Widespread Amazon forest tree mortality from a single cross-basin squall line event

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Abstract.

Climate change is expected to increase the intensity of extreme precipitation events in Amazonia that in turn might produce more forest blowdowns associated with convective storms. Yet quantitative tree mortality associated with convective storms has never been reported across Amazonia, representing an important additional source of carbon to the atmosphere. Here we demonstrate that a single squall line (aligned cluster of convective storm cells) propagating across Amazonia in January, 2005, caused widespread forest tree mortality and may have contributed to the elevated mortality observed that year. Forest plot data demonstrated that the same year represented the second highest mortality rate over a 15-year annual monitoring interval. Over the Manaus region, disturbed forest patches generated by the squall followed a power-law distribution (scaling exponent α=1.48) and produced a mortality of 0.3-0.5 million trees, equivalent to 30% of the observed annual deforestation reported in 2005 over the same area. Basin-wide, estimated tree mortality from this one event was 542±121 million trees, equivalent to 23% of the mean annual biomass accumulation estimated for these forests. Our results highlight the vulnerability of Amazon trees to wind-driven mortality associated with convective storms. Storm intensity is expected to increase with a warming climate, which would result in additional tree mortality and carbon release to the atmosphere, with the potential to further warm the climate system.

1. Introduction

The Amazon forest is a key component of major global biogeochemical cycles, storing 80 ± 20 Pg of biomass carbon [*Saatchi et al*., 2007], accounting for 15% of global terrestrial photosynthesis [*Field et al*., 1998] and recycling back to the atmosphere more than 30% of rainfall through evapotranspiration [*Negrón Juárez et al*., 2008a]. Although anthropogenic activities are responsible for the loss of 15% of the 6.2 million km^2 of the original extent of the Amazon forest [*Soares-Filho et al*., 2006] natural events can also generate forest disturbances [*Nelson et al*., 1994; *Running et al*., 2008; *Frolking et al*., 2009] producing important feedbacks in the Earth system [*Running*, 2008; *Negrón Juárez* et al., 2008b; *IPCC*, 2007]. In 2005 the Amazon basin experienced one of the most severe droughts of the past 100 years [*Marengo et al*., 2008] and analyses of forest plot data suggest that the drought produced elevated tree mortality across the entire Amazon basin [*Phillips et al*., 2009]. Yet, the 2005 drought most strongly affected western and southwestern Amazonia [*Marengo et al*., 2008] which raises a question as to whether the tree mortality observed across the basin was the result of drought alone. Here we present an approach linking field-measured tree mortality data, remote sensing analyses, and an empirical model to quantify widespread tree mortality across the Amazon produced by a single squall line observed from January 16 to January 18, 2005. Results demonstrate the potential for strong squall-lines to produce episodic and clustered [*Chambers et al*., 2009] tree mortality events across the Amazon basin.

2. Data and Methods

2.1. Squall lines

Squall lines are aligned clusters (typical length of 1000 km, width of 200 km and velocity displacement of 16 ms^{-1}) [*Cohen et al*., 2009; *Garstang et al*., 1994] of deep convective cells (characterized by the occurrence of downbursts) [*Gamache and Houze*, 1982] responsible for heavy rainfall during the dry season (April-August) and significant rainfall during the wet season [*Cohen et al.*, 2009]. Most squall lines in Amazonia form along the northeastern coast of South America as sea breeze-induced instability lines and propagate inside the continent and can reach the central and even the extreme western parts of Amazonia. Their propagation into the continent occurs on average 4 times per month [*Cohen et al.*, 2009] and can produce large forest blowdowns [*Garstang et al.*, 1998]. Squall lines can also be generated inside the Amazon basin by cold surges associated with extra-tropical frontal systems that propagate toward the equator producing intense precipitation rates during the December-April period [*Molion et al.*, 2006].

On 16-18 of January 2005, a squall line was observed propagating from southwest to northeast Brazil at ~19 ms^{-1} (Figure 1 and Auxiliary Material Figure S1). This squall line was triggered by convection induced by the convergence associated with a cold front that reached southeast Brazil on January 16th and by a cold surge from the Northern Hemisphere (Figure S2). Its propagation from southwest to northeast was associated with the observed lower middle troposphere wind regime (southwesterly, Figure S2). The total outflow velocity of the squall line was on the order of 24-29 ms^{-1} (the propagation speed plus the velocity of the basic current which was determined to be between 5 and 10 ms^{-1}, Figure S3) plus a velocity surplus of 2-11 ms^{-1} associated with the storm generated pressure gradient field [*Garstang et al.*, 1998]. Thus, for this squall line, we determined downburst velocities between 26 and 41 ms^{-1} which are sufficient to generate large-scale (≥30 ha) forest blowdowns [*Garstang et al.*, 1998]. The intensity of the downbursts and the long-lived character associated with this squall line is supported by the moderate-to-strong lower-troposphere vertical wind shear almost perpendicular to the squall line (Figure S4), a key feature for the evolution, intensity and maintenance of long-lived squall lines [*Rotunno et al*., 1998]. The downburst intensity associated with this squall line was also evidenced by the significant loss of both human life and property reported in the Brazilian Amazonian cities of Manaus, Manacapuru and Santarem (www.cptec.inpe.br/products/climanalise/0105/index.html). Squall lines propagating toward the northeast Amazon are observed, on average, around twice per year as verified by surveying 3-hourly 3B42-V6 rainfall data from TRMM from 1998 to 2008 (ftp://disc3.nascom.nasa.gov/data/s4pa/TRMM_L3/TRMM_3B42).

2.2. Satellite data and Spectral Mixture Analysis

We employed a method similar to *Chambers et al*. [2007] to investigate forest disturbance and tree mortality produced by this squall line. Landsat images from Brazil's National Institute for Space Research (INPE) covering the Manaus area (scene P231 R062, 3.4×10^4 Km^2) collected on 10 July 2001 (Landsat 7, L7, for calibration), 14 October 2004 (Landsat 5, L5, previous to disturbance) and 29 July 2005 (Landsat 5, for disturbance evaluation) were used in this work. These images are available in encoded radiance values and must be converted to reflectance values. All images were georeferenced (400 control points per image) with respect to the NASA Geocover data (https://zulu.ssc.nasa.gov/mrsid/). The Carlotto technique [*Carlotto*, 1999] which accounts for correction due to haze and smoke contamination was applied over the images, as needed. The L7 image was used as a reference image which was atmospherically corrected and converted to reflectance using the Atmospheric CORrection Now (ACORN) software (ImSpec LLC, Boulder, CO). L5 images were radiometrically calibrated band by band with respect to the L7 image using invariant targets. Spectral mixture analysis (SMA) [*Adams et al*., 1995] based on scene-derived endmembers of green vegetation (GV; photosynthetically active vegetation), non-photosynthetic vegetation (NPV; wood, dead vegetation and surface litter), soil, and shade were obtained using a pixel purity index (PPI) algorithm. PPI and SMA are tools available in the Environment for Visualizing Images (ENVI, ITT industries, Inc, Boulder CO, USA) software. As SMA deals with the spectral signature of each pixel (Landsat bands used were 1,2,3,4,5 and 7) this approach also allowed us to separate land-use areas from natural forest disturbances since the first have exposed soil while the second are covered by damaged vegetation [*Souza et al*., 2005]. A visual quality control attending both the shape and direction of blowdown patches was performed to validate the results.

2.3. Landscape forest disturbance

To quantify landscape-scale forest disturbance associated with this squall line event we combined field-measured tree mortality, remote sensing data and modeling. First, SMA was applied to the Landsat images collected on the 14th of October, 2004 and the 29th of July, 2005 to determine per-pixel fractional abundance of GV, NPV, soil, and shade. Changes in NPV (ΔNPV) provide a quantitative measure of changes in forest structure from tree mortality (increase in tree mortality) and were calculated by subtracting the 2004 NPV image from the 2005 NPV image. Second, over one of the blowdown areas (centered at 2.6°S, 60.3°W) we established five sites each containing six 20m×20m forest inventory plots (N = 30) randomly distributed across the entire ΔNPV disturbance gradient (Figure 2a). To estimate tree mortality and biomass loss we use two approaches: (i) Landsat derived ΔNPV was combined with an aboveground biomass distribution map [*Saatchi et al*., 2007], and (ii) a Monte Carlo (MC) simulation model which used a distribution function for stem density and tree biomass generated from permanent forest inventory plots (Figure S5).

In our MC model, the number of trees (N_{trees}) affected by the squall line was calculated as $N_{trees}=\rho\times Mortality\times A$, where ρ is the stem density per pixel. Mortality was obtained from linear regressions between ΔNPV and field-measured tree mortality (Figure 2a), and A is the pixel area. Biomass loss was calculated as: $B_{loss}= \sum_{i=1}^{N_{trees}} M_i$, where N_{trees} is the total number of dead trees in each pixel, and M_i is the biomass for each tree. ρ and M_i were randomly selected from their respective distribution functions obtained from permanent inventory plots across the Amazon forest (Figure S5). MC simulations calculated N_{tree} and B_{loss}, with modeled variability including the standard errors of coefficients from linear regressions, the spatial autocorrelation of forest mortality calculated from geographical information system (GIS) software ArcGIS, and the variation of ρ and M_i (Figure S5).

3. Results and Discussions

A strong relationship was observed between Landsat ΔNPV and field-measured tree mortality (Figure 2b). This enabled us to generate quantitative regional tree mortality rates across the forested landscape, which had previously been limited to only the spatial dimensions of the affected area [*Nelson et al*., 1994]. Disturbed patches produced by the squall line over the Manaus region (3.4×10^4 km^2, Landsat scene, path 231 row 062) followed a power-law frequency distribution with the scaling exponent, α, equal to 1.48 (Figure 3, Text S1). The spectral characteristics of disturbed patches [*Nelson et al*., 1994] with geometrical characteristics associated with the SW to NE propagating squall line demonstrated that widespread tree mortality was associated with this particular event. Detectable high-mortality areas ranged from 5-10 fallen trees (Text S2) occupying single pixels, to blowdown patches of ~30 ha in size. The disturbance produced by the squall line across the Manaus region encompassed 2668 ha causing estimated mortality of 0.32± 0.05 (SD) million trees, equivalent to a total biomass loss of 85 ± 25 (SD) Gg C which will be respired to the atmosphere over an ~18 year period [*Chambers et al*., 2004]. The MC model predicted a mortality of 0.5 ± 0.056 million trees, equivalent to a total biomass loss of 128 ± 14 Gg C (using Figure S5). This calculated disturbance in the Manus region represents (using Figure S5) more than 30% of the annual deforestation (reported as 18 km^2, http://www.obt.inpe.br/prodes) in 2005 over the same region.

Our calculated disturbance is conservative since our analysis is only capable of detecting gaps greater than 5-10 fallen trees. Smaller treefall clusters and single windthrown trees were not amenable to detection with 900 m^2 Landsat data. However, forest plot data collected annually (in July) at the biomass and nutrient experiment (BIONTE, centered at 2.63°S, 60.17°W, located within our Landsat scene) demonstrated that 2005 represented the second-highest mortality rate since annual monitoring began in 1989, 23% higher than the average mortality rate (Figure S6) [*Higuchi et al*., 1997]. Additionally, we only included tree mortality in our carbon calculations, although many snapped trees with significant biomass loss survive by resprouting and were not included.

The impact of the squall line extended well beyond the Manaus region, as verified by surveys of Landsat scenes (Figure S7a). These images revealed disturbed forest areas with blowdown characteristics associated with the squall line ranging from small to large patches (Figure S8). In general, large blowdown patches were more frequent in the Southwest and Central Amazon images. Assuming a similar proportion of disturbed area that was observed over the Manaus area (0.2% of forested area, Text S3) over the total forested area affected by the squall line ($4.5x10^6$ km^2, Figure S7b) across the Amazon, we estimated a total potential damage of 542±121 million trees across the basin by the squall (Text S3). This represents a loss of 0.14 Pg C, and equivalent to 23% of the estimated mean annual carbon accumulation (0.6 Pg C) [*Baker et al*., 2004] of Amazon forests.

The elevated mortality observed in the Central Amazon in 2005 is unlikely to be related to the 2005Amazon drought since analysis of both rainfall and river discharge data showed that this drought had little effect on Central or Eastern Amazonia [*Marengo et al*., 2008]. In Manaus, the effects of rainfall anomalies were observed late in the dry season (September-October) [*Marengo et al*., 2008], whereas the elevated mortality reported here from both Landsat images and forest plot data occurred before the late dry season. Also, for drought to kill trees, multi-year severe rainfall reduction is needed to produce drought-induced tree mortality [*Nepstad et al*., 2002; *Meir et al*., 2008]. Furthermore, individual snapped and windthrown trees comprised a significant fraction of the observed mortality at the BIONTE plots (data collected in July). Interestingly, a recent study [*Phillips et al*., 2009] found elevated tree mortality in forest inventory plots across the Amazon basin (including the BIONTE plots), and suggested that elevated tree mortality was caused by the 2005 drought alone. Our study shows that widespread disturbance produced by a single squall line event in January 2005 must be considered as contributing factor to the high mortality observed in that year, particularly in the Central and Eastern Amazon.

The need for a better understanding of forest disturbances associated with convective storm processes is growing more critical given the projected increase in heavy precipitation events over the Amazon consistent with an anthropogenically warming climate [*IPCC*, 2007]. Observational evidence for this increase has been reported over a number of tropical areas [*IPCC*, 2007] including the Amazon region [*Khan et al*., 2007; *Haylock et al*., 2006]. If a warming climate increases storm intensity, forest mortality may also increase, resulting in an unexpected carbon release to the atmosphere over many years, with the potential to further warm the climate system.

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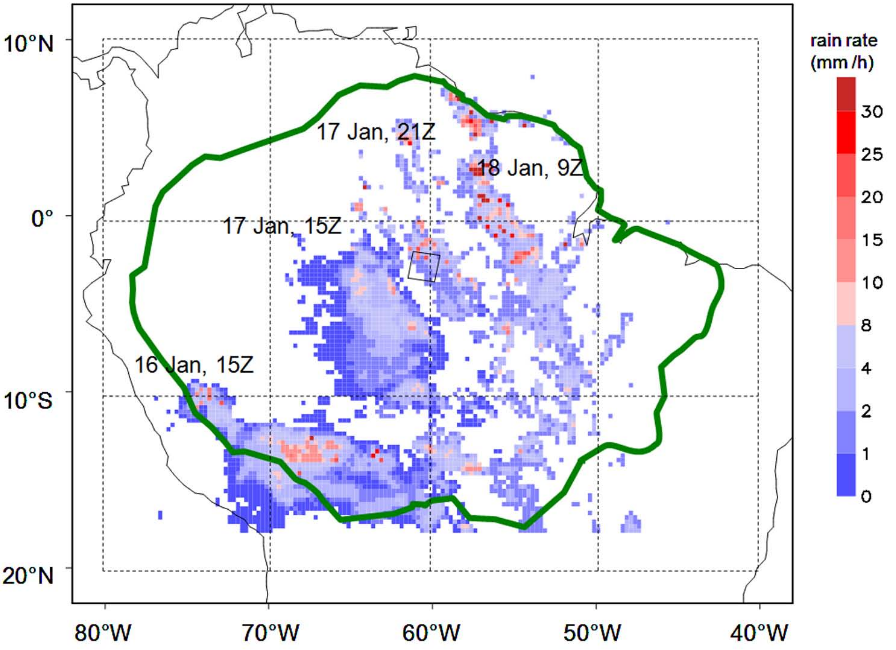
Figure Captions

Figure 1. Squall line event observed on 16-18 January 2005 across the Amazon basin. Precipitation data provided by TRMM (TRMM 3B42-V6, 3-hour temporal resolution, 0.25°, ftp://disc3.nascom.nasa.gov/data/s4pa/TRMM_L3/TRMM_3B42). The green contour line encompasses the Amazon rainforest area. The location of the Landsat image encompassing the Manaus region is illustrated by the solid line square.

Figure 2. Relationship between Landsat ΔNPV and field-measured tree mortality. (**a**) Location of the 30 plots (20mx20m) at 5 sites where field-measured tree mortality was collected. (**b**) A strong relationship between Landsat-derived ΔNPV and field-measured tree mortality data was observed. Site 1 (open circle) was an outlier (r^2 increases to 0.9 when removed) due to contamination by a cloud shadow (**a**).

Figure 3. Forest disturbance over the Manaus landscape produced by the 16-18 January 2005 squall line. Disturbance patches appear as intense red (high middle-infrared reflectance). The inlet shows the respective gap size distribution that followed a power-law, with a scaling exponent (α) of 1.48.


rain rate
(mm /h)
30
25
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15
10
8
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17 Jan, 21Z
18 Jan, 9Z
17 Jan, 15Z
16 Jan, 15Z
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20°N
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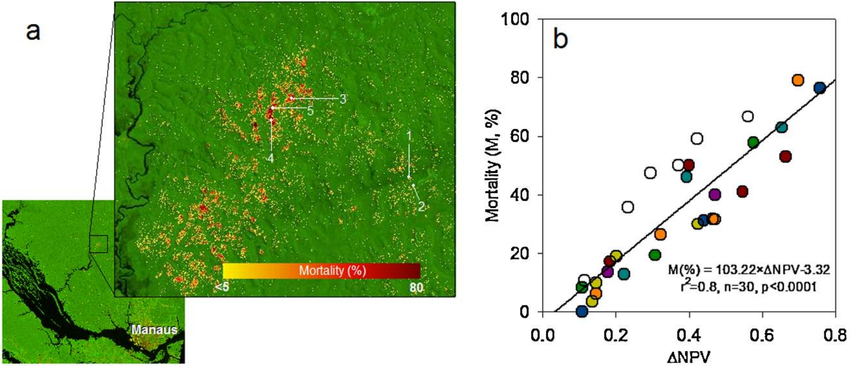
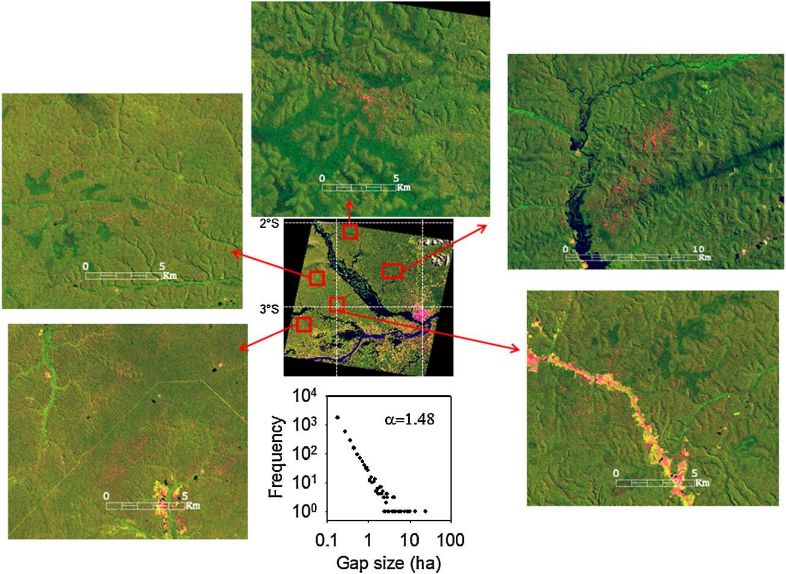
60°W
50°W
40°W


a
Manaus
1
2
3
4
5
Mortality (%)
<5
80
b
Mortality (M, %)
ΔNPV
M(%) = 103.22×ΔNPV-3.32
r2=0.8, n=30, p<0.0001
0
20
40
60
80
100
0.0
0.2
0.4
0.6
0.8



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5
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α=1.48
Frequency
Gap size (ha)