Amazon forests did not green-up during the 2005 drought

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Abstract. The sensitivity of Amazon rainforests to dry-season droughts is still poorly understood, with reports of enhanced tree mortality and forest fires on one hand, and excessive forest greening on the other. Here, we report that the previous results of large-scale greening of the Amazon, obtained from an earlier version of satellite-derived vegetation greenness data – Collection 4 (C4) Enhanced Vegetation Index (EVI), are irreproducible, with both this earlier version as well as the improved, current version (C5), owing to inclusion of atmosphere-corrupted data in those results. We find no evidence of large-scale greening of intact Amazon forests during the 2005 drought – approximately 11%-12% of these drought-stricken forests display greening, while, 28%-29% show browning or no-change, and for the rest, the data are not of sufficient quality to characterize any changes. These changes are also not unique – approximately similar changes are observed in non-drought years as well. Changes in surface solar irradiance are contrary to the speculation in the previously published report of enhanced sunlight availability during the 2005 drought. There was no co-relation between drought severity and greenness changes, which is contrary to the idea of drought-induced greening. Thus, we conclude that Amazon forests did not green-up during the 2005 drought.

INTRODUCTION

This study attempts to reconcile contradictory reports of increased tree mortality [*Phillips et al.*, 2009] and extensive biomass burning [*Aragao et al.*, 2007] with anomalous greening of Amazon forests [*Saleska et al.,* 2007, hereinafter SDHR07] during the 2005 drought. Our analysis here is focused on the answering the following five questions.

1. Are the results published in SDHR07 reproducible with both the current (C5) and previous (C4) versions of EVI data?
2. What fraction of the intact forest area impacted by the drought exhibited anomalous greening in year 2005?
3. Is there evidence of higher than normal amounts of sunlight during the 2005 drought, which may have somehow caused the forests to green-up, as speculated in SDHR07?
4. If drought caused the forests to green-up, is there a relationship between the severity of drought and the spatial extent or magnitude of greening?
5. Are greenness changes during the 2005 drought unique compared to changes in non-drought years?

Data

- Collection 5 (C5) Enhanced Vegetation Index (EVI) at 1x1 km^2 spatial resolution and 16-day frequency (MOD13A2), obtained from the NASA LP DAAC [WWW1] for July-September of the period 2000-2008.
- Collection 4 (C4) EVI at 1x1 km^2 spatial resolution and 16-day frequency, obtained from SDHR07 for July-September of period 2000-2005. These data lacked quality flags, so C5 quality flags were used.
- Collection 5 (C5) landcover at 1x1 km^2, obtained from NASA LPDAAC [WWW1].
- Version 6 precipitation data (3B43) at 0.25°x0.25° spatial resolution and monthly frequency, obtained from Tropical Rainfall Measuring Mission (TRMM) [WWW2] for July-September of the period 1998-2008.
- Level 3 Regional Radiative Fluxes and Clouds product (CER_AVG_Terra-FM1-MODIS-Edition2C & CER_AVG_Terra-FM2-MODIS-Edition2C) at 1°x1° spatial resolution and monthly frequency, obtained from NASA Langley Research Center Atmosphere Science Data Center [WWW3] for period July-September of period 2000-2005.
- 2005 July-September standardized anomalies of EVI, precipitation and surface radiation are used in this study.

IRREPRODUCIBILITY OF RESULTS

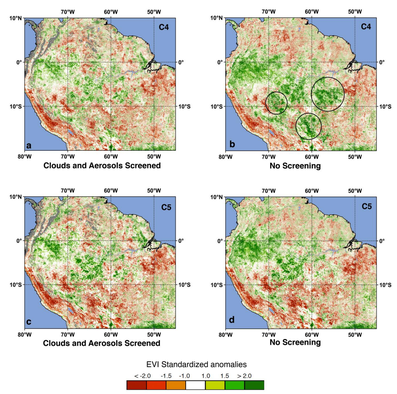

Figure 1. Spatial patterns of July to September (JAS) 2005 standardized anomalies of Enhanced Vegetation Index (EVI) at 1x1 km^2 spatial resolution. (a) Collection 4 (C4) EVI data filtered for clouds (adjacent cloud, mixed clouds and possible shadow) and aerosols (high and climatology aerosols); and anomalies calculated as in SDHR07. (b) C4 EVI with no data-quality filtering (same as Fig. 1B of SDHR07). (c) Collection 5 (C5) EVI data filtered for clouds (adjacent cloud, mixed clouds and possible shadows) and aerosols (high and climatology aerosols); and anomalies calculated as in SDHR07. (d) C5 EVI with no data-quality filtering. For consistency between C4 and C5 EVI, anomalies are calculated relative to the base period 2000-2004.

Figure	ΔGreening (%)	ΔBrowning (%)	ΔNo-change (%)
1a	-35.98	65.12	11.57
1c	-35.42	72.74	8.81
1d	-28.36	72.00	6.03

Table 1. Changes in spatial extent of EVI anomalies of drought-stricken forest areas in the Amazon region (0° to 20°S and 45°W to 80°W) in year 2005 during the July to September quarter. Pixels with EVI anomalies in the range -1 to +1 std. are classified as showing no changes. Pixels with EVI anomalies less than -1 std. are classified as browning. Pixels with EVI anomalies greater than +1 std. are classified as greening. Pixels with precipitation deficit less than -1 are classified as drought-stricken. The changes in spatial extent of EVI anomalies (ΔGreening, ΔBrowning and ΔNo-change) are calculated for Figs. 1a, c and d, relative to Fig. 1b (Our Fig. 1b is the same as Fig. 1B of SDHR07).

- The greening patterns in SDHR07 cannot be reproduced with C4 EVI data when atmosphere-corrupted data are filtered and analyzed following SDHR07 (Fig. 1a). Extent of greening decreases by 36% (Table 1).
- The greening patterns can be reproduced when when atmosphere-corrupted data are not screened out (Fig. 1b compared to Fig. 1B of SDHR07).
- The published patterns also cannot be reproduced with the newer C5 EVI data irrespective of whether corrupted data are filtered or not (Fig. 1c and 1d). Extent of greening decreases by 28-36% (Table 1).
- Three prominent patches of greening (encircled in Fig. 1b) are missing (Fig. 1a, 1c and 1d) – the largest one being approximately 300,000 km^2. These patches are located in regions of atmosphere-corruption of EVI (Fig. 2).
- Exclusion of atmosphere-corrupted data produces somewhat similar greenness changes between C4 and C5 EVI data (Fig. 1a, 1c and Table 1).

1. We conclude that the results of SDHR07 cannot be reproduced either with C4 or C5 EVI data owing to inclusion of atmosphere-corrupted data in their analysis.

GREENNESS CHANGES DURING 2005 DROUGHT

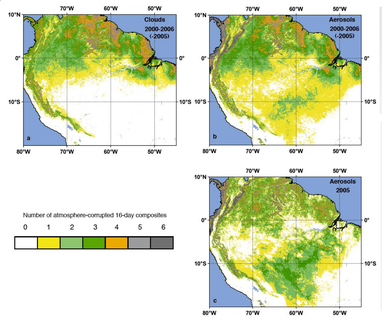

Figure 2. Spatial patterns of atmosphere corruption of EVI data. (a) Average number of 16-day EVI composites in the July to September quarter of 2000-2006, excluding 2005, with quality flags indicating clouds (adjacent clouds, mixed clouds and possible shadows). A 16-day EVI composite refers to one best-quality EVI value to represent a 16-day period. (b) Same as (a) but with quality flags indicating aerosols (climatology and high aerosols). (c) Same as (b) but for 2005 only. 19.03% pixels in the 2005 drought affected forests south of the equator have 2 or more 16-day composites with aerosol corruption during the July to September quarter of the period 2000-2006, excluding 2005. In 2005 this percentage increases to 36.84%.

- Aerosols are the dominant source of atmosphere corruption of EVI data during the dry season in the Amazon region (Fig. 2) – large quantities of aerosols emanate from biomass burning during this time [e.g., *Eck et al*., 1998; *Schafer et al.*, 2002].
- Aerosol contamination, as indicated by the "high" and "climatology" quality flags, was higher during the dry season of 2005 compared to non-drought years (Fig. 2b and 2c) – consistent with several other reports of anomalous aerosol loads during the 2005 dry season [e.g., *Koren et al.*, 2007; *Bevan et al.*, 2009].
- EVI data corrupted with clouds, shadows, high and climatology aerosols must be screened out [e.g., *Didan and Huete*, 2006; *Vermote and Vermeulen*, 1996].

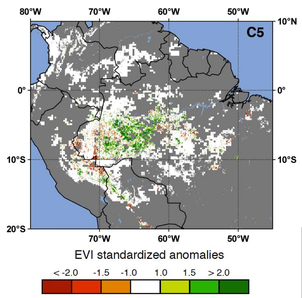

Figure 3. Spatial patterns of July to September (JAS) 2005 standardized anomalies of Collection 5 (C5) Enhanced Vegetation Index (EVI) at 1x1 km^2 spatial resolution. Cloud, shadow, climatology aerosol and high aerosol contaminated data are screened out. Standardized EVI anomalies of intact forests in the drought-stricken region (July to September 2005 precipitation standardized anomalies that are less than -1) south of the equator are shown. EVI anomalies are calculated relative to the base period of 2000-2006, but excluding 2005. Note that the changes in greenness are insignificant north of the equator.

- Greenness changes are calculated using uncontaminated C5 EVI of consistent data records (spanning July-September of the 2000-2006 period).
- About 11-12% of the drought-stricken forests, south of the equator, show greening, while 28-29% of these forests show no-changes or browning, and for nearly 60% of this drought impacted area, there are no valid EVI data to make a determination of changes.

2. We conclude that there is no evidence of large-scale greening of the Amazon during the 2005 drought in regions for which valid EVI data exist.

CHANGES IN SUNLIGHT AVAILABILITY

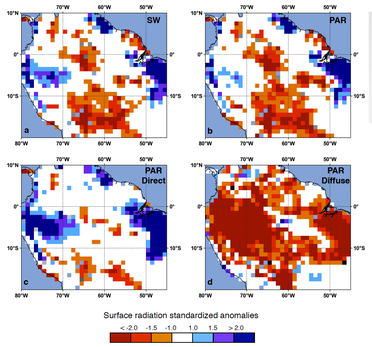

Figure 4. Spatial patterns of July to September (JAS) standardized anomalies of all sky (total sky) surface radiation at 1°x1° spatial resolution for 2005. (a) Shortwave (SW) radiation. (b) Photosynthetically active radiation (PAR, 400-700 nm). (c) Direct PAR. (d) Diffuse PAR. The reference period for anomaly calculation is 2000-2004.

- Surface shortwave radiation declined over 35% of the Amazon forests (Fig. 4a) during the dry season of 2005 and PAR declined over an even larger region (47.5%) (Fig. 4b).
- Reductions in diffuse PAR were observed over 78.5% of Amazon forests (Fig. 4d). The extent of decline in direct PAR (14%) was much smaller (Fig. 4c). Amazon forests refers to forests south of the equator affected with drought (drought-stricken) during July-September, 2005.
- The observed changes in total and direct-to-diffuse fractions of surface solar radiation are contrary to the expectation of enhanced surface sunlight levels during the drought of 2005.

3. We conclude that the speculation of light driven greening of Amazon forests during the drought of 2005 is without basis.

GREENNESS CHANGES VIS-À-VIS DROUGHT

EVI Anomaly	-1.5< PD< -1.0	-2.0< PD< -1.5	PD< -2.0
Greening (%) [Magnitude (std)]	11.63 [1.99]	14.16 [1.98]	11.56 [1.91]
Browning (%) [Magnitude (std)]	4.99 [-1.87]	5.67 [-1.88]	6.40 [-1.90]
No Change (%)	19.12	23.63	24.24

Table 2. Changes in spatial extent and magnitude of EVI anomalies of forest areas in the Amazon region 0° to 20°S and 45°W to 80°W in year 2005 during the July to September quarter. Pixels with EVI anomalies in the range -1 to +1 std. are classified as showing no changes. Pixels with EVI anomalies less than -1 std. are classified as browning. Pixels with EVI anomalies greater than +1 std. are classified as greening. The average level of browning or greening is also shown in brackets. The changes in spatial extent and magnitude of EVI anomalies are calculated for varying levels of precipitation deficit (anomaly) (PD).

- 11%-14% of Amazon forests show greening, while, 24%-30% display browning or no change, irrespective of how the precipitation deficit, a measure of drought severity, is varied (increased or decreased) (Table 2).
- The magnitudes of greening and browning also do not change with drought severity (Table 2).

4. We conclude that there was no co-variation between the severity of drought and the spatial extent and magnitude of greenness changes of Amazon forests in 2005.

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WWW3:http://eosweb.larc.nasa.gov/PRODOCS/ceres/SYN-AVG-ZAVG/Quality_Summaries/CER_SYN-AVG-ZAVG_Edition2.html
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COMPARISON WITH NON-DROUGHT YEARS

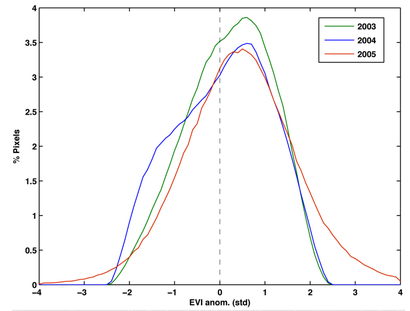

Figure 5. Frequency distribution (%) of July to September EVI standardized anomalies in intact forests within the 2005 drought region, south of the equator. Shown here are distributions from two non-drought years – 2003 and 2004; and drought year 2005. The reference period used for anomaly calculation is 2000-2008, but excluding 2005.

Year	Precipitation Deficit Area (%)	Greening (%) [Magnitude (std)]	Browning (%) [Magnitude (std)]	No Change (%)	Valid Pixels (%)
2000	0.99	5.19 [1.37]	6.13 [-1.43]	23.75	35.09
2001	6.09	5.15 [1.38]	5.68 [-1.43]	24.24	35.09
2002	10.5	5.08 [1.38]	6.05 [-1.44]	23.95	35.09
2003	5.34	8.05 [1.43]	4.12 [-1.43]	22.90	35.09
2004	4.68	7.56 [1.46]	6.72 [-1.50]	20.80	35.09
2005	87.04	10.80 [1.88]	3.89 [-1.70]	18.98	33.68
2006	26.46	4.95 [1.35]	3.86 [-1.37]	26.27	35.09
2007	41.59	4.76 [1.37]	6.43 [-1.42]	23.88	35.09
2008	18.95	3.10 [1.34]	6.57 [-1.41]	25.40	35.09

Table 3. Changes in EVI anomalies and precipitation during the July to September (JAS) quarter of years 2000 to 2008. Only forest pixels in the region 0° to 20°S and 45°W to 80°W that fall within JAS 2005 precipitation anomaly less than -1 std. (relative to the mean for the 1998 to 2006 period, excluding 2005) are considered. The EVI (1x1 km^2) anomalies are relative to the mean for the 2000 to 2008 period. The precipitation anomalies are relative to the mean for the 1998 to 2008 period. In both cases, year 2005 data are excluded. Pixels with EVI anomalies in the range -1 to +1 std. are classified as showing no changes. Pixels with EVI anomalies less than -1 std. are classified as browning. Pixels with EVI anomalies greater than +1 std. are classified as greening. Note that the greening, browning, no-change and validity shown in the table are relevant to the kind of analysis presented here.

- EVI anomalies of Amazon forests display nearly identical negatively skewed (i.e. dominated by positive EVI anomalies) frequency distributions in 2003, 2004 and 2005 (Fig. 5).
- During the non-drought years of 2003 and 2004, approximately 8% of the intact forests show greening compared to 11% in the drought year 2005 (Table 3).
- The extents of browning or no-change in 2003 (27%) and 2004 (27%) are also similar to that in 2005 (23%) (Table 3).
- Prominent spatial patterns of greening and browning, unrelated to precipitation anomalies, are found in other non-drought years as well.

5. We conclude that the spatial patterns of EVI changes seen in drought year 2005 are not unique in comparison to non-drought years.

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