has not increased. Callede et al. (2004) also suggested increased mean discharge of the main river near Obidos and interpret this as a result of deforestation, but Marengo (2004) attributes this to natural decadal variability. The effect of deforestation has been investigated by coupled climate models (e.g., Zhang et al., 2001). Most models indicate significant reduction in precipitation, evapotranspiration and runoff together with increased air temperature. In most models, the dry season becomes longer. The models are able to capture decadal fluctuations and ENSO-type variability.

Data

Space gravimetry data from GRACE

Raw GRACE data are processed by different groups from the GRACE project (CSR and JPL, USA, and GFZ in Germany). GRACE data are also processed by other groups (GSFC/NASA, USA; GRGS, France and DUT, The Netherlands). The GRACE products provided over land by all groups are expressed in equivalent water height, either as spherical harmonic coefficients up to a given degree and order or as gridded data. Successive GRACE products releases have been produced by the GRACE project during the last few years. Here we use the latest release (RL04) of the CSR solutions (1°x1° global grids at monthly interval). This new data set (available at http://grace.jpl.nasa.gov/data/mass/) includes an implementation of the carefully calibrated combination of de-striping and smoothing, with a 300 km half width Gaussian filter (Chambers 2006). (http://grace.jpl.nasa.gov/data/mass/). Compared to earlier products (contaminated by north-south strips due to aliasing of high-frequency atmospheric perturbations by the GRACE coverage), the latest release is much less noisy owing to the de-stripping procedure applied to the data. The spatial resolution is consequently improved. The gridded time series used in this study covers the time span from January 2003 through December 2007.

Precipitation

We use daily precipitation data from Global Precipitation Climatology Project (Huffman et al., 2001). These data, which consist of global gridded time series with a spatial resolution of 1°x1°, are available at http://www.precip.gsfc.nasa.gov/.

Water level data

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

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

Interannual total water storage (TWS) from GRACE, from 2003 to 2007, has been computed in successive 4°x4° pixels (approximately the GRACE resolution) along the Amazon River, arranged from upstream to downstream. Fig.2a shows the pixel location while Fig.2b shows TWS temporal evolution for each pixel. To compute TWS, 1°x1° gridded GRACE data have been spatially averaged over the pixel area and the annual cycle has been removed by simply adjusting a sinusoid of 12-month period. TWS is expressed in water volume by simply multiplying GRACE equivalent water height by the pixel area. From Fig.2b, we note that TWS interannual variability significantly evolves along the main river. Upstream curves (pixels 1 and 2) show a large negative trend, of 7-8 km^3, during the first half 2005. The minimum is reached by mid-

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

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

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

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

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

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

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

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

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

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

These EOFs results provide another way of displaying the spatio-temporal variability of Amazon hydrology. We see that during the time span of analysis, two major events occurred: a temporary drought during year 2005 affecting essentially the western part of the basin and very wet conditions over a broad area covering the southern, northern and eastern portions of the basin. Wetness maximum occurred in mid-2006 and was particularly high over the main river portion located between Manaus (Negro-Solimoes confluence) and the Amazon mouth.

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

Change in TWS and the Southern Oscillation Index

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

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

Conclusion

In this study, we have investigated the spatio-temporal evolution of the vertically-integrated water storage over 2003-2007, as given by GRACE space gravimetry, over the Amazon basin, focusing on the interannual variability. We have compared TWS over individual pixels of 4°x4° from upstream to downstream along the Amazon River, as well as over different portions of the main tributaries. A clear difference is noticed between the western and northeastern/southeastern parts of the basins. The 2005 drought reported by earlier studies affects TWS in the center of the basin. The largest signal detected by this analysis is a strong positive TWS anomaly in 2006 affecting the eastern, northeastern and southern parts of the basin. Another positive anomaly is also apparent by the end of 2007 that we can link to the recent La Nina event.

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

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Figure captions

Fig.1: Amazon river watershed with its main subbasins

Fig.2 : (a) location of the 4°x4° pixels in which terrestrial water storage (TWS) from GRACE and average in situ river levels are computed. (b) Temporal evolution of TWS (black) and average river level (red) for each pixel

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

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

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

Table caption

Table 1 – EOF leading modes: % of explained variance

Table 1

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

Figure 1

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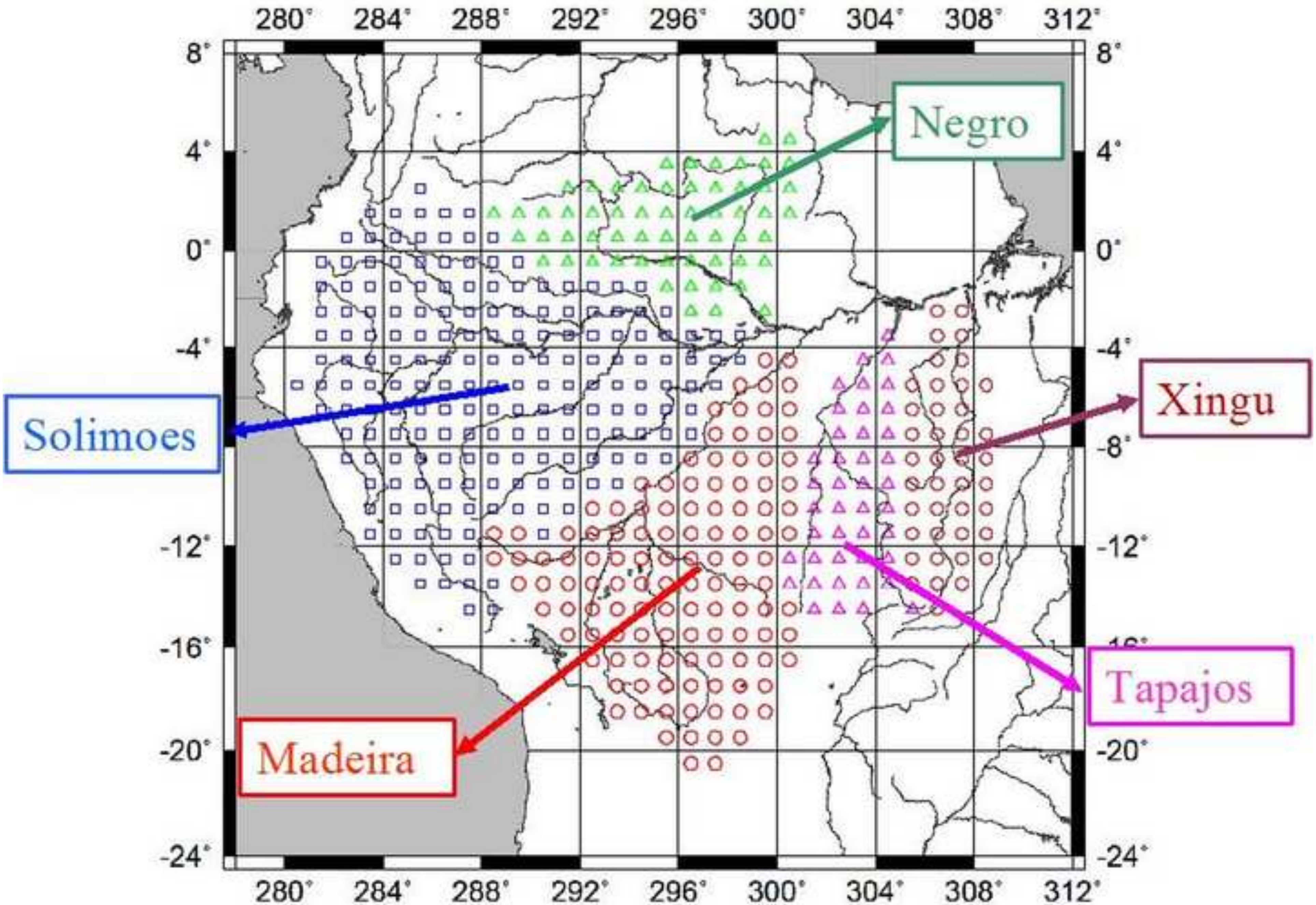

Figure 2a
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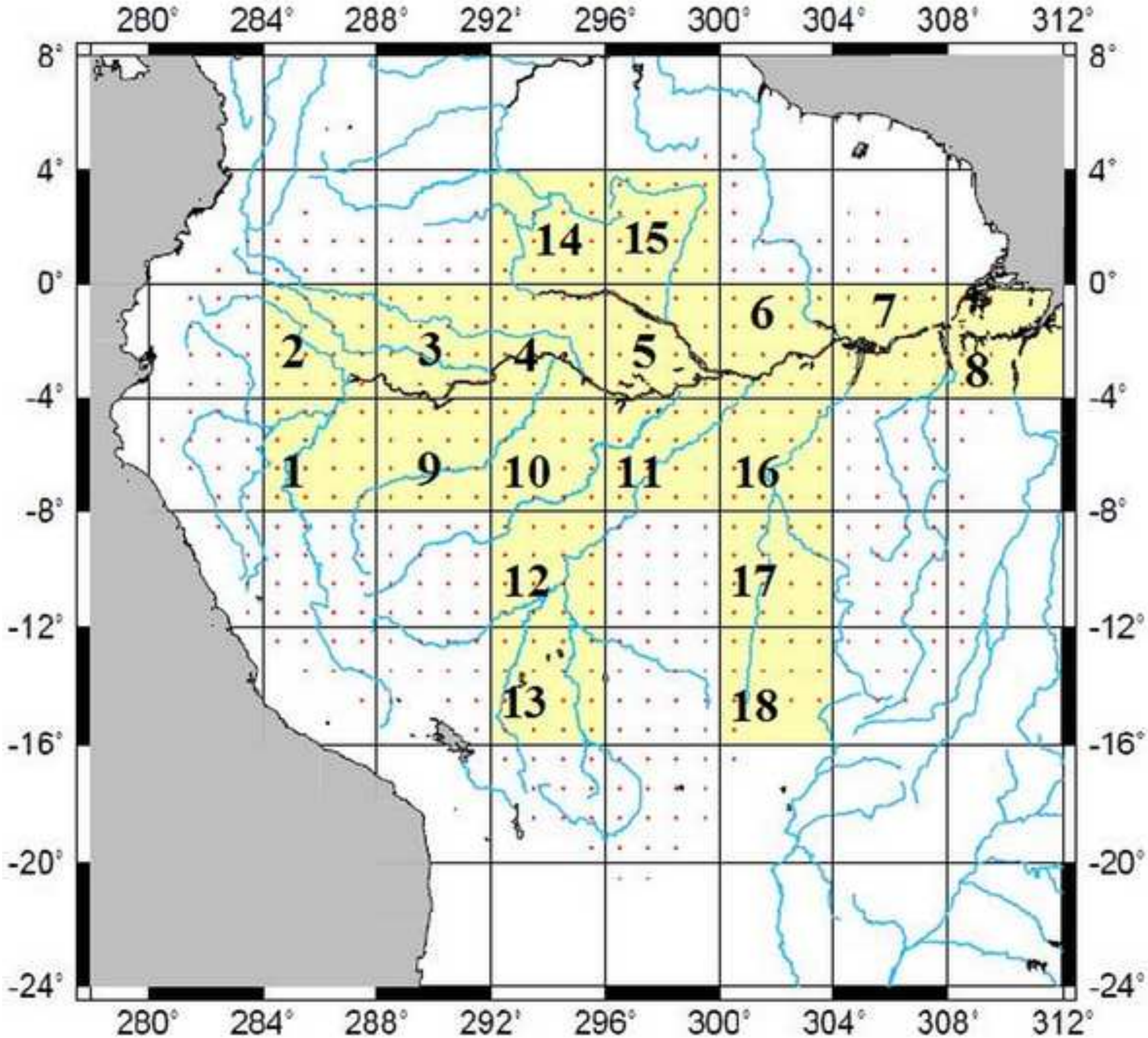

Figure 2b

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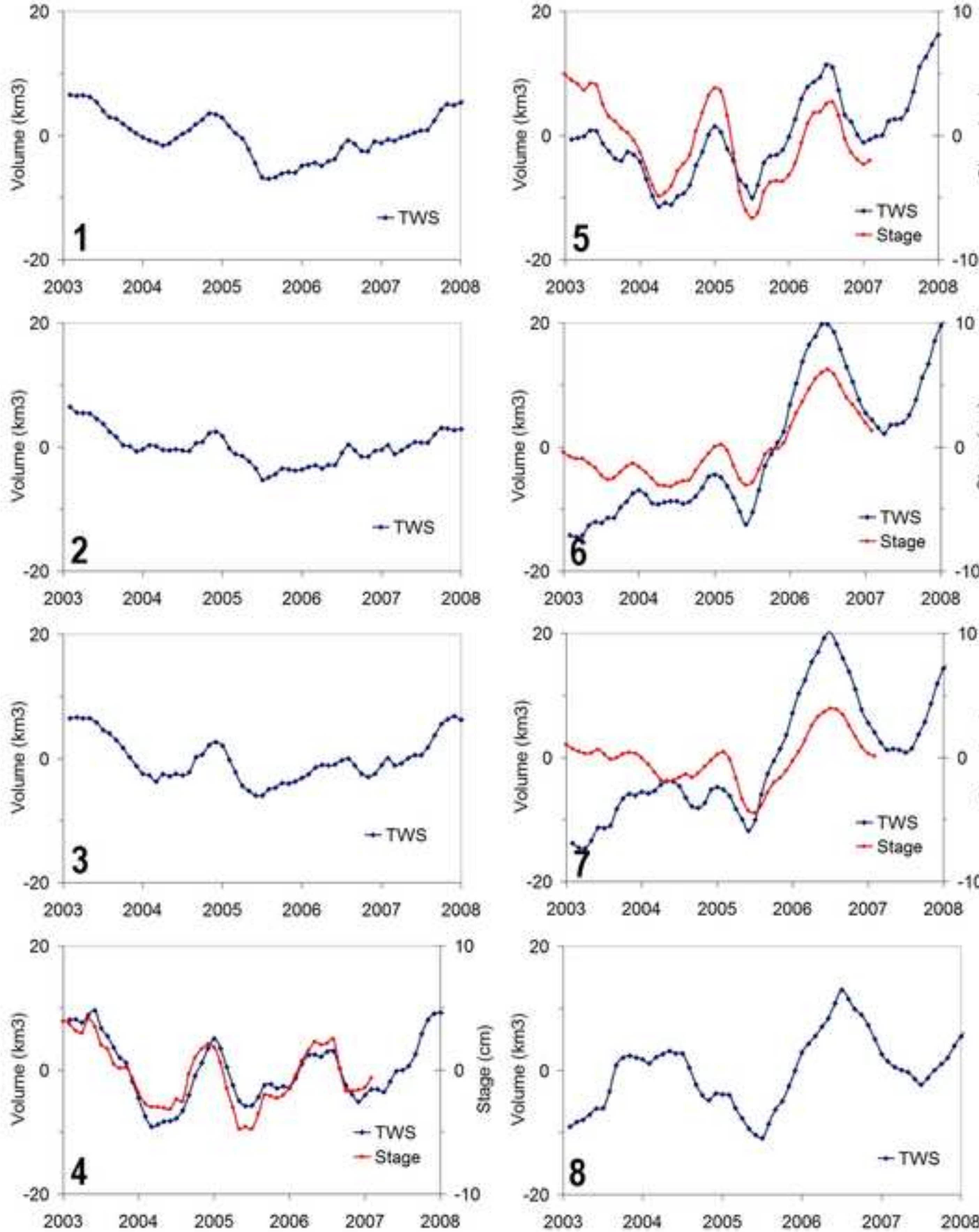

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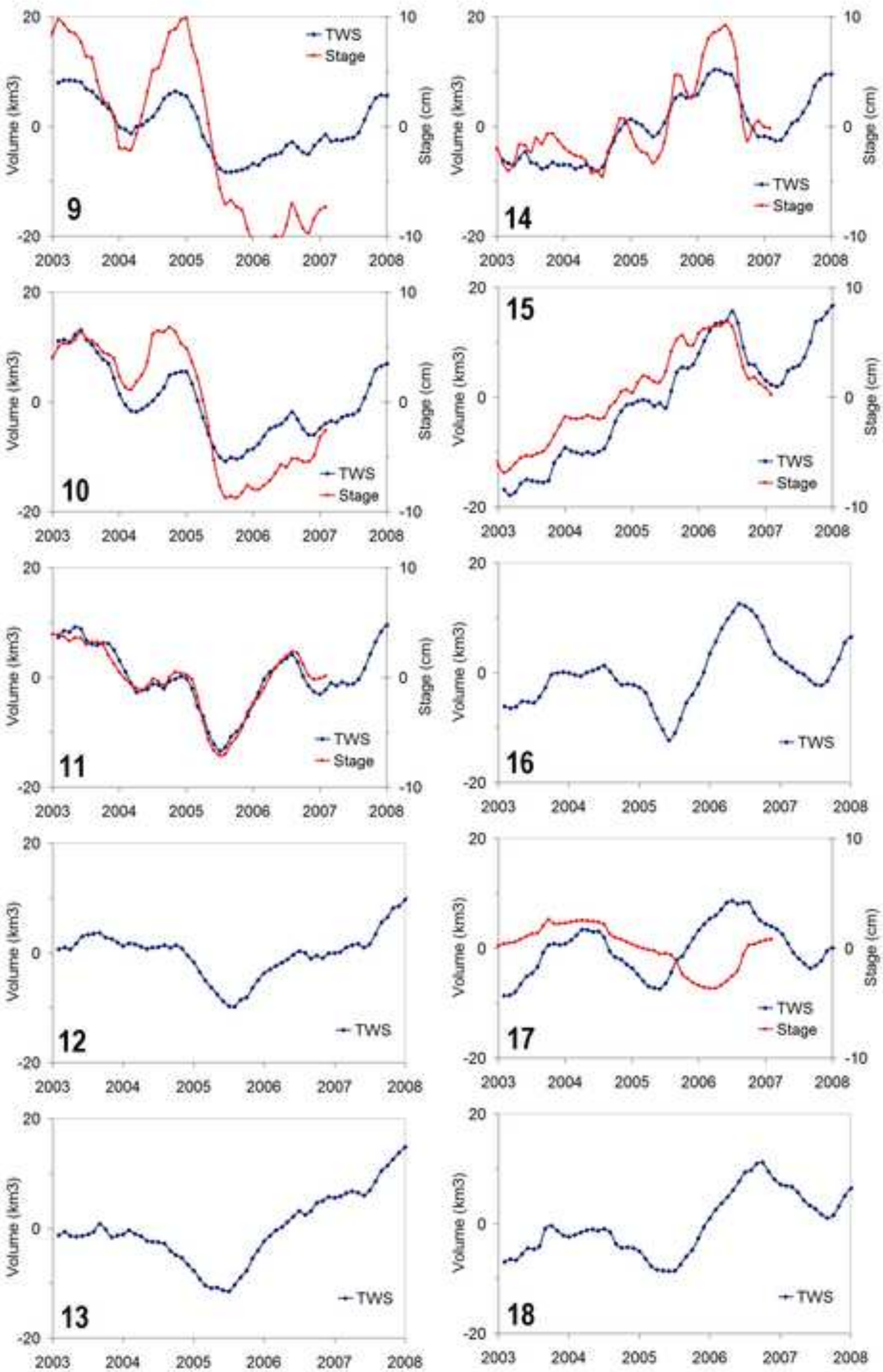

Figure 3a
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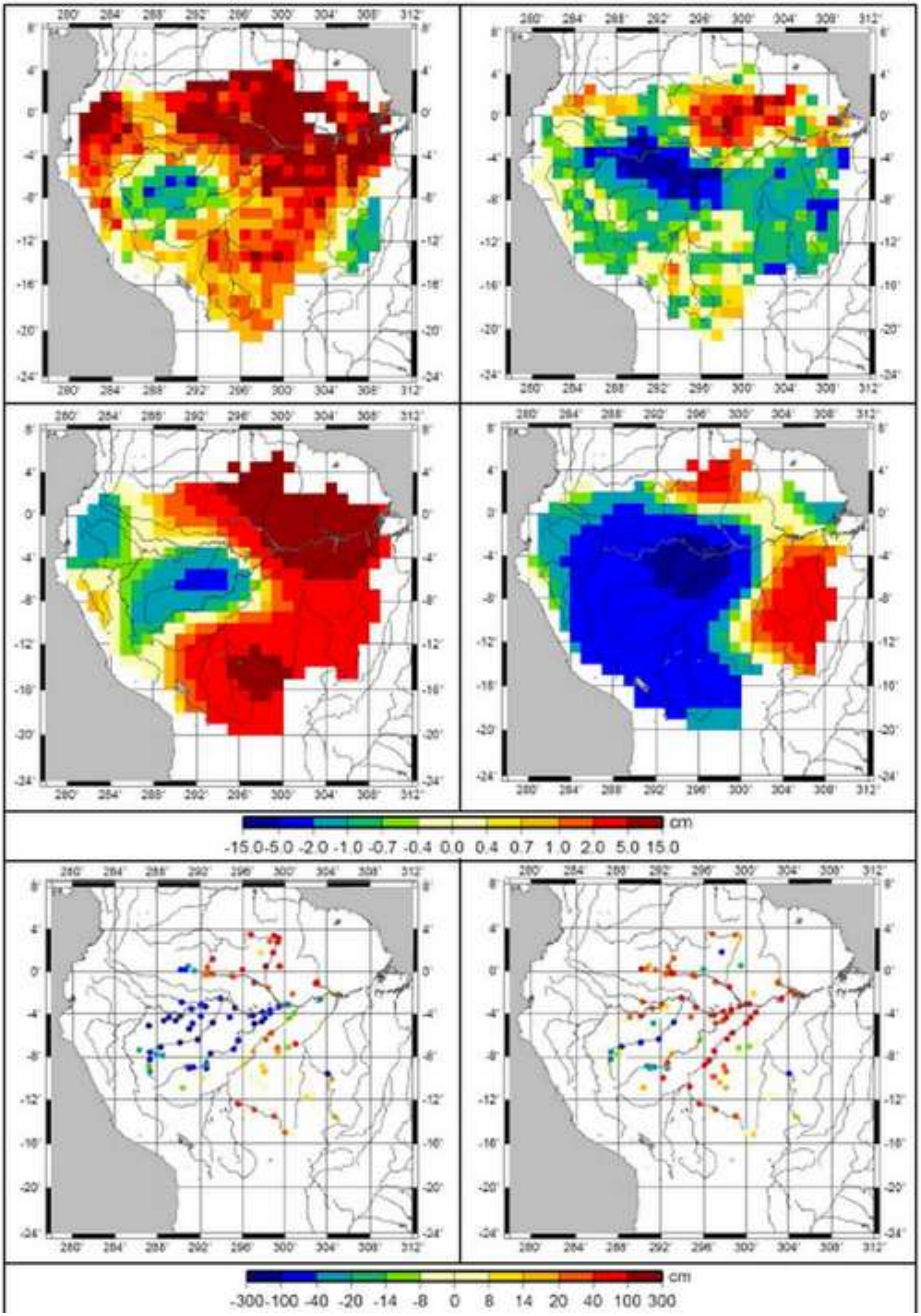

Figure 3b

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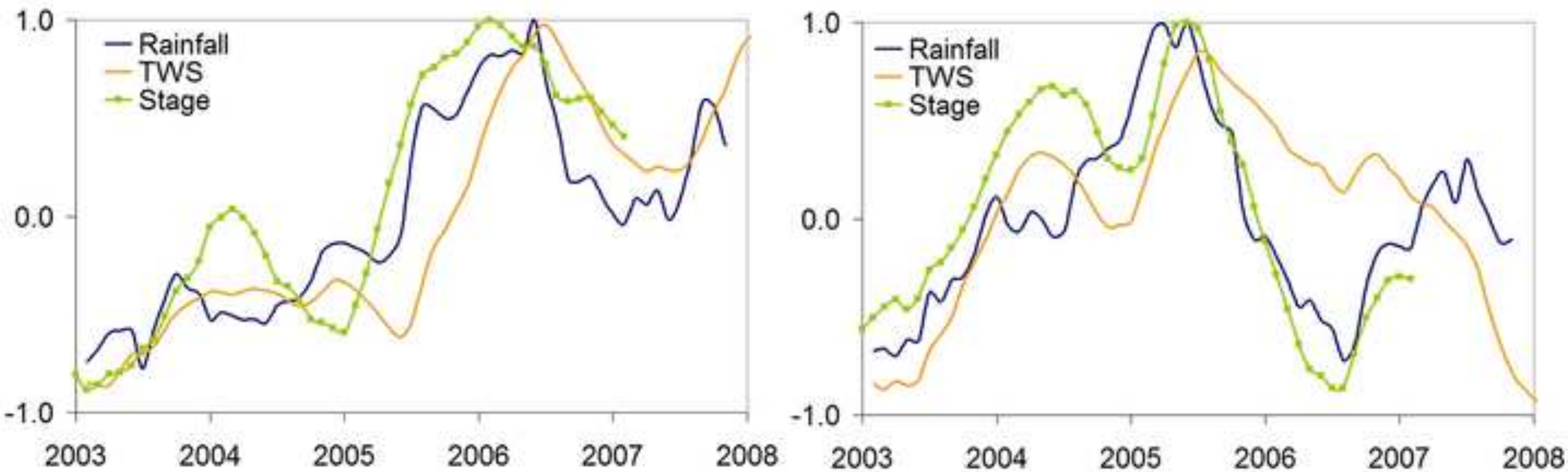

Figure 4
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