Auxiliary Materials for Paper

Widespread Decline in Greenness of Amazonian Vegetation Due to the 2010 Drought

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Revised for Geophysical Research Letters

03-02-2011

Introduction

This auxiliary section includes detailed information on data, methods to determine the validity of EVI/NDVI and detailed description of methods to calculate standardized anomalies of EVI/NDVI and precipitation not given in the main text. Also included are Figure S1 to S4 and Table S1.

1. Data

1.1 Precipitation

The dataset "Tropical Rainfall Measuring Mission (TRMM) and Other Data" – 3B43 – consists of monthly precipitation rate (millimeters/hour, mm/hr) at 0.25^{o}x0.25^o spatial resolution (http://disc.sci.gsfc.nasa.gov/precipitation/documentation/TRMM_README/TRMM_3B43_readme.shtml) [*Huffman et al.*, 1995]. This dataset covers the region 50^{o}N-50^{o}S and 180^{o}W-180^{o}E. We used the latest version (version6) from January 1998 to December 2010 in this study.

1.2 Collection 5 (C5) Vegetation Indices (VI)

The vegetation index data sets are produced by NASA using atmosphere-corrected surface reflectance data in blue (459-479 nanometers (nm)), red (620-670 nm) and near-infrared (842-876 nm) bands of the Moderate Resolution Imaging Spectroradiometer (MODIS) aboard the NASA Terra satellite (https://lpdaac.usgs.gov) [*Huete et al.*, 2002].

The MODIS vegetation index product suite consists of Normalized Difference Vegetation Index (NDVI) and Enhanced Vegetation Index (EVI). NDVI is a radiometric measure of photosynthetically active radiation (400-700 nm) absorbed by canopy chlorophyll, and therefore, is a good surrogate measure of the physiologically functioning surface greenness level in a region [*Myneni et al.,* 1995]. NDVI has been used in many studies of vegetation dynamics in the Amazon [*Asner et al.,* 2000; *Dessay et al.,* 2004]. EVI generally correlates well with ground measurements of photosynthesis and found to be especially useful in high biomass tropical broadleaf forests like the Amazon [*Huete et al.,* 2002; 2006]. The latest versions of NDVI and EVI from the Terra MODIS instrument, called Collection 5 (C5), are used in this study.

The dataset “Vegetation Indices 16-Day L3 Global 1km” – MOD13A2 contains EVI and NDVI at $1x1km^2$ spatial resolution and 16-day frequency. This 16-day frequency arises from compositing, i.e. assigning one best-quality EVI and NDVI value to represent a 16-day period. This dataset is available in tiles (10^ox10^o at the equator) of Sinusoidal projection – 16 such tiles cover the Amazon region (approximately 10^oN-20^oS and 80^oW-45^oW). These were obtained from the NASA Land Processes Data Active Archive Center (LP DAAC) (https://lpdaac.usgs.gov) for the period February 2000 to December 2010.

1.2.1 VI data quality

The quality of 16-day vegetation index data (EVI and NDVI) in each $1x1km^2$ pixel can be assessed using the accompanying 16-bit quality flags. Sets of bits, from these 16 bits, are assigned to flags pertaining to clouds and aerosols, as well as, flags that provide aggregate measures of data quality called VI Usefulness Indices**.** Cloud quality flags are single bit (binary) flags indicating the presence (1) or absence (0) of clouds. There are two binary cloud quality flags – "Adjacent cloud detected" (bit 8), "Mixed Clouds" (bit 10), and "Possible Shadows" (bit 15). The aerosol quality flag, 2 bits in precision, provides information on aerosol content, and is named "Aerosol quantity". It occupies bit positions 6 through 7. The aerosol quality flag can have one of four values – "Climatology" (00), "Low" (01), "Average" (10) and "High" (11). "Low", "Average" and "High" refer to aerosol optical thickness (AOT) at 550 nm less than 0.2, between 0.2 and 0.5, and greater than 0.5, respectively [*Vermote and Vermuelen,* 1999]. On the other hand, "Climatology" indicates that the actual AOT is unknown, most likely due to presence of clouds, and climatological (long-term average) AOT is used in the process of atmospheric correction. The VI Usefulness flag, 4 bits in precision, provides an aggregate measure of VI quality. It occupies bit positions – bits 2 through 5 – and can have values from 0 (0000 – best quality) to 15 (1111 – not useful).

<u>Determination of VI validity</u>: The presence of clouds (adjacent clouds and mixed clouds) "obscures" the surface in a radiometric sense, thus corrupting inferred VI values. In addition, two types of aerosol loadings typically corrupt data – climatology and high aerosols. Use of aerosol climatology indicates that the actual aerosol content is unknown, most likely due to the presence of clouds, and aerosol correction was performed using historical or climatological aerosol optical thickness (AOT) data [*Vermote and Vermuelen,* 1999]. Moreover, atmospheric correction methods are ineffective for high

aerosol loadings (AOT > 0.5), especially in the shorter red and blue spectral [*Vermote and Kotchenova*, 2008].

Based on the above information, each 1x1km^2 16-day pixel is considered valid when (a) VI data is produced – "MODLAND_QA" equals 0 (good quality) or 1 (check other QA), (b) VI Usefulness is between 0 and 11, (c) Clouds are absent – "Adjacent cloud detected" (0), "Mixed Clouds" (0), "Possible Shadows" (0), and (d) Aerosol content is low or average – "Aerosol Quantity" (1 or 2). Note that "MODLAND_QA" checks whether VI is produced or not, and if produced, its quality is good or whether other quality flags should also be checked. Besides, VI Usefulness Indices 0 to 11 essentially include all VI data. Thus, these two conditions serve as additional checks.

1.3 Land cover

Land cover information was obtained from the "MODIS Terra Land Cover Type Yearly L3 Global 1 km SIN Grid" product – MOD12Q1. This is the official NASA C5 land cover data set (https://lpdaac.usgs.gov/) [*Friedl et al.*, 2010]. It consists of five land cover classification schemes at 1x1km^2 spatial resolution. The International Geosphere Biosphere Programme (IGBP) land cover classification scheme was used to identify forest and non-forest vegetated pixels in the Amazon region (see Fig. S2).

2. Methods

2.1 Standardized Anomaly

Standardized anomalies (anomaly divided by the standard deviation) of precipitation, and VI (NDVI and EVI) are calculated for 2005 and 2010 pixel-by-pixel as, $a = (x\text{-}m)/s$, where *a* is the 2005 (or, 2010) standardized anomaly of a given quantity (precipitation, NDVI, EVI) calculated from its value in 2005 (or, 2010) *x* and long term mean *m* and standard deviation *s* over a reference period. The reference period is 2000-2009, but excluding 2005. Thus, 2005 and 2010 are not part of the reference period.

2.1.1 VI Standardized Anomaly

For each year, we use six 16-day VI (NDVI or EVI) composites – 177 through 257 – covering the July-September (JAS) period. The VI value of a pixel is considered valid if it is free of atmospheric contamination due to clouds (adjacent clouds, mixed clouds and cloud shadows) and aerosols (climatology and high aerosols), which is determined by examining the corresponding quality flags (cf. Section 1.2.1). For each year, the JAS mean VI is calculated using only valid values. The mean (*m*) and standard deviation (*s*) are evaluated over the base period, years 2000 to 2009, but excluding 2005. Finally, if the 2005(or, 2010) JAS mean VI (*x*) exists, the 2005 (or, 2010) standardized anomaly is calculated.

We found blocks and strips of anomalously low VI values (especially in NDVI data) even after screening for clouds and aerosol contamination using quality flags, as described above. This points to further residual atmospheric corruption effects. To remove these artifacts, we estimated the 11-year (2000 to 2010) mean NDVI for each 16-day composite and screened VI values that were two standard deviations (95% envelope) or more below the mean. This additional filtering greatly reduced blocks and strips of anomalously low VI values.

2.1.2 Precipitation Standardized Anomaly

The monthly precipitation value is considered "valid" if it is not equal to -9999. If all three monthly – July, August and September - precipitation values are valid, the total of the three represents the quarterly (JAS) cumulative value. Else, the pixel is tagged and not used in further calculations. The long term mean (*m*) and standard deviation (*s*) of JAS cumulative precipitation are evaluated over the period 1998-2009, but excluding 2005. Finally, if the 2005 (or, 2010) JAS cumulative precipitation (*x*) exists, the 2005 (or, 2010) standardized anomaly (*a*) is estimated. Pixels with precipitation anomalies less than -1 standard deviation (std. dev.) are classified as drought-stricken.

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Figure Captions

Figure S1. Spatial patterns of July to September (JAS) 2010 and 2005 standardized anomalies of precipitation.

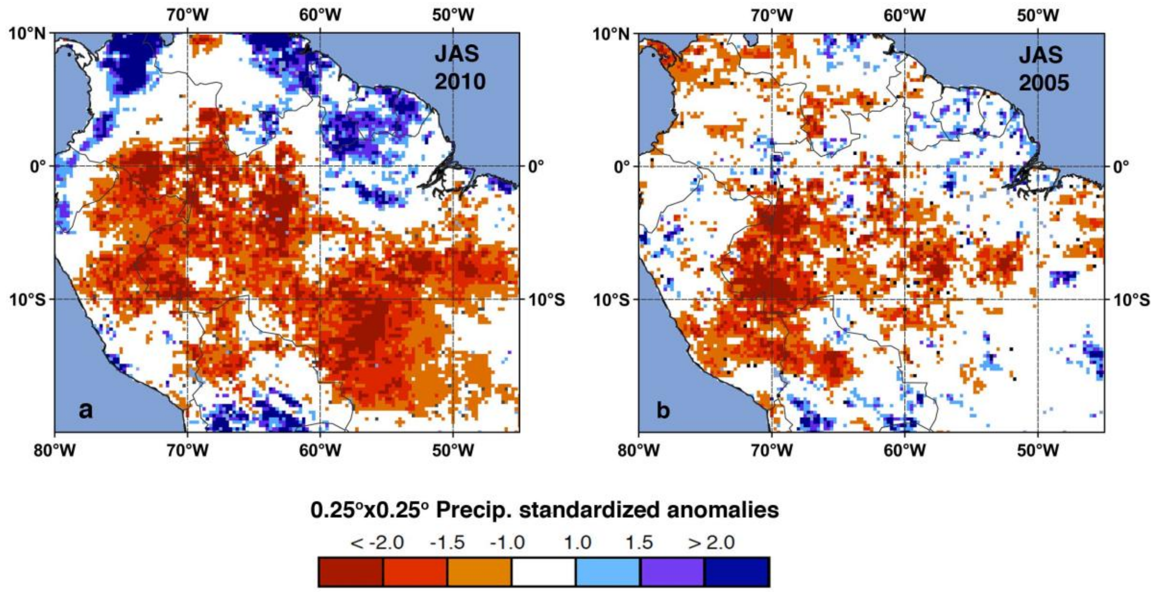
Figure S2. Aggregated International Geosphere Biosphere Program landcover classes of Amazonia at $0.05^{o}x0.05^{o}$ spatial resolution, derived from the MODIS Collection 5 (C5) landcover product.

Figure S3. Spatial patterns of drought impact on Amazonian vegetation in 2005 and 2010. (a) Vegetated areas where the July to September (JAS) precipitation anomalies are less than -1 standard deviations (std.)) in 2010 that show greenness declines (JAS NDVI anomalies less than -1 std.) and. (b) same as (a) but for EVI. (c) and (d) same as (a) and (b), respectively, but for 2005.

Figure S4. Spatial patterns of October to December (OND) 2010 and 2005 standardized anomalies of normalized difference vegetation index (NDVI, a and c) and precipitation (b and d). In each year the OND NDVI anomalies are shown only for drought-stricken vegetated areas (July to September precipitation anomalies less than -1 standard deviation).

Table Captions

Table S1. The 10 lowest stages recorded on the Rio Negro at the Manaus harbor, 1902-2010 (n=109). Source: CPRM/ANA (Serviço Geológico do Brasil/Agência Nacional das Águas - Brazil Geological Service/National Agency for Water). Return periods of droughts were calculated by ranking, from low to high, the lowest level reached by the river in each year of the time series of length n=109 (1902-2010), and calculating the probability of occurrence by dividing the rank by n+1 (110). The return period is the inverse of the probability of occurrence.



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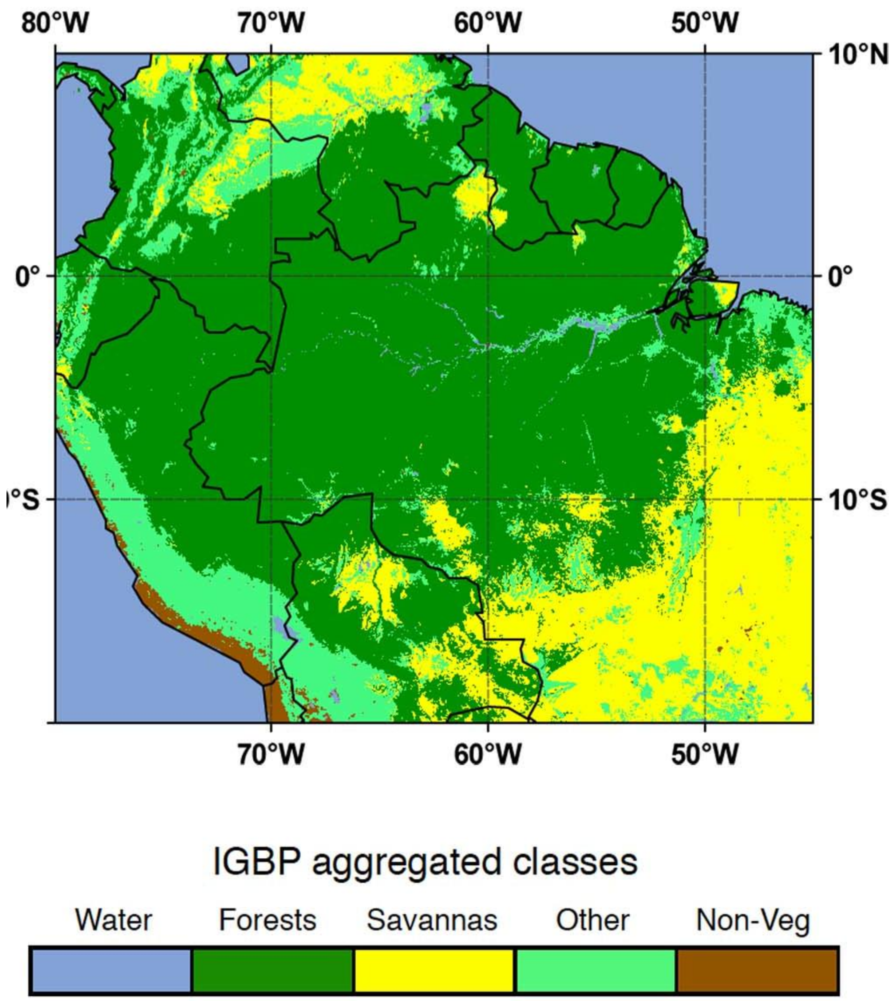

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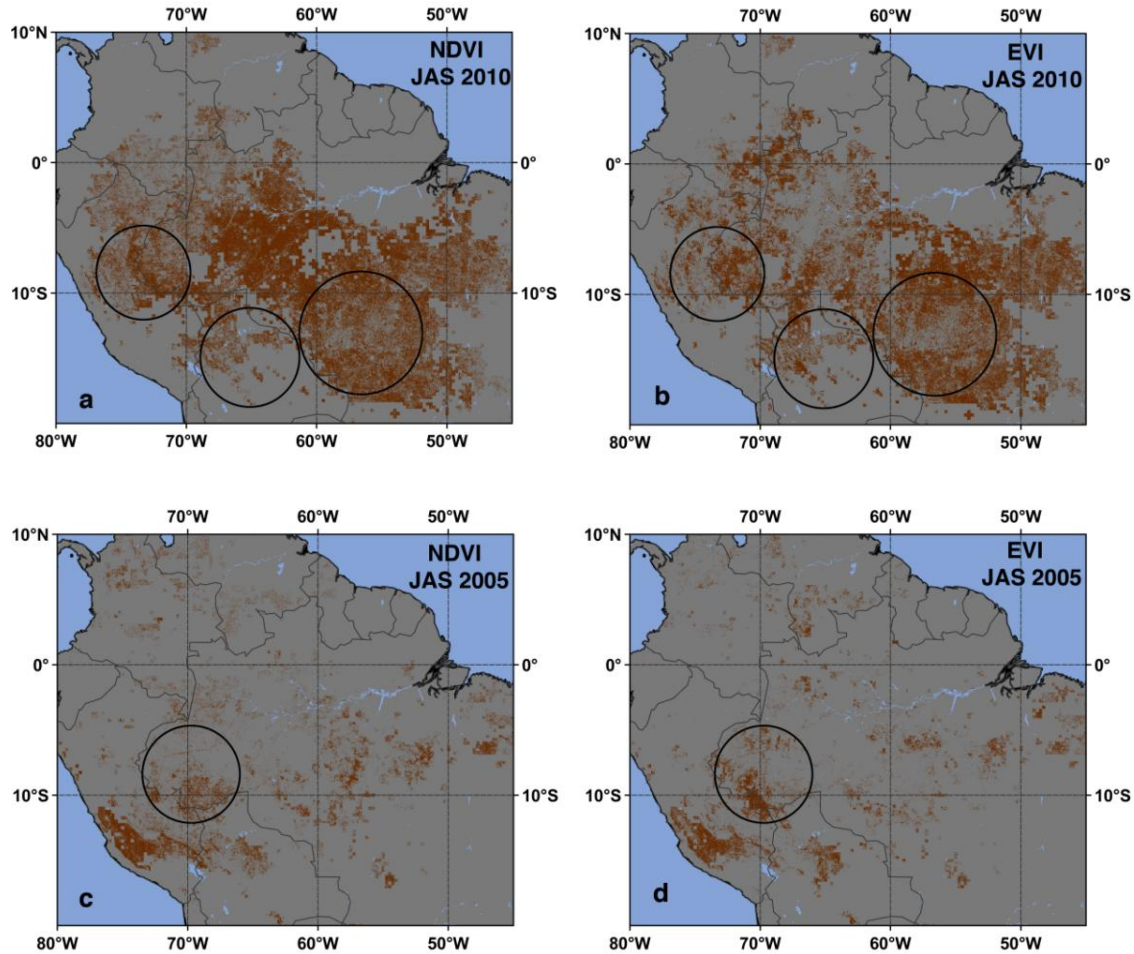

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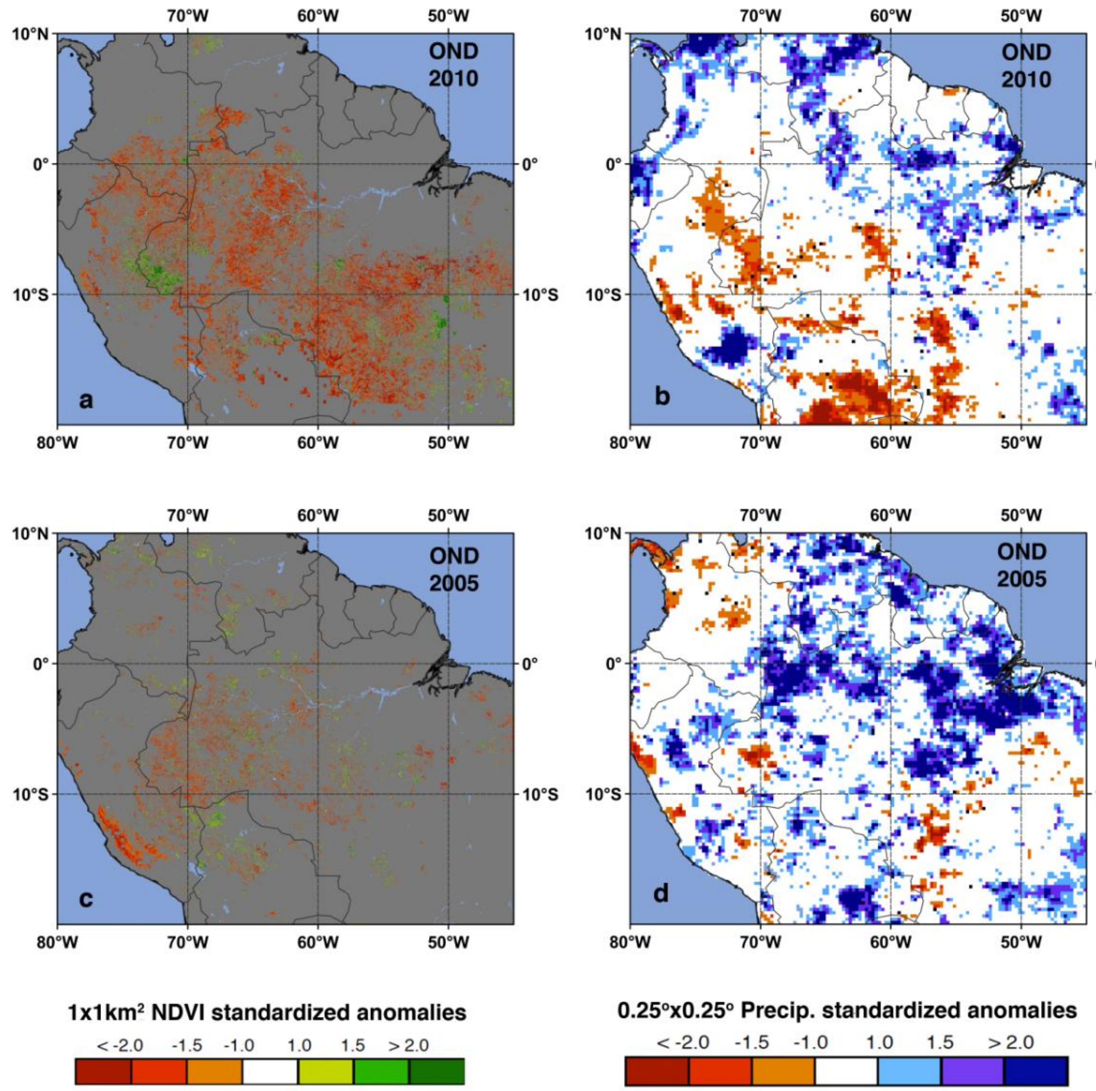

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Rank	Year of Occurrence	Lowest River Stage (m)	Probability of event being exceeded	Return period (years)
1	2010	13.63	0.9%	110.00
2	1963	13.64	1.8%	55.00
3	1906	14.20	2.7%	36.67
4	1997	14.34	3.6%	27.50
5	1916	14.42	4.5%	22.00
6	1926	14.54	5.5%	18.33
7	1958	14.74	6.4%	15.71
8	2005	14.75	7.3%	13.75
9	1936	14.97	8.2%	12.22
10	1998	15.03	9.1%	11.00