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Enhanced canopy growth precedes senescence in 2005 and 2010 Amazonian droughts

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ABSTRACT

Unprecedented droughts hit southern Amazonia in 2005 and 2010, causing a sharp increase in tree mortality and carbon loss. To better predict the rainforest's response to future droughts, it is necessary to understand its behavior during past events. Satellite observations provide a practical source of continuous observations of Amazonian forest. Here we used a passive microwave-based vegetation water content record (i.e., vegetation optical depth, VOD), together with multiple hydrometeorological observations as well as conventional satellite vegetation measures, to investigate the rainforest canopy dynamics during the 2005 and 2010 droughts. During the onset of droughts in the wet-to-dry season (May–July) of both years, we found large-scale positive anomalies in VOD, leaf area index (LAI) and enhanced vegetation index (EVI) over the southern Amazonia. These observations are very likely caused by enhanced canopy growth. Concurrent below-average rainfall and above-average radiation during the wet-to-dry season can be interpreted as an early arrival of normal dry season conditions, leading to enhanced new leaf development and ecosystem photosynthesis, as supported by field observations. Our results suggest that further rainfall deficit into the subsequent dry season caused water and heat stress during the peak of 2005 and 2010 droughts (August–October) that exceeded the tolerance limits of the rainforest, leading to widespread negative VOD anomalies over the southern Amazonia. Significant VOD anomalies were observed mainly over the western part in 2005 and mainly over central and eastern parts in 2010. The total area with significant negative VOD anomalies was comparable between these two drought years, though the average magnitude of significant negative VOD anomalies was greater in 2005. This finding broadly agrees with the field observations indicating that the reduction in biomass carbon uptake was stronger in 2005 than 2010. The enhanced canopy growth preceding drought-induced senescence should be taken into account when interpreting the ecological impacts of Amazonian droughts.

1. Introduction

The Amazonian rainforest plays a critical role in the global hydrological and carbon cycles (Pan et al., 2011). However, over the last decades, droughts over Amazonia have intensified (Marengo and Espinoza, 2016), with a once-in-a-century drought in 2005 followed by

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even more severe droughts in 2010 (Lewis et al., 2011) and 2015 (Jiménez-Muñoz et al., 2016). These large-scale droughts resulted in unprecedented low river discharges (Xu et al., 2011), increased tree mortality (Phillips et al., 2009) and a reversal of a large and long-term net carbon uptake (Doughty et al., 2015; Feldpausch et al., 2016; Gatti et al., 2014; Lewis et al., 2011).

To better anticipate Amazonian rainforest response to severe droughts in the future and the associated influence on the carbon cycle, it is important to characterize and understand its forest dynamic behavior during the 2005 and 2010 droughts. A long-term research network, RAINFOR, has been monitoring more than 100 forest plots across Amazonia over several decades. These field observations suggest that increased tree mortality in 2005 was the main cause for reduced carbon uptake and was strongly related to drought severity (Phillips et al., 2009). In the 2010 drought, Feldpausch et al. (2016) found that a combination of increased tree mortality and slow tree growth was the primary reason for reduced carbon uptake, but the distribution of increased tree mortality in 2010 seemed unrelated to local precipitation anomalies and independent of local pre-2010 drought history. Furthermore, rainfall deficit in 2010 occurred over a larger area than in 2005 (Phillips et al., 2009), but the overall reduction in carbon uptake was greater in 2005 (Feldpausch et al., 2016). Comparing the hydrometeorological conditions and forest dynamics in 2005 and 2010 should contribute to a better understanding of different Amazonian rainforest responses during these two droughts.

In addition to field studies, vegetation properties derived by different remote sensing techniques have also been used to investigate Amazonian rainforest responses during the two droughts. Two vegetation indices derived from the optical Moderate Resolution Imaging Spectroradiometer (MODIS), the Normalized Difference Vegetation Index (NDVI) and the Enhanced Vegetation Index (EVI), have extensively been used to characterize rainforest canopy greenness. Widespread below-average canopy greenness was observed in the dry season (July–September) during the 2010 drought from NDVI and EVI (Atkinson et al., 2011; Xu et al., 2011), but there is debate about the canopy greenness anomalies in the 2005 dry season (Saleska et al., 2007; Samanta et al., 2010). Interpretation of these optical sensor observations is challenging as they are strongly influenced by sun-sensor geometry changes and atmospheric effects, e.g., clouds and aerosols (Morton et al., 2014; Saleska et al., 2016; Samanta et al., 2010). Over southern Amazonia, the aerosol concentration was extremely high during the 2005 and 2010 dry season due to large-scale biomass burning (Ten Hoeve et al., 2012), which makes it difficult to obtain reliable optical sensor observations of the vegetation canopy.

Satellite-based sun-induced chlorophyll fluorescence (SIF) and active microwave (i.e., radar) observations were also explored to understand Amazon drought responses (Lee et al., 2013b, Saatchi et al., 2012). Lee et al. (2013b) utilized the SIF measured by the Greenhouse gases Observing SATallite (GOSAT) launched in January 2009. SIF was reduced by 15% across Amazonia during the extended dry season of 2010 compared with the non-drought year 2009. Saatchi et al. (2012) used the radar backscatter at microwave frequency (13.4 GHz) from the SeaWinds Scatterometer onboard QuickSCAT (QSCAT, launched in June 1999 and deactivated in November 2009). An advantage of active microwave sensor observations is that they are minimally affected by clouds and aerosols. They found a strong negative anomaly in the radar backscatter over southwestern Amazonia during the 2005 drought, indicating impacts on the canopy structure and a decline in canopy moisture. Despite the importance of these studies, neither covers both the 2005 and 2010 droughts.

The passive microwave-based vegetation optical depth (VOD) (Owe et al., 2001), derived from 6.9 GHz observations by the Advanced Microwave Scanning Radiometer – Earth Observing System (AMSR-E, June 2002–October 2011) onboard NASA's Aqua Satellite, covers both 2005 and 2010 droughts, and can represent the canopy water content dynamics over closed-canopy Amazonian rainforest, including leaf and branches components (Andela et al., 2013; Jones et al., 2013; Liu et al., 2015). The advantages of passive microwave-based VOD include that the signal remains sensitive to variations at a relatively high biomass density (Zhou et al., 2014); that, similarly to radar, it is minimally affected by clouds and aerosols, which are very frequent in Amazonia; and that it is less affected by sun-sensor geometry issues, as it relies on natural microwave emission from the Earth rather than reflected sunlight.

The field observations suggest the mechanisms for reduced carbon uptake in rainforests were different in 2005 and 2010 droughts (Feldpausch et al., 2016). Therefore, the primary objective of this study is to analyze the spatiotemporal evolution of these two droughts based on the passive microwave-based AMSR-E VOD and a series of satellite-based hydrometerological observations and identify their unique characteristics to better understand the similarities and differences in Amazonian rainforest responses between 2005 and 2010 events. Specifically, the rainforest canopy anomalies from satellite observations during both droughts are investigated together with the hydrometeorological variables over the extended dry season (May–October), which covers both the drought onset and peak periods.

2. Materials and methods

2.1. Satellite-based datasets

We utilized several independent sources of satellite data to characterize vegetation and hydrometeorological dynamics over Amazonia (see Table 1). All data cover the same period from January 2003 through December 2010. The focus is on the dynamics of intact rainforest during 2005 and 2010 droughts. The 0.05° MODIS land cover product (MCD12C1, v051) based on the International Geosphere-Biosphere Programme (IGBP) classification scheme (Friedl et al., 2010) for the year 2010 was used to delineate the spatial distribution of Amazonian forests (see Fig. 1a).

A new source of vegetation data used here is the passive microwave-based vegetation optical depth (VOD) at 0.10° spatial resolution. The VOD data were obtained based on brightness temperature derived from C-band (6.9 GHz) and Ka-band (36.5 GHz) observations by the Advanced Microwave Scanning Radiometer – Earth Observing System (AMSR-E) onboard the Aqua satellite. These were retrieved using the Land Parameter Retrieval Model (LPRM) (Meesters et al., 2005; Owe et al., 2008; Owe et al., 2001). The smoothing filter-based intensity modulation (SFIM) approach was utilized to downscale brightness temperature to 0.10° spatial resolution (Santi, 2010), and then the downscaled brightness temperature was used as the input to LPRM (de Jeu et al., 2014; Parinussa et al., 2014). The VOD is a dimensionless variable and can be interpreted as being directly proportional to the total vegetation water content, but varying with wavelength, vegetation structure and viewing angle (Jackson and Schmugge, 1991; Kerr and Njoku, 1990; Kirdyashev et al., 1979). Over closed canopy rainforest, the C-band VOD retrievals can be assumed to represent water content dynamics at the canopy level, including the leaves and branches (Guglielmetti et al., 2007; Jones et al., 2011; Jones et al., 2014).

An important assumption in the LPRM approach is that canopy surface temperature is equal to soil surface temperature (Meesters et al., 2005; Owe et al., 2008; Owe et al., 2001). The minimal temperature gradients during the night are therefore more favorable for the retrieval, while the uncertainty is expected to be higher for the day-time overpasses. AMSR-E has daily descending (01:30 equatorial local crossing time) and ascending (13:30 equatorial local crossing time) overpasses. The VOD retrievals from both night- and day-time overpasses were used in this study, with the emphasis on the night-time VOD. Hereafter VOD represent retrievals from night-time overpasses, except where specified otherwise. Optical satellite vegetation data were also used to characterize canopy dynamics, including LAI and EVI. LAI is defined as the one-sided green leaf area per unit ground area. The LAI product used is the latest version (Collection 6) of MODIS from Terra