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Disruption of hydroecological equilibrium in southwest Amazon mediated by drought

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Key Points:
- A fragile hydroecological equilibrium is observed in the western Amazon
- Drought events are linked to persistent disruptions on ecosystem functioning
- Permanent impacts on vegetation likely to occur in case of increasing drought frequency

Supporting Information:
- Supporting Information S1

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Abstract The impacts of droughts on the Amazon ecosystem have been broadly discussed in recent years, but a comprehensive understanding of the consequences is still missing. In this study, we show evidence of a fragile hydrological equilibrium in the western Amazon. While drainage systems located near the equator and the western Amazon do not show water deficit in years with average climate conditions, this equilibrium can be broken during drought events. More importantly, we show that this effect is persistent, taking years until the normal hydrological patterns are reestablished. We show clear links between persistent changes in forest canopy structure and changes in hydrological patterns, revealing physical evidence of hydrological mechanisms that may lead to permanent changes in parts of the Amazon ecosystem. If prospects of increasing drought frequency are confirmed, a change in the current hydroecological patterns in the western Amazon could take place in less than a decade.

1. Introduction

The Amazon rainforest plays a fundamental role in the global atmospheric circulation, water balance, and biogeochemical cycles. Due to the vast geographical dimensions of the Amazon ecosystem, changes in vegetation functioning and canopy characteristics are likely to have profound impacts on the Earth system [*Werth and Avissar*, 2002]. Hence, the consequences of climate extremes on the Amazon have raised the attention of scientists in recent years, as two major droughts have stricken the region in less than one decade. In 2005, a large portion of the western Amazon experienced one of the worst droughts in the last hundred years [*Marengo et al.*, 2008]. This event was followed by an even stronger drought in 2010 [*Espinoza et al.*, 2011; *Marengo et al.*, 2011], raising widespread concern among scientists, stakeholders, and governments.

Although many studies have been undertaken to evaluate the consequences of these events, a full understanding of the extent and magnitude of the impacts on the hydrology and canopy structure, as well as potential links between both, remains incomplete. Field surveys indicate that the 2005 drought has caused widespread tree mortality [*Phillips et al.*, 2009, 2010], leading to a biomass carbon impact of up to 1.6×10^{15} g [*Phillips et al.*, 2009]. Yet the factors contributing to the resilience or susceptibility of the forest to droughts are still poorly understood.

Recent studies have contributed to improving our understanding of the response of vegetation functioning to environmental factors [e.g., *Hasler and Avissar*, 2007; *Hutyra et al.*, 2007; *Costa et al.*, 2010; *Restrepo-Coupe et al.*, 2013; *Brando et al.*, 2014; *Jones et al.*, 2014; *Guan et al.*, 2015]. However, direct measurements and validation data are often based on flux tower measurements and field surveys, providing a limited representation of spatial patterns. As a result, a satisfying explanation for the spatial heterogeneity of the forest response to droughts has not yet been achieved.

One major bottleneck lies in the uncertainties in optical satellite observations over the Amazon. For instance, studies demonstrate that spectral vegetation indices often used for assessing the impacts of droughts in the Amazon can be highly affected by atmospheric effects and bidirectional reflectance distribution function (BRDF) artifacts [*Samanta et al.*, 2010; *Morton et al.*, 2014; *Maeda and Galvão*, 2015]. Furthermore, some vegetation indices were shown to have limited sensitivity to vegetation canopy changes caused by environmental factors [*Maeda et al.*, 2014]. Although recent efforts have significantly improved algorithms for removing atmospheric and BRDF effects on optical data [*Lyapustin et al.*, 2012], and some studies have successfully

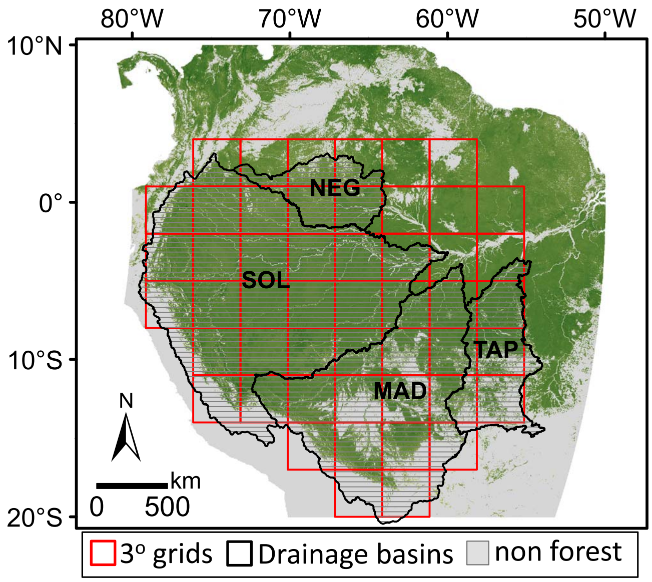

Figure 1. River basins in which the water balance assessments were performed: NEG = Negro River basin; SOL = Solimões River basin; MAD = Madeira River basin; and TAP = Tapajós River basin, and 3° by 3° grids distributed over the Amazon basin.

applied these products in the Amazon forest [*Hilker et al.*, 2014], the relationships between hydrological patters and vegetation remain uncertain. Consequently, while models indicate that climate change may lead to an increase in the frequency of droughts in the Amazon [*Cox et al.*, 2008], having the potential to trigger large scale biome shifts [*Salazar and Nobre*, 2010], currently, there is little observational evidence of the hydrological processes and vegetation responses leading to these changes.

Recently, assessments based on microwave satellites, which are virtually unaffected by clouds, show evidence that the 2005 drought has led to persistent changes in the vegetation canopy [*Saatchi et al.*, 2013]. They argued that up to 70×10^6 ha of forest in western Amazonia were affected during the 2005 event, causing a decline in canopy structure and moisture. Nevertheless, the hydrological mechanisms driving these changes, as well as the spatially heterogeneous patterns of the changes, were not explicitly quantified. More importantly, it is unclear whether the persistence of canopy changes was caused by biotic (e.g., permanent plant structure damage) or environmental factors (e.g., lasting water constrains).

In this study we provide new insight into the hydrological consequences of the recent droughts and their links with changes in forest canopy properties. Using a novel combination of data sets and methods, we aim to answer the following questions: How have the recent droughts affected the water balance of the Amazon basin? How persistent are the impacts of droughts on local hydrological patterns? And finally, are changes in hydrological patterns related to changes in forest canopy structure?

2. Material and Methods

Assessments were undertaken considering two spatial boundaries. First, water balance assessments were carried out at the watershed level, considering the drainage area of the four major rivers of the Amazon basin: the Negro, Solimões, Madeira, and Tapajós Rivers (Figure 1a). Next, the relationship between hydrological patterns and vegetation canopy properties were assessed within each grid cell in a 3° by 3° grid over the Amazon basin (Figure 1a).

The cumulative rainfall deficit (CRD) of a watershed in a certain month n can be calculated as follows:

$$\mathrm{CRD}_n = \mathrm{CRD}_{n-1} + P - \mathrm{ET} \tag{1}$$

where ET is the monthly evapotranspiration and P is the monthly rainfall. Considering the water balance equation

$$P - \mathrm{ET} = R + \frac{\mathrm{d}S}{\mathrm{d}T} \tag{2}$$

where R is the river discharge and dS/dT is the change in terrestrial water storage in month n, the term $P - \mathrm{ET}$ in equation (1) can be replaced and the CRD equation can be rewritten as follows:

$$\mathrm{CRD}_n = \mathrm{CRD}_{n-1} + R + \frac{\mathrm{d}S}{\mathrm{d}T} \tag{3}$$

R values were obtained from monthly river discharge measurements provided by the Environmental Research Observatory geodynamical, hydrological, and biogeochemical control of erosion/alteration and material transport in the Amazon basin. The changes in water storage (dS) were calculated using Total Water Storage Anomalies (TWSAs) estimated by NASA's Gravity Recovery and Climate Experiment (GRACE) satellites [*Tapley et al*., 2004; *Landerer and Swenson*, 2012], using the following equation [*Swenson and Wahr*, 2006]:

$$dS_n = (\mathrm{TWSA}_n - \mathrm{TWSA}_{n-1})$$

As this study was undertaken at monthly timescale, dT is approximately 30 days, which is consistent with the temporal resolution of GRACE data. Numerous previous studies have utilized GRACE data to characterize deficit-based drought [e.g., *Thomas et al*., 2014]. Given that our interest was solely on water stress conditions associated with droughts, only negative CRD were considered; i.e., if the right side of equation (3) was positive, the CRD of the respective month was set to zero. For further information about the GRACE and data processing methods, please refer to the supporting information.

Changes in vegetation canopy structure were assessed using microwave backscatter data from the SeaWinds Scatterometer on board the QuikSCAT satellite (QSCAT). We herewith define changes in canopy structure as any variation in canopy roughness, moisture, or other seasonal attributes, such as leaf density profile [*Saatchi et al*., 2013]. QSCAT measurements are carried out at a frequency of 13.4 GHz, resulting in backscatter that is strongly sensitive to variations in the water content and structure of the forest canopy. Given that QSCAT operates at a higher frequency than other similar sensors, it has less penetration into the forest canopy and has almost no interference from soil moisture variations in densely vegetated areas [*Saatchi et al*., 2013]. Previous studies indicate that QSCAT backscatter data provide a reliable proxy of biophysical properties of the forest, being well correlated with canopy structure and water content [*Frolking et al*., 2006, 2011].

Two approaches were undertaken to evaluate the connections between hydrological patterns and forest canopy properties. First, the relationship between seasonally adjusted QSCAT backscatter and GRACE TWSA were assessed inside every 3° by 3° grid cells over the Amazon basin. Next, we evaluate potential changes in the seasonal patterns of QSCAT and GRACE time series calculating temporal trends using the BFAST method (Breaks For Additive Seasonal and Trend) [*Verbesselt et al*., 2010]. The BFAST method integrates time series decomposition procedures with an iterative approach for detecting change within time series trends. The method is efficient for identifying abrupt, gradual, and seasonal change types in the time series.

3. Results and Discussion

Our results show that in Solimões and Negro River basins, dry season CRD is not observed in every year, indicating that a combination of weather extreme events is necessary to cause water deficit in these regions (Figure 2). On the other hand, in Madeira and Tapajos, where rainfall volumes are considerably lower, a CRD seasonal cycle is consistent in all years observed in our analysis.

An interesting pattern can be observed in the Solimões River basin, where during the years 2002, 2003, and 2004, CRD was virtually not observed. This fact changed during the 2005 drought, when a CRD of approximately 30 mm month^{-1} was observed during August. Interestingly, although annual rainfall volumes were above average during the following years, CRD was still evident in the watershed for two more years. The CRD returned to zero in 2008 and 2009 but was again observed in 2010, when a strong meteorological drought was observed. Once again, CRD could be observed in the following years (2011 and 2012), until it returned to zero in 2013.

These results provide evidence that the Solimões watershed holds a hydrological equilibrium particularly susceptible to climate extremes. We show that drought events in this region are followed by a gradual hydrological recover, with a time lag of approximately 2 years to recover from single drought events. As a consequence, recurring extreme events, such as observed in 2005 and 2010, which are expected to be exacerbated in frequency and intensity by climate change, are likely to result in longer recovering periods in this region. This assessment is strengthened by observations from the Obidos station, which accumulates water discharge from three major rivers in the Amazon basin: the Madeira, Solimões, and the Negro. Estimates of CRD for this entire region indicate that the patterns observed in the Solimões River are dominant, having a major role in defining CRD values for the Amazon River drainage area (Figure S2 in the supporting information).

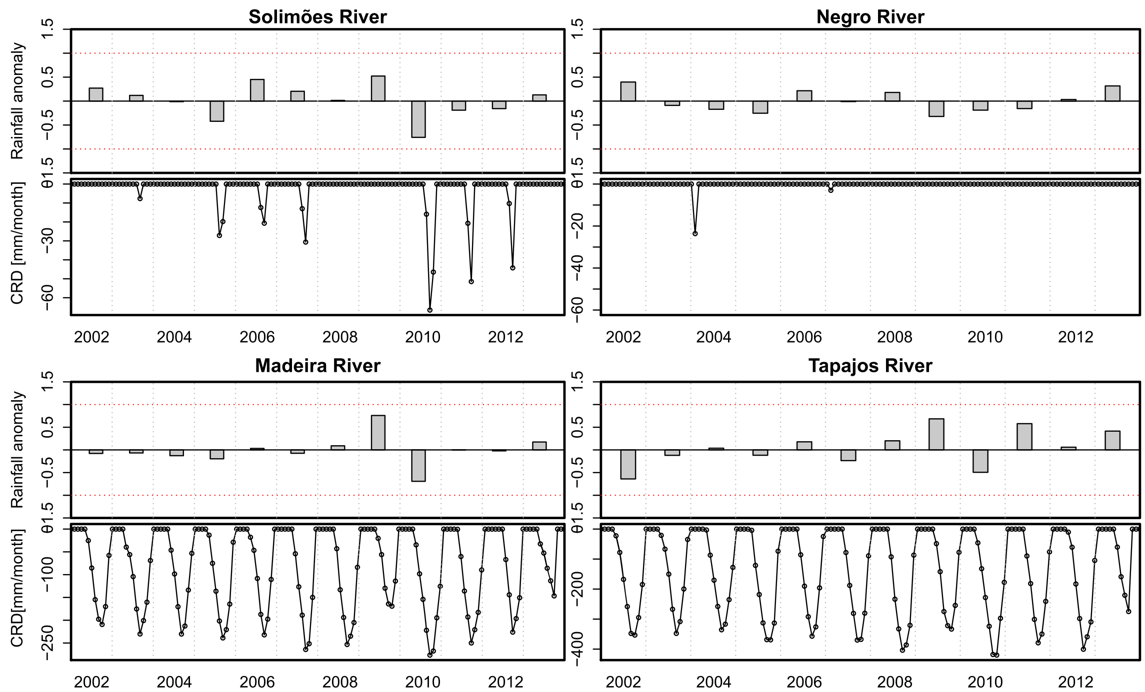

Figure 2. Cumulative Rainfall Deficit (CRD) and annual rainfall anomalies in four watersheds over the Amazon basin.

This persistent effect on hydrological patterns can be explained by a combination of biotic and abiotic factors. Intense droughts reduce the net water storage in the hydrological systems, therefore reducing average water table levels. It is therefore plausible to infer that during the following years, rainfall volumes higher than usual are necessary for the system to recover its previous levels. While this condition is not met, water table levels will remain below average, reducing the capacity of some plants to extract water from deep soils. In these conditions, rainfall input that would otherwise be used by plants for photosynthesis and returned to the atmosphere as a result of ET is instead lost by subsurface runoff at faster rates (higher ds/dt absolute values). Likewise, accelerated runoff output during wet season is likely to lead to reduced dry season runoff (Figure S3).

A remaining question is whether or not such variations in hydrological pattern may affect the Amazon forest vegetation. To answer this question, we carry out a comparison between seasonally adjusted values of TWSA and vegetation backscatter (Figures 3b and 3c). More evidently, the results show a large cluster of areas with significant relationship in the western part of the basin, while a diagonal cluster, covering the central and southeast regions, shows no significant correlation. This pattern initially contrasts with the traditional paradigm of a north-south gradient of vegetation and climatic characteristics in the Amazon [*Nepstad et al.*, 1994; *Marengo*, 2005; *Davidson et al.*, 2012]. Although recent studies indicate that some parts of the Amazon forest may temporally adjust net leaf flush to maximize the use of light and water [*Jones et al.*, 2014], we found that the relationship between TWSA and forest backscatter is not improved in cross-correlation analyses with time lag (Figure S6).

We argue that the lack of relationship between TWSA and forest backscatter in the central and southeast Amazon are explained by different reasons. In the central region, rainfall volumes are considerably higher (Figure 3a) and vegetation functioning is not likely to be limited by water. This argument is supported by recent studies evaluating flux data in the central Amazon [*Hasler and Avissar*, 2007; *Costa et al.*, 2010]. For instance, *Costa et al*. [2010] demonstrates that in wet equatorial areas evapotranspiration in the dry season is higher than that in the wet season, and surface net radiation is the main driver of evapotranspiration. So the observed lack of a consistent seasonal pattern of forest backscatter in the central area (Figure S5) gives further indications that canopy phenology is not significantly constrained by water input seasonal cycles.

On the other hand, forest backscatter in the southeast area shows a clear seasonal pattern, consistent with rainfall seasonality (Figure S5). Given the lower rainfall in this region it would be expected that changes in

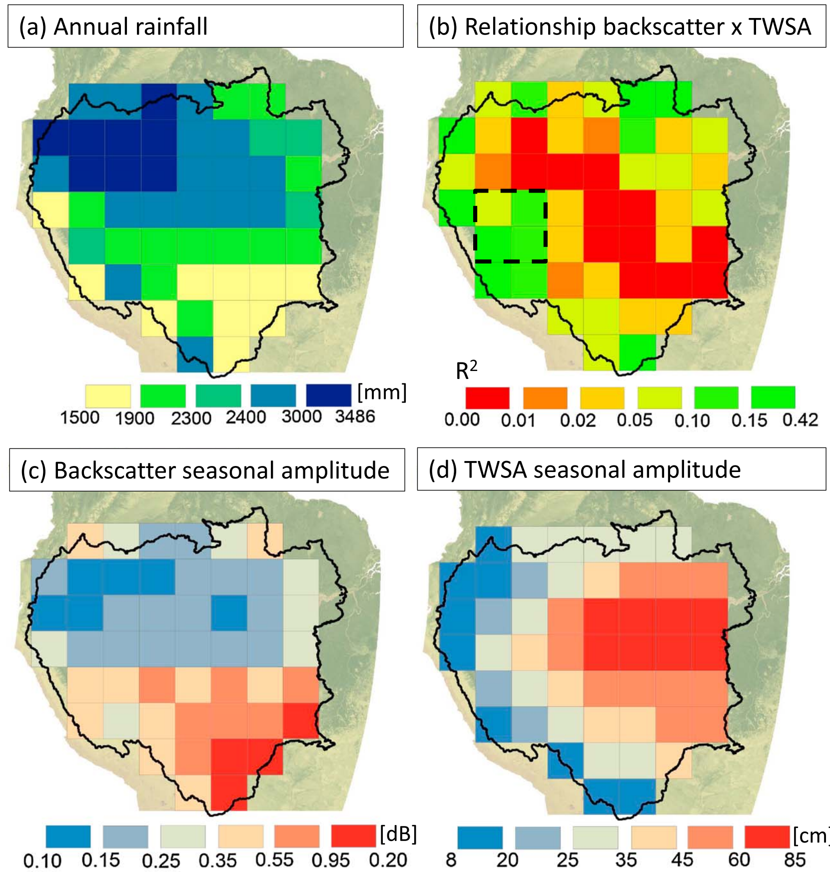

Figure 3. (a) Average accumulated annual rainfall obtained from TRMM 3B43 product; baseline period is from 1998 to 2012. (b) Coefficient of determination (R^2) from the relationship between seasonally adjusted total water storage anomalies (TWSA) and evergreen forest backscatter, calculated independently for each 3° grid cell inside the Amazon basin. The dashed line square in Figure 3b indicates the area where the BFAST analysis was carried out. (c) SeaWinds QSCAT backscatter seasonal amplitude [(annual_max)-(annual_min)] and (d) GRACE TWSA seasonal amplitude.

water availability are more strongly related to variations in forest canopy structure. However, seasonally adjusted TWSA and forest backscatter are not significantly correlated. One possible explanation for this fact is that in the Savanna transition regions, vegetation has lower access to water deeply stored in the soils, and TWSA (including the entire soil column water change) is not a good indicator of moisture available for plants. To evaluate whether forest backscatter anomalies respond to changes in readily available shallow soil moisture, we also evaluate the relationship between seasonally adjusted rainfall and forest backscatter (Figure S4b). Nevertheless, no significant relationships were found in the southeastern Amazon basin.

This may be explained by the fact that plants in this area are better adapted to abrupt variations in water input, given that the region is located in a transition zone between tropical rainforest and savannas. This hypothesis is supported by flux tower experiments indicating that in seasonally dry tropical areas, changes in vegetation functioning are not only driven by environmental factors but also have a strong biotic component (e.g., stomatally mediated reduction in surface conductance) [*Costa et al.*, 2010; *Christoffersen et al.*, 2014]. Studies using satellite measurements of Sun-induced chlorophyll fluorescence also suggest that during extreme climatic conditions, carbon uptake in parts of the Amazon is reduced because of the larger suppression of photosynthesis driven by dynamic stomatal response [*Lee et al.*, 2013]. In these cases, the regulation of stomatal aperture operates as a mechanism to avoid hydraulic failure while maximizing productivity for a given amount of water loss [*Lee et al.*, 2013].

The western portion of the Amazon basin, including large areas of the higher Solimões River watershed, shows a significant relationship between seasonally adjusted TWSA and forest backscatter. These results indicate that variations in vertical water column, as indicated by GRACE TWSA, have direct influence on changes

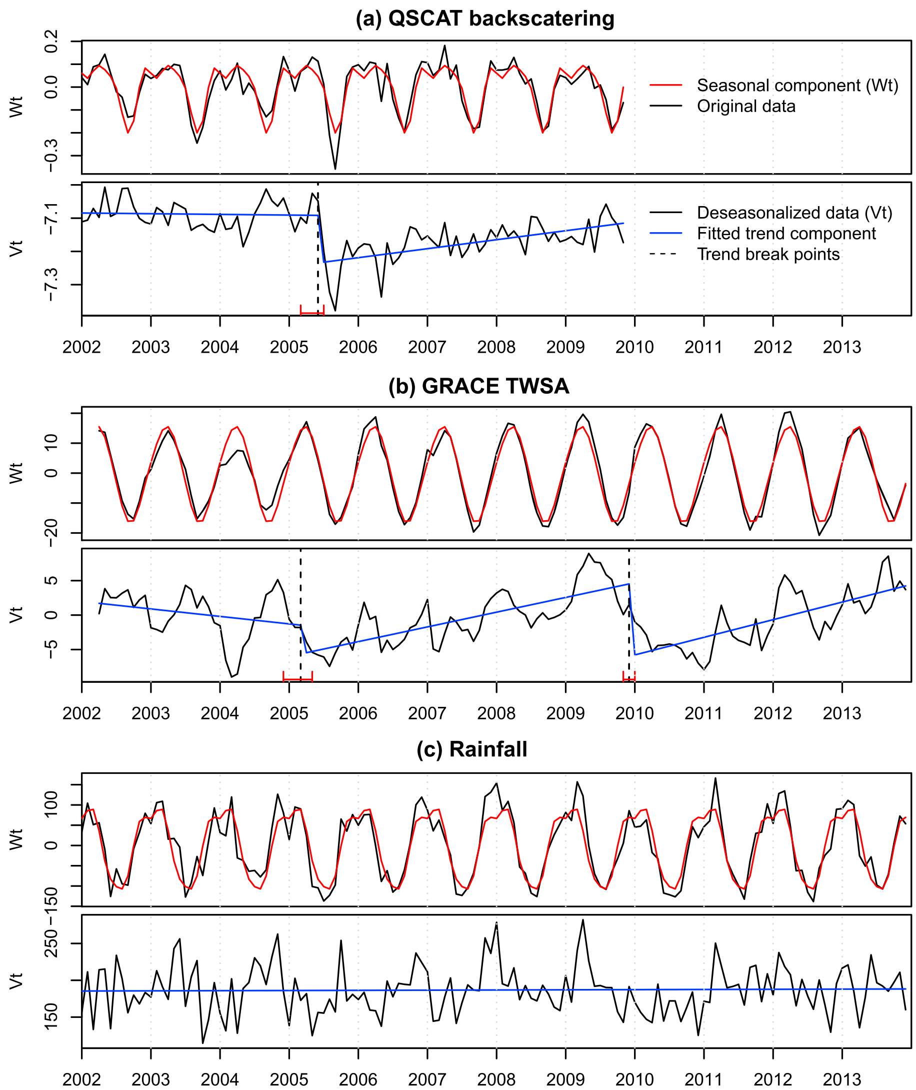

Figure 4. Seasonal decomposition and trend break analysis (BFAST) carried out in (a) the QSCAT backscatter, (b) GRACE total water storage anomalies (TWSA), and (c) TRMM rainfall data sets. Wt refers to the seasonal component and Vt refers to the deseasonalized time series. Trend breaks were detected using a confidence level of 99% (window: 5°S–11°S, 76°W–70°W).

in canopy structure and water content. Given this relationship, it would be expected that changes in forest canopy structure are consistent with the changes in hydrological patterns previously demonstrated (Figure 2). To test this hypothesis, we carry out a time series decomposition and trend break analysis [*Verbesselt et al.*, 2010] in the QSCAT backscatter, GRACE TWSA, and Tropical Rainfall Measuring Mission (TRMM) rainfall data sets, over part of the Solimões River basin that presents significant relationship between QSCAT and GRACE (dashed square in Figure 3b).

In agreement with *Saatchi et al.* [2013], we show an abrupt decline in forest backscatter over the western Amazon in the year 2005. This decline is followed by a smooth and continuous increasing trend until the end of the time series in 2009. Furthermore, our results show that TWSA trends are consistent with this pattern, showing striking resemblance in forest canopy disturbances that occurred in the 2005 drought, as well as in the continuous recovery until 2009. Another abrupt decline in TWSA trends is then observed slightly before 2010, when a second drought affected the Amazon basin. This break is followed by a recovery of TWSA values at a similar rate as occurred after the 2005 drought, which continues until the end of the time series in 2013.

Hence, we show evidence that changes in water availability do affect vegetation canopy structure and water content in the western Amazon, having potential impacts on ecosystem functioning. Furthermore, our results show contrasting patterns between the wet western and the seasonally dry southeastern Amazon basin, indicating different physiological (e.g., water use efficiency) and morphophysiological (e.g., root system and stomatal control) attributes of plants in these two regions. In other words, forests located near the savanna transition zone may be better adapted to water stress than those in the west Amazon. As a consequence, forests located in the western Amazon may be less resilient to environmental changes and more susceptible to climate extreme events. Similar BFAST analysis for equatorial and savanna transition regions is presented in Figure S5 in the supporting information.

Interestingly, no trend breaks are detected in the rainfall time series (Figure 4c). In fact, we found no evidence of an increase or decrease in precipitation over the Solimões River drainage area during the past decade (Figure 4c—fitted trend component). This fact demonstrates that isolated extreme rainfall shortage events are sufficient to persistently affect hydrological patterns and vegetation in the southwest flank of the Amazon. More importantly, it shows that this process can occur independently of long-term wetting trends in the Amazon basin suggested by previous studies [*Gloor et al*., 2013].

When placed in the context of climate change studies, our finding brings serious concerns to the future of the western Amazon forest. We show that in the 2005 and 2010 droughts, a recovery period of at least 2 years was necessary for reestablishing normal hydrological patterns in the Solimões basin. Hence, if the frequency of similar droughts is increased beyond 1-in-3 years, the recovery period will no longer be enough to restore the water deficit values. If this happens, hydrological patterns in the Solimões watershed are likely to resemble more closely the patterns observed in the Madeira and Tapajós drainage areas (i.e., consistent dry season CRD). In this case, if our hypothesis of lower forest resilience in the western Amazon is correct, a massive climate-mediated forest degradation process could be observed in this region, as a response to water stress.

Recent studies suggest that the 2005 drought is an approximately 1-in-20 years event [*Cox et al*., 2008]. However, model simulations indicate that under conditions of reduced aerosol loading and increased greenhouse gases, the frequency of similar events may be increased to 1-in-2 years by 2025 and a 9-in-10 years event by 2060 [*Cox et al*., 2008]. The hypothesis of future increase in drought frequency in the western Amazon is also supported by other studies based on recent Intergovernmental Panel on Climate Change model simulations [*Aragão et al*., 2014]. If these scenarios are confirmed, a permanent change in the current hydroecological patterns of the Solimões River basin could be observed in less than 10 years.

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