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Remotely sensed heat anomalies linked with Amazonian forest biomass declines

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[1] The occurrence of two major Amazonian droughts in 2005 and 2010 underscores the need for improved understanding of how drought affects tropical forest. During both droughts, MODIS land surface temperature data detected anomalously high daytime and nighttime canopy temperatures throughout drought-affected regions. Daytime thermal anomalies explained 38.6% of the variability in the reduction of aboveground living biomass ($p < 0.01$; $n = 17$) in drought-affected forest sites. Multivariate linear models of heat and moisture stress explained a greater proportion of the variability, at 65.1% ($p < 0.01$; $n = 17$), providing substantively greater explanatory power than precipitation-only models. Our results suggest that heat stress played an important role in the two droughts and that models should incorporate both heat and moisture stress to predict drought effects on tropical forests. **Citation:** Toomey, M., D. A. Roberts, C. Still, M. L. Goulden, and J. P. McFadden (2011), Remotely sensed heat anomalies linked with Amazonian forest biomass declines, *Geophys. Res. Lett.*, *38*, L19704, doi:10.1029/2011GL049041.

1. Introduction

[2] The Amazon basin has experienced two major droughts in the past decade. In 2005, a dry season precipitation anomaly, peaking in September, affected 2.5 million km^2 in southwestern and central Amazon which has been shown to be one of the worst of the past century [*Marengo et al.*, 2008]. After the 2005 drought, significant increases in tree mortality were documented for a large number of long-term forest plots, yielding estimates of basin-wide carbon losses of 1.2–1.6 Pg [*Phillips et al.*, 2009]. In 2010 there was an even more widespread drought (3.2 million km^2); extrapolating moisture deficit-mortality relationships of *Phillips et al.* [2009], *Lewis et al.* [2011] estimated carbon losses as high as 2.2 Pg. Surprisingly, Enhanced Vegetation Index (EVI) observations from the Moderate Resolution Imaging Spectrometer (MODIS) suggested a "greening-up" during the 2005 drought [*Huete et al.*, 2006; *Saleska et al.*, 2007]. Subsequent studies have not documented the same result when using improved EVI products [*Brando et al.*, 2010; *Samanta et al.*, 2010] and widespread EVI declines have been observed during the 2010 drought [*Xu et al.*, 2011]. Frequent, large-scale drought events and the continuing uncertainty related to EVI variability underscore the need for improved understanding of Amazonian forest drought response.

[3] In this study, we investigate Amazon forest drought response using MODIS Land Surface Temperature (LST) data. Remote sensing measurements using the reflective bands (e.g. the EVI) are sensitive to leaf age [*Brando et al.*, 2010], solar zenith angle [*Galvão et al.*, 2011], atmospheric aerosol loading [*Anderson et al.*, 2010], epiphyll cover [*Toomey et al.*, 2009], and canopy structural changes [*Anderson et al.*, 2010], challenging our understanding of tropical forest drought response. LST data, however, provide an independent means of assessing relationships among thermal anomalies, precipitation and forest ecophysiology. For example, high temperatures can *induce* near-instantaneous reductions in carbon assimilation and increases in autotrophic respiration [*Doughty and Goulden*, 2008], enhancing forest mortality rates [*Allen et al.*, 2010]. Alternatively, high temperatures may be *indicative* of drought stress if they result from decreased evaporative cooling due to stomatal closure and/or leaf loss [*Nepstad et al.*, 2004]. The questions we address in this study are: 1. Is there an observable relationship between precipitation anomaly, LST anomaly and forest stress? 2. Is relative heat stress more or less damaging than absolute heat stress? 3. Do the combined effects of heat and moisture stresses better explain biomass losses and are the effects additive or interactive? 4. What is the mechanistic relationship among precipitation anomaly, LST anomaly, and forest biomass?

2. Data and Methods

[4] We used an 11-year time series (2000–2010) of Collection 5 MODIS LST 8-day 1 km data (MOD11A2, *Wan* [2008]) from NASA's Terra satellite. Eleven MODIS tiles (H10-13V8-10, excluding H13V08) were used, covering the entire Amazon basin. All LST imagery was screened for cloud, aerosol and fire contamination (see auxiliary material).[1] Monthly means and standard deviations for the time series were calculated separately for day and night; monthly means were also calculated for each of the years. Monthly Thermal Anomalies (TA) were calculated for all years, defined as the deviation from monthly mean (2000–2010) temperature; TA were divided by the monthly standard deviation to derive Normalized TA (NTA; analogous to the *z*-score). We also constructed MODIS NDVI time series, using Collection 5 Nadir BRDF-Adjusted Reflectance (MCD43B4) 16-day 1 km data. Monthly NDVI averages and standard deviations were calculated for the same temporal domain as the LST data. Similar to the LST data, we calculated monthly z-scores for

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[1] Auxiliary materials are available in the HTML. doi:10.1029/2011GL049041.

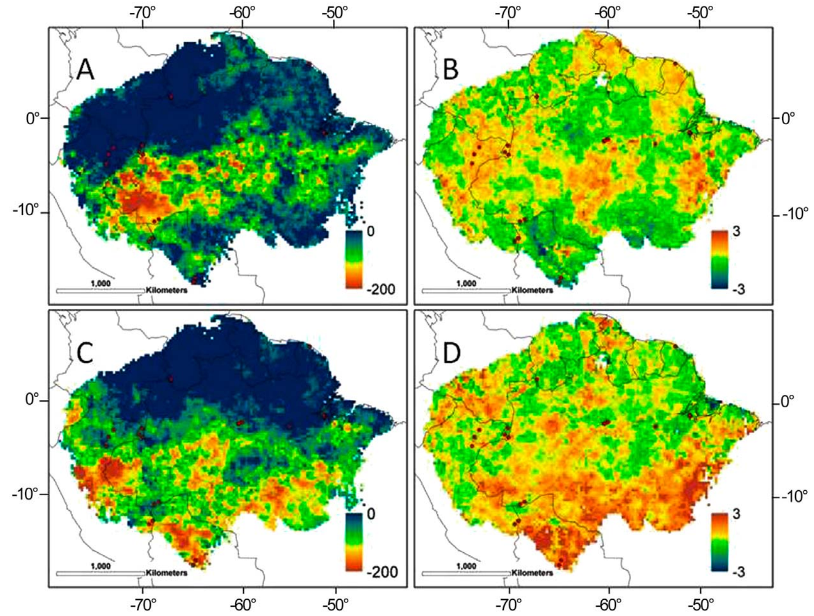

Figure 1. The *d*MCWD (mm) and September daytime TA (°C) in (a and b) 2005 and (c and d) 2010. MODIS images are resampled to 0.25° resolution for display. Red points indicate the location of RAINFOR sites; black lines delineate national borders.

the 2010 dry season, during which dramatic NDVI declines were observed [*Xu et al.*, 2011].

[5] We related LST anomalies in 2005 to net aboveground biomass change (AGBC; Mg ha^{-1} yr^{-1}) and difference in AGBC (*d*AGBC; $AGBC_{2005} - AGBC_{pre\text{-}2005}$) data from 25 well-distributed sites (Table S1 of Text S1 of the auxiliary material) in the RAINFOR network [*Phillips et al.*, 2009] (see auxiliary material). AGBC and *d*AGBC primarily reflect rises in the mortality rate during the drought period. Linear regression was performed between TA or NTA (monthly) and AGBC or *d*AGBC (annual) to examine the heat stress-mortality relationship. Drought severity was calculated using the Tropical Rainfall Measurement Mission (TRMM; 3B43; monthly, 0.25° resolution [*Kummerow et al.*, 1998]) data record from the years 2000–2010. Precipitation anomalies for the 2005 and 2010 drought events were calculated as cumulative precipitation deficit (CPD) and difference in the monthly maximum climatological water deficit (*d*MCWD; see auxiliary material). CPD (mm^{-1}) is defined as deviations from cumulative monthly rainfall for a hydrological year of October–September [*Marengo et al.*, 2008]. *d*MCWD (mm^{-1}) is the difference between a given month's MCWD and the time series mean MCWD, calculated using the formulation of *Aragao et al.* [2007]. To assess the combined effects of heat and moisture stress we performed multiple linear regression, with NTA or TA and CPD or *d*MCWD as the predictors and AGBC or *d*AGBC as the response variable. Statistical analysis focused on the principal dry season months (<100 mm $month^{-1}$), August to October. Dry season timing and duration are variable throughout the basin from June–September in the southwest to July–November in the east Amazon.

3. Results and Discussion

[6] There were widespread daytime warm anomalies in the western, central and southern Amazon during both the 2005 and 2010 droughts (Figures 1 and S1 of the auxiliary material), largely coincident with precipitation deficits. Daytime warm anomalies in sub-equatorial Amazon (the northern basin was largely unaffected during both droughts) exhibited relatively weak but highly significant negative relationships with *d*MCWD during the peaks of the two droughts ($r = -0.25$ and -0.34, respectively; $p < 0.0001$; $n = 8418$; Figure S2 of the auxiliary material). Within drought-affected areas, defined as those having <−25 *d*MCWD [*Phillips et al.*, 2009; *Lewis et al.*, 2011], annual daytime temperatures in 2005 and 2010 were the warmest of the 11 year period. NTA >1 standard deviation was observed for 12.6% and 25.5% of the drought-affected regions in 2005 and 2010, respectively. Twenty-five percent of drought-affected areas incurred TA of >1°C at peak drought intensity in 2005 and >1.4°C in 2010 (Figure 2). Similarly, air temperatures were 0.5–2°C warmer than normal in 2005 and 1–4°C in 2010 (http://data.giss.nasa.gov/gistemp/); *Marengo et al.* [2008] reported heat anomalies of 3–5°C. Although the TA magnitude at the scale of a 1-km LST pixel appears modest, emergent crowns, which are most sensitive to drought [*Nepstad et al.*, 2007; *Phillips et al.*, 2009], likely incurred higher TA means and maxima [*Doughty and Goulden*, 2008]. Both precipitation (Figures 1 and S1 of the auxiliary material) and thermal metrics (Figures 1, 2 and S1 of the auxiliary material) indicate a more widespread and severe drought in 2010, in agreement with *Lewis et al.* [2011] and *Xu et al.* [2011].

[7] All results involving AGBC and *d*AGBC pertain to the 2005 drought. There were significant correlations between daytime TA and AGBC in October ($R^2 = 0.25$; $p = 0.01$; $n = 25$; Table 1), when the epicenters of heat and moisture stress match most closely (Figure S3 of the auxiliary material). When only drought-affected plots are considered (<−25 mm *d*MCWD), a stronger correlation is observed ($R^2 = 0.386$; $p < 0.01$; $n = 17$; Table 1). Thermal anomalies generally

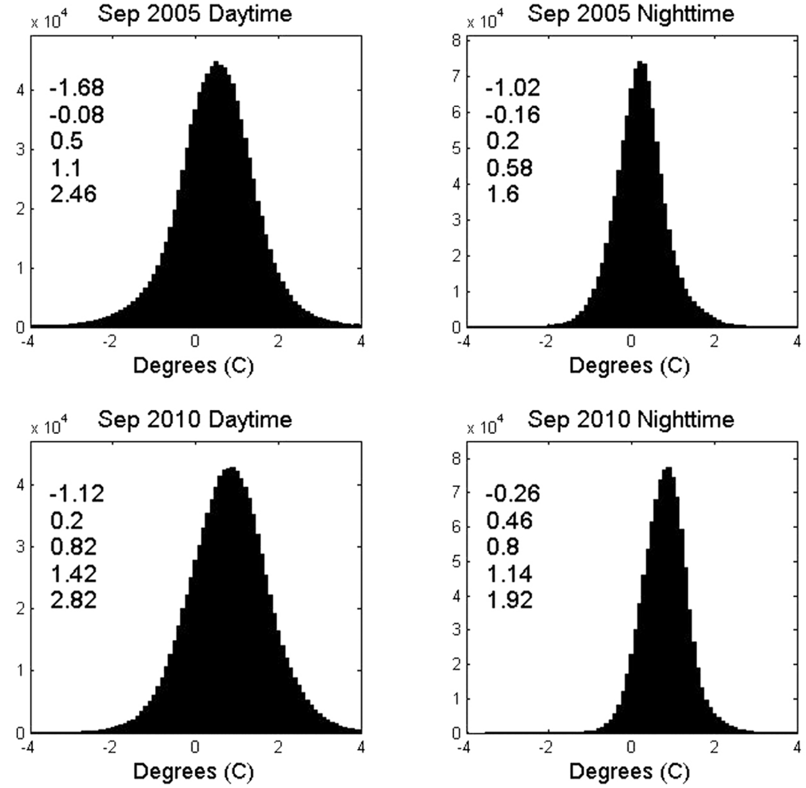

Figure 2. Frequency histograms of daytime and nighttime thermal anomalies (TA) at peak drought for all drought-affected (*d*MCWD < -25 mm) forested pixels. The 2.5th, 25th, 50th, 75th and 97.5th percentiles, respectively, are shown in descending order.

explain more variability in AGBC than CPD or *d*MCWD alone (Table S2) but less variability in *d*AGBC. Relationships were somewhat stronger for TA than for NTA (Table 1), suggesting that the absolute magnitude of heat stress was more important than its relative magnitude. Relationships were stronger for *d*AGBC than for AGBC, in agreement with the drought-biomass relationships of *Phillips et al.* [2009]. Nighttime TA and NTA did not show significant relationships with either AGBC or *d*AGBC, perhaps due to the smaller dynamic range of nighttime temperatures. Multiple linear regressions including moisture and thermal anomalies explained 45.9% ($p < 0.01$; Table 2) of the variability in AGBC and 59.6% ($p < 0.001$) of the variability *d*AGBC among all plots. When only drought-affected sites were considered, moisture and thermal anomalies explained up to 58.9% of AGBC variability ($p < 0.01$) and 65.1% of *d*AGBC variability ($p < 0.01$). On average, the coefficients of determination of the full models were 0.176 higher (range: 0.00–0.48 higher) than those of CPD or *d*MCWD alone (Table S2), a substantive increase in explanatory power. For the strongest full model relationship observed ($R^2 = 0.651$), this constitutes a near doubling over CPD alone ($R^2 = 0.340$). Both TA and NTA produced strong, significant relationships with biomass declines when coupled with precipitation (Table 2). There were no significant ($\alpha = 0.05$) interactions between moisture and thermal anomalies in 40 out of 48 multiple regression models, including most of the strongest relationships (Table 2), suggesting that the effects of moisture and temperature on forest biomass are additive.

[8] Our results indicate that large portions of the Amazon experienced anomalously high daytime temperatures during the 2005 and 2010 droughts. The heat anomalies were linked

Table 1. R^2 From Simple Linear Regression of 2005 Daytime LST Anomalies vs. RAINFOR Data[a]

	AGBC-All Sites (n = 25)	AGBC-Drought Sites (n = 17)	dAGBC-All Sites (n = 23)	*d*AGBC-Drought Sites (n = 17)
Aug TA	0.085	0.160	0.028	0.023
Sep TA	0.003	0.040	0.009	0.037
Oct TA	0.250***	0.386***	0.224**	0.256**
Aug NTA	0.124*	0.098	0.014	0.000
Sep NTA	0.003	0.034	0.008	0.033
Oct NTA	0.201**	0.276**	0.170**	0.181*

[a] TA, LST thermal anomalies; NTA, normalized thermal anomalies. AGBC, RAINFOR 2005 aboveground biomass change; *d*AGBC, difference between 2005 and pre-2005 AGBC. The number of asterisks refers to significance at the 90, 95 and 99% confidence levels, respectively.

Table 2. R^2 From Multiple Linear Regression of 2005 Daytime LST and TRMM Precipitation Anomalies vs. RAINFOR Data[a]

	AGBC-All Sites (n = 25)	AGBC-Drought Sites (n = 17)	*d*AGBC-All Sites (n = 23)	*d*AGBC-Drought Sites (n = 17)
Aug TA + CPD	0.181	0.475**	0.292**	0.580***
Sep TA + CPD	0.142	0.204	0.319**	0.411*
Oct TA + CPD	0.394***	**0.575*****	0.518***	0.573***
Aug TA + *d*MCWD	0.093	0.245	0.157	0.219
Sep TA + *d*MCWD	0.061	0.107	0.232*	0.301
Oct TA + *d*MCWD	**0.290****	0.510**	**0.509*****	0.531**
Aug NTA + CPD	0.278**	0.588***	0.322**	**0.651*****
Sep NTA + CPD	0.144	0.212	0.333**	0.417**
Oct NTA + CPD	0.459***	0.493**	0.596****	0.540**
Aug NTA + *d*MCWD	0.187	**0.406***	0.202	**0.394***
Sep NTA + *d*MCWD	0.063	0.107	0.236*	0.314
Oct NTA + *d*MCWD	**0.406****	0.447**	**0.484*****	0.490**

[a] TA, LST thermal anomalies; NTA, normalized thermal anomalies; CPD, TRMM 2005 cumulative precipitation deficit; *d*MCWD, TRMM 2005 difference in maximum climatological water deficit. AGBC, RAINFOR 2005 aboveground biomass change; *d*AGBC, difference between 2005 and pre-2005 AGBC. The number of asterisks refers to significance at the 90, 95, 99 and 99.9% confidence levels, respectively. Bold values represents cases with an interaction term significant at the 95% confidence level.

with reductions in aboveground biomass and were significant in both absolute and relative terms. Further, we have detected predominantly additive effects between heat and moisture stress which explain substantively more variability in biomass losses than precipitation-only models. To address our final question regarding the mechanistic relationship among LST, drought and biomass, we employed lag analysis between NDVI and TA for the dry season of 2010, finding weak but significant ($p < 0.0001$; $n \sim 4.5$ million) correlations that are strongest ($r = -0.25$; Table S3) and most consistent with a 1 month lag in the NDVI. These correlations begin in June 2010, when widespread (1.98×10^6 km^2) drought conditions (<-25 *d*MCWD) first appear and continue through September. These observations offer some support to the theory that thermal anomalies are a driver of canopy stress rather than a symptom. We recommend field experimentation to further investigate the matter of causation.

[9] In this study we provide evidence of the effect of heat stress which exacerbates aboveground biomass losses, indicating that models of tropical forest drought response should include both moisture and heat effects. Similarly, *Clark et al.* [2010] found that dry season rainfall and nighttime minimum temperature explained 91% of the variability in stand-level tree growth while mortality showed a significant negative correlation with nighttime temperature. The short interval between the 2005 and 2010 droughts and larger thermal anomalies during the second drought are alarming, raising the question of tropical forest resilience to repeated droughts. Moreover, our analysis suggests that even in the absence of moisture stress, climate change-related increases in canopy temperatures, already near an upper physiological threshold [*Corlett et al.*, 2011], may decrease AGBC. Given the high likelihood of rapidly increasing seasonal heat in the tropics during the early 21st century [*Diffenbaugh and Scherer*, 2011], accurate modeling of tropical forest thermal sensitivity will be vital to predict forest health and composition.

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References

Allen, C. D., et al. (2010), A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests, *For. Ecol. Manage.*, *259*, 660–684, doi:10.1016/j.foreco.2009.09.001.

Anderson, L. O., et al. (2010), Remote sensing detection of droughts in Amazonian forest canopies, *New Phytol.*, *187*, 733–750, doi:10.1111/j.1469-8137.2010.03355.x.

Aragao, L. E. O. C., et al. (2007), Spatial patterns and fire response of recent Amazonian droughts, *Geophys. Res. Lett.*, *34*, L07701, doi:10.1029/2006GL028946.

Brando, P. M., et al. (2010), Seasonal and interannual variablility of climate and vegetation indices across the Amazon, *Proc. Natl. Acad. Sci. U. S. A.*, *107*(33), 14,685–14,690, doi:10.1073/pnas.0908741107.

Clark, D. B., et al. (2010), Annual wood production in a tropical rain forest in NE Costa Rica linked to climatic variation but not to increasing CO$_2$, *Global Change Biol.*, *16*, 747–759, doi:10.1111/j.1365-2486.2009.02004.x.

Corlett, C. T. (2011), Impacts of warming on tropical lowland rainforests, *Trends Ecol. Evol.*, in press.

Diffenbaugh, N. S., and M. Scherer (2011), Observational and model evidence of global emergence of permanent, unprecedented heat in the 20th and 21st centuries, *Clim. Change*, *107*, 615–624, doi:10.1007/s10584-011-0112-y.

Doughty, C. E., and M. Goulden (2008), Are tropical forests near a high temperature threshold?, *J. Geophys. Res.*, *113*, G00B07, doi:10.1029/2007JG000632.

Galvão, L. S., et al. (2011), On the intra-annual EVI variability in the dry season of tropical forest: a case study with MODIS and hyperspectral data, *Remote Sens. Environ.*, *115*, 2350–2359, doi:10.1016/j.rse.2011.04.035.

Huete, A. R., et al. (2006), Amazon rainforests green-up with sunlight in dry season, *Geophys. Res. Lett.*, *33*, L06405, doi:10.1029/2005GL025583.

Kummerow, C., et al. (1998), The TRMM sensor package, *Bull. Am. Meteorol. Soc.*, *79*(6), 809–817.

Lewis, S. L., et al. (2011), The 2010 Amazon drought, *Science*, *331*, 554, doi:10.1126/science.1200807.

Marengo, J. A., et al. (2008), The drought of Amazonia in 2005, *J. Clim.*, *21*, 495–516, doi:10.1175/2007JCLI1600.1.

Nepstad, D. C., et al. (2004), Amazon drought and its implications for forest flammability and tree growth: A basin-wide analysis, *Global Change Biol.*, *10*, 704–717, doi:10.1111/j.1529-8817.2003.00772.x.

Nepstad, D. C., et al. (2007), Mortality of large trees and lianas following experimental drought in an Amazon forest, *Ecology*, *88*(9), 2259–2269, doi:10.1890/06-1046.1.

Phillips, O. L., et al. (2009), Drought sensitivity of the Amazon rainforest, *Science*, *323*, 1344–1347, doi:10.1126/science.1164033.

Saleska, S. R., et al. (2007), Amazon forests green-up during 2005 drought, *Science*, *318*, 612, doi:10.1126/science.1146663.

Samanta, A., et al. (2010), Amazon forests did not green-up during the 2005 drought, *Geophys. Res. Lett.*, *37*, L05401, doi:10.1029/2009GL042154.

Toomey, M., et al. (2009), The influence of epiphylls on remote sensing of humid forests, *Remote Sens. Environ.*, *113*, 1787–1798, doi:10.1016/j.rse.2009.04.002.

Wan, Z. (2008), New refinements and validation of the MODIS land-surface temperature/emissivity products, *Remote Sens. Environ.*, *112*, 59–74, doi:10.1016/j.rse.2006.06.026.

Xu, L., et al. (2011), Widespread decline in greenness of Amazonian vegetation due to the 2010 drought, *Geophys. Res. Lett.*, *38*, L07402, doi:10.1029/2011GL046824.

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