Widespread decline in greenness of Amazonian vegetation due to the 2010 drought

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[1] During this decade, the Amazon region has suffered two severe droughts in the short span of five years – 2005 and 2010. Studies on the 2005 drought present a complex, and sometimes contradictory, picture of how these forests have responded to the drought. Now, on the heels of the 2005 drought, comes an even stronger drought in 2010, as indicated by record low river levels in the 109 years of bookkeeping. How has the vegetation in this region responded to this record-breaking drought? Here we report widespread, severe and persistent declines in vegetation greenness, a proxy for photosynthetic carbon fixation, in the Amazon region during the 2010 drought based on analysis of satellite measurements. The 2010 drought, as measured by rainfall deficit, affected an area 1.65 times larger than the 2005 drought – nearly 5 million km^2 of vegetated area in Amazonia. The decline in greenness during the 2010 drought spanned an area that was four times greater (2.4 million km^2) and more severe than in 2005. Notably, 51% of all drought-stricken forests showed greenness declines in 2010 (1.68 million km^2) compared to only 14% in 2005 (0.32 million km^2). These declines in 2010 persisted following the end of the dry season drought and return of rainfall to normal levels, unlike in 2005. Overall, the widespread loss of photosynthetic capacity of Amazonian vegetation due to the 2010 drought may represent a significant perturbation to the global carbon cycle. **Citation:** Xu, L., A. Samanta, M. H. Costa, S. Ganguly, R. R. Nemani, and R. B. Myneni (2011), Widespread decline in greenness of Amazonian vegetation due to the 2010 drought, *Geophys. Res. Lett.*, *38*, L07402, doi:10.1029/2011GL046824.

1. Introduction

[2] There is concern that in a warming climate the ensuing moisture stress could result in Amazonian rainforests being replaced by savannas [*Cox et al.*, 2004; *Salazar et al.*, 2007; *Huntingford et al.*, 2008; *Malhi et al.*, 2008], in which case the large reserves of carbon stored in these forests, about 100 billion tons [*Malhi et al.*, 2006], could be released to the atmosphere, which in turn would accelerate global warming significantly [*Cox et al.*, 2000]. Hence, the drought sensitivity of these forests is a subject of intense study – recent articles on the response and vulnerability of these forests to droughts illustrate the various complexities [*Phillips et al.*, 2009; *Saleska et al.*, 2007; *Samanta et al.*, 2010a, 2010b; *Malhi et al.*, 2008; *Brando et al.*, 2010; *Anderson et al.*, 2010; *Meir and Woodward*, 2010]. Severe droughts such as those associated with the El Niño Southern Oscillation (ENSO), when the plant – available soil moisture stays below a critical threshold level for a prolonged period, are known to result in higher rates of tree mortality and increased forest flammability [*Nepstad et al.*, 2004, 2007; *da Costa et al.*, 2010]. The drought of 2005, however, was unlike the ENSO-related droughts of 1983 and 1998 – it was especially severe during the dry season in southwestern Amazon but did not impact the central and eastern regions [*Marengo et al.*, 2008]. Of particular interest are reports of loss of biomass [*Phillips et al.*, 2009], decreased vegetation moisture content [*Anderson et al.*, 2010] and higher fire counts [*Aragao et al.*, 2007] during the 2005 drought, and contradictory reports of vegetation greenness changes inferred from satellite observations [*Saleska et al.*, 2007; *Samanta et al.*, 2010a, 2010b]. This lively state of current affairs is documented in two news items [*Tollefson*, 2010a, 2010b].

[3] On the heels of the once-in-a-century [*Marengo et al.*, 2008] drought in 2005, comes an even more severe drought in the Amazon region [*Lewis et al.*, 2011]. The causes of the 2010 drought still need to be investigated and are presently unknown, but like the 2005 drought it was intense and coincided with the dry season. The *Rio Negro* water level at the Manaus harbor is one of the most useful drought characterization indexes in Amazonia because it integrates rainfall totals over the entire western Amazon basin and is the longest available time series record in the region (since 1902). This index was at its lowest level (13.63 m above the local reference level, not 13.63 m lower in October than the long-term average for that month, as stated by *Lewis et al.* [2011]) since 1902 on October 23, 2010 (Figure 1). The lowest level in 2005 was 14.75 m, or eighth lowest in the 109-year *Rio Negro* Manaus time series (Table S1). The main Amazon channel, *Rio Solimões*, also reached record low levels between October 14 and October 23, 2010 at various stations on its course (Tabatinga, Itapéua, Careiro, and Parintins). The river levels began to ascend with the arrival of rains in mid- to late-October 2010. As of November 25th 2010, the *Rio Negro* level is tracking the minimum-ever recorded river stage recovery (Figure 1). Year 2010 is now the driest year on record according to these river stage data.

[4] There is presently only a single report on the impact of the 2010 drought on Amazon vegetation, namely *Lewis et al.*

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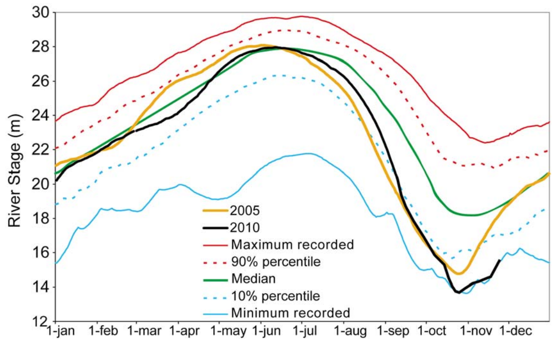

Figure 1. Variation of the stage of the *Rio Negro* at the Manaus Harbor in 2005 and 2010. Also shown are the median, top and bottom 10% percentiles and maximum and minimum recorded in the 1902–2009 record. The 2010 data are through November 25. Source: CPRM/ANA (Serviço Geológico do Brasil/Agência Nacional das Águas – Brazil Geological Service/National Agency for Water).

[2011], who evaluated changes in above ground biomass as a function of maximum climatological water deficit using satellite-based precipitation data. However, direct evidence of the impact of the 2010 drought on Amazonian vegetation is currently lacking, and this is presented in this article using satellite-based estimates of vegetation greenness, which is a proxy for photosynthetic carbon fixation. In addition, a comparative analysis of the impacts of the 2005 and 2010 droughts with regards to their areal extents, severity and post-drought effects is presented in this article to assess the two droughts that occurred in a relatively short time span.

2. Data and Methods

[5] We used the latest versions of satellite-based datasets of precipitation and vegetation greenness in this study. The greenness data consisted of Normalized Difference Vegetation Index (NDVI) and Enhanced Vegetation Index (EVI) from the Moderate Resolution Imaging Spectroradiometer (MODIS) aboard the Terra satellite. These indices, when evaluated from space-based reflectance measurements free of atmospheric corruption, that is, contamination of vegetation-reflected radiation with cloud- and/or aerosol-reflected radiation, represent direct observations of the physiologically functioning greenness level of vegetation canopies [*Myneni et al.*, 1995; *Huete et al.*, 2006]. Although the satellite data were cloud-filtered and corrected for aerosol-corruption effects, the data were further processed to remove residual atmosphere-corruption to produce the best possible signals from the vegetation. The precipitation data consisted of monthly precipitation rate (millimeters/hour, mm/hr) available from the Tropical Rainfall Measuring Mission (TRMM). The details of each dataset are provided in the auxiliary material.[1] The analyses presented in this paper mainly consist of evaluating standardized anomalies of satellite-based data, expressed as

$$a = \frac{(x - m)}{s} \quad (1)$$

Where, a is the standardized anomaly of a given quantity (e.g., precipitation, vegetation greenness etc.) in a specific year (2005 or 2010) calculated using its value, x, in that year and long term mean, m, and standard deviation, s, over a reference period. Full details of data processing and anomaly calculation are provided in the auxiliary material.

[6] The *Rio Negro* water levels started to recede fast in August 2010, setting the start of 2010 drought, whereas in 2005, the drought started in July (Figure 1). Plant-available soil moisture data across the wide Amazon basin are not available to assess the spatial extent and impacts of droughts here. Therefore, we resorted to characterizing the drought through surrogates such as precipitation anomalies, as has been done before [*Aragao et al.*, 2007; *Saleska et al.*, 2007; *Anderson et al.*, 2010]. Rain gauge network is also too sparse across the basin and the available gauge data merged with rainfall amounts inferred from satellite scatterometer (Tropical Rainfall Measuring Mission, TRMM) observations [*Huffman et al.*, 1995] offer the best characterization of precipitation deficit, and possibly drought [*Aragao et al.*, 2007], in the Amazon region. Therefore, we analyzed merged precipitation data from TRMM satellite and other sources for the period January 1998 to December 2010 to assess the spatial extent and severity of droughts in the Amazon, in spite of well-known limitations of this merged precipitation data set [*Adler et al.*, 2000] (cf. auxiliary material).

3. Results and Discussion

[7] We characterize the 2010 dry season drought as July to September (JAS) precipitation anomalies less than −1 to be consistent with previous studies [*Aragao et al.*, 2007; *Saleska et al.*, 2007; *Samanta et al.*, 2010b]. The 2010 drought impacted nearly the entire tropical region of South America south of the Equator unlike the 2005 drought, which affected mostly the southwestern Amazon (Figure S1). These patterns of precipitation deficit are approximately consistent with river stage data – the *Rio Negro* and the main stem Amazon river are hydrologically connected in Manaus, so receding levels on the main stem, which drains the most affected southwestern parts of the basin, can be measured at the Manaus harbor. About 41% of the vegetated area between 10°N–20°S and 80°W–45°W experienced JAS precipitation standardized anomalies less than −1 in 2010 (4.94 million km^2) compared to 25% in 2005 (3 million km^2). Notably, 50% of all forests within this vegetated region were subject to third quarter precipitation anomalies less than −1 std. in 2010 (3.3 million km^2) compared to 34% in 2005 (2.3 million km^2). The 2010 drought thus impacted a larger area and more rainforests than the 2005 drought, consistent with the analysis presented by *Lewis et al.* [2011].

[8] To assess the impact on vegetation from these two droughts, we analyzed two different satellite-derived vegetation index data (cf. section 2). The Normalized Difference Vegetation Index (NDVI) and Enhanced Vegetation Index (EVI) data, which are proxies for photosynthetic carbon fixation [*Myneni et al.*, 1995; *Huete et al.*, 2006; *Yang et al.*, 2007; *Brando et al.*, 2010], show wide spread declines, especially south of the Equator, during the 2010 drought, in contrast to the 2005 drought (Figure 2). About 49.1% of the vegetated area that was subject to drought shows greenness index declines (July to September NDVI standardized

[1] Auxiliary materials are available in the HTML. doi:10.1029/2011GL046824.

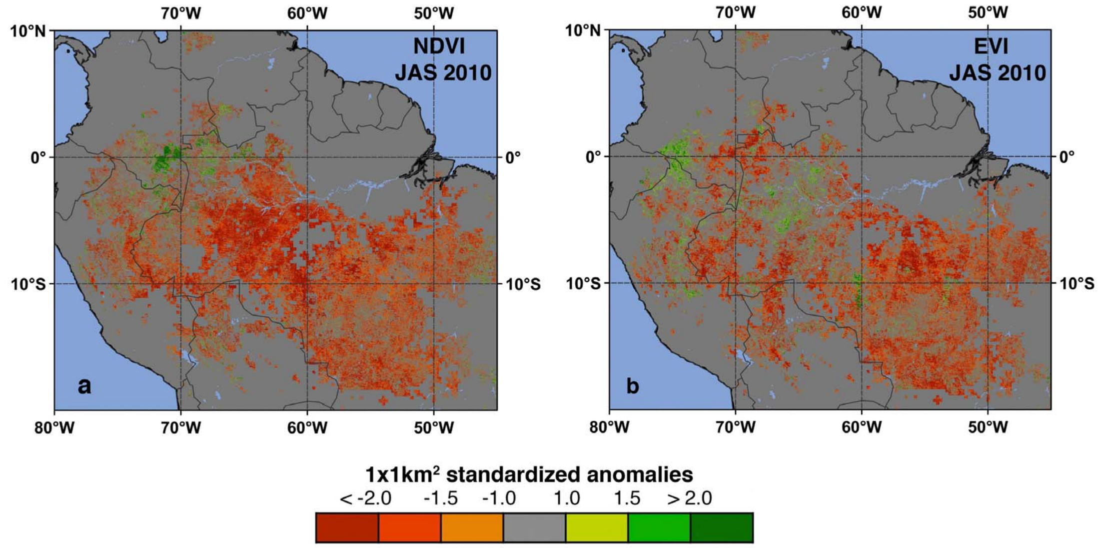

Figure 2. Spatial patterns of July to September (JAS) 2010 standardized anomalies of normalized difference vegetation index (NDVI) and enhanced vegetation index (EVI) in vegetated areas of drought (precipitation anomalies less than −1 standard deviation).

anomalies less than −1) in 2010 (2.43 million km^2) compared to 19.9% in 2005 (0.60 million km^2). Notably, 51.4% of all forests subjected to drought show similar declines in 2010 (1.68 million km^2) compared to 14.3% in 2005 (0.32 million km^2). The areas of greenness declines in 2005 and 2010 (Figure S3) generally coincide with the drought epicenters identified by *Lewis et al.* [2011]. In addition, there are large areas of vegetation greenness declines in 2010 (Figure S3) that were not identified in the *Lewis et al.* [2011] study. Overall, these declines represent a significant loss of photosynthetic capacity of Amazonian vegetation [*Myneni et al.*, 1995; *Huete et al.*, 2006; *Yang et al.*, 2007; *Brando et al.*, 2010] and thus may represent a significant perturbation to the global carbon cycle, as the Amazon rainforests contribute a disproportionately large fraction to global annual net primary production (about 15%) relative to their area [*Nemani et al.*, 2003]. The scale of this perturbation, though, is still to be quantified.

[9] Undisturbed Amazon rainforests were reported to have greened-up during the 2005 drought based on analysis of a previous version of the Enhanced Vegetation Index (EVI) data [*Saleska et al.*, 2007]. This has now been shown not to be the case with current versions of both EVI [*Samanta et al.*, 2010a, 2010b] and NDVI data (Figure S3). With respect to the 2010 drought, both EVI and NDVI data show widespread declines in vegetation greenness (Figure 2). The two droughts coincided with the dry season (July to September), and in both cases, rainfall returned to its normal level in the following months (Figures S4b and S4d). However, the greenness declines observed during the dry season persisted into the following three months, October through December, in 2010, but not in 2005 (Figures S4a and S4c), clearly indicating the severity and potential damage to the vegetation in this region.

[10] A comparison of NDVI and EVI anomalies from vegetated areas affected by both droughts also reveals the varied impacts of these two droughts (Figure 3). The spatial extent of greenness declines increased nearly five-fold in 2010 compared to 2005, which is consistent with TRMM precipitation analysis (Figure S1) that shows a much larger area under precipitation deficit in 2010 compared to 2005. The intensification of these declines in 2010 is also evident in the distributions of NDVI and EVI anomalies (Figure 3). The NDVI anomalies in 2010 display a strong positive skew, i.e. characterized by a majority of negative anomalies, with a peak value between −1 and −1.5 std., which is statistically different than that observed in 2005 ($p < 0.001$ from a two-sided t-test). A similar positive skew is also observed in the distribution of EVI anomalies in 2010, with a peak value at about −1 std., which is also statistically different ($p < 0.001$) than the 2005 EVI anomaly distribution (Figure 3). Hence we conclude that the impacts of 2010

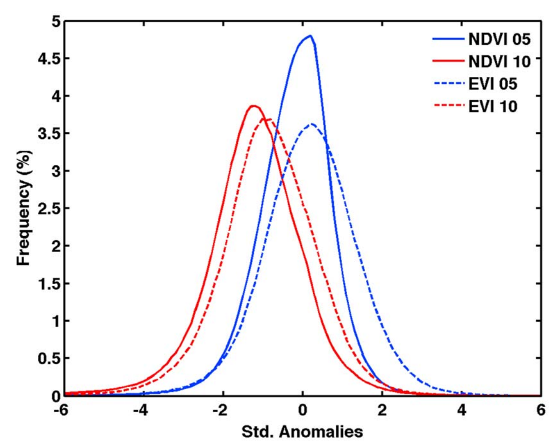

Figure 3. Distributions of greenness anomalies within the vegetated area affected by both the 2005 and 2010 droughts. Shown here are July to September (JAS) standardized anomalies of NDVI (solid lines) and EVI (dashed lines) during July to September 2005 (blue lines) and 2010 (red lines).

drought on vegetation in the Amazon region were not only more widespread but also more severe and persisted well beyond the drought period, when compared to the 2005 drought. Finally, a simple analysis of the probability of occurrence of these droughts suggests that the 2010, rather than the 2005, drought to be the "once-in-a-century" drought (Table S1).

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