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Precipitation Variability over the Forest-to-Nonforest Transition in Southwestern Amazonia

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ABSTRACT

Prior research has shown that deforestation in the southwestern Amazon enhances the formation of non-precipitating shallow cumulus clouds, while deep cumulus convection was favored over forested land. The research presented here further investigates the trends of hydrometeors in the area by examining how precipitation frequency changes as a function of distance to the forest’s edge. Measurements are made from the precipitation radar on the Tropical Rainfall Measuring Mission (TRMM; TRMM 2A25) satellite, and continuous forest coverage is retrieved from the Moderate Resolution Imaging Spectroradiometer (MODIS; MODIS MCD12Q1). The event-based areal fractions of precipitation coverage (precipitation fraction) are calculated; referenced to forested, nonforested, and forest-edge land cover; and compared. As results are generally consistent with previous findings, the novel conclusions here extend that precipitation frequency in the southwestern Amazon (i) decreases over regions of nonforests far removed (10-plus km) from forest borders but (ii) increases within several kilometers of the forest edges, particularly over the nonforest side of the transition.

1. Introduction

Current estimates and forecasts of Amazonian development suggest that as of 2001, 17% of the basin’s primary canopies had been deforested and that by 2050, only 53% of pre-anthropogenic closed canopy forest stands will remain (Soares-Filho et al. 2006). Some have asked if the disturbance to the ecosystem structure will or has had significant impacts on the basin’s hydrologic climate and if the changing climate will have feedbacks on the ecosystem in return.

There is theoretical support for the idea that land-cover heterogeneities drive solenoidal circulations (Atkinson 1981; Pielke 1984, 2001; Rennó and Ingersoll 1996). Updrafts can be analytically related to near-surface heat flows across dissimilar patches of land, the plumes themselves occurring over the deforested patches with higher surface temperatures. Low-level forest-to-pasture momentum fluxes and high-level pasture-to-forest momentum fluxes have been observed in the southwestern Amazon (Souza et al. 2000). Assuming that deforested patches are indeed warmer, the high sensible heat flux influences vigorous boundary layer development (Pielke 2001). The combination of boundary layer development and convergent lifting winds provides the mechanical energy necessary to lift air parcels to the level of free convection.

There is some general agreement that land-cover length scales on the order of tens of kilometers, or perhaps the Rossby radius, are most optimal for promoting solenoidal circulations (Pielke 2001; Dalu et al. 1996). Heterogeneity scales larger than 100 km cannot produce significant gradients in surface temperatures, whereas scales smaller than several kilometers diffusion processes tend to homogenize thermal properties, thereby destroying the thermal gradients that drive circulation (Baldi et al.)
2008; Anthes 1984; Dalu and Pielke 1993). Ambient winds can potentially strengthen or ameliorate updrafts depending on various factors, including wind strength and plume tilting.

Thus far, uncovering the water cycling effects of structured deforestation in the Amazon have been elusive. D’Almeida et al. (2007) found agreement among experiments with general circulation models that widespread Amazonian deforestation promotes a weakened water cycle, although there is inconsistency in results at finer scales and more realistic land-use scenarios. A land–atmosphere model intercomparison at the 2008 Moore Foundation–National Science Foundation workshop on Amazonian savannization provided evidence that more realistic deforestation scenarios (Soares-Filho et al. 2006) alter patterns of hydrologic energy, including rainfall, yet results differed regarding the sign of mean precipitation anomalies at various locations under different land-use scenarios. Other mesoscale numerical simulation experiments have found that increased deforestation leads to reduced precipitation, preferentially reduced over the deforested areas themselves (Silva et al. 2008). Some have shown increased convective precipitation resulting from various scales of forest–nonforest heterogeneities, particularly over deforested areas, thus creating positive regrowth conditions (Avisser and Liu 1996).

It has already been observed that dry-season afternoon shallow cumulus clouds show a positive bias over deforested areas of the region (Cutrim et al. 1995; Rabin et al. 1990; Chagnon et al. 2004). Wang et al. (2009) found the opposite was true for high cold clouds, which were more prevalent over intact forests. Correspondingly, both convective available potential energy and convective inhibition were typically weaker over nonforests and stronger over intact forests, suggesting that nonforested land covers are associated with relatively rapid boundary layer development but have a lesser ability to generate deep convection.

The objective here is to use observations from the Tropical Rainfall Measuring Mission (TRMM)’s precipitation radar (PR) to further elucidate the precipitation component of this relationship between the land cover of the southwestern Amazon and its hydrometeors, and consider its current and potential implications to the local ecohydrology. We continue the focus of previous papers on dry-season (June–October) afternoon precipitation events. First, we present the methodology of matching precipitation with land cover and forming comparative statistics. Then, we analyze the results from three tests: (i) the comparison of precipitation fractions over forested and nonforested landscapes; (ii) the comparison of precipitation fraction over interior nonforest regions with both forested and forest edge regions; and (iii) the three-way comparison of precipitation fraction over interior forests, interior nonforests, and transition zones between the two.

2. Methods

Three experiments were performed and will be explained in more detail. The experiments were common in that we observed a series of TRMM rainfall maps and counted the cells with rainfall, keeping a record of which type of land cover (forested or not) was present beneath it. All experiments derived the condition of forestation from the same dataset, but they differ in how this dataset was ultimately processed.

a. Datasets MODIS 12Q1 and TRMM 2A25

Forest coverage in Rondônia, Brazil, was retrieved from the Moderate Resolution Imaging Spectroradiometer (MODIS) Land Cover Type product MCD12Q1, a yearly product providing land-cover classifications from 2001 to 2008 on a 500-m sinusoidal grid. These data were reprojected via nearest neighbor, to an equal angle 4-km grid that roughly matches the resolution of the TRMM 2A25 product. The land-cover classes follow the International Geosphere-Biosphere Programme (IGBP) standard. Cells identified as evergreen needleleaf, evergreen broadleaf, deciduous needleleaf, deciduous broadleaf, and mixed forested were deemed “forested,” while the remainder were deemed “nonforested.” This binary 4-km map of forested and nonforested cells was used as the basis for comparing rainfall measurements in the following experiments.

The nonforested portion of the binary map was drawn from croplands, urban areas, permanent wetlands, grasslands, savannas, woody savannas, closed shrublands, and water. A map of these coverage types is shown in Fig. 1. In 2001, 75% of the grid was composed of broadleaf evergreen forests, 3% mixed forests, 2% woody savanna, 10% savanna, 2% grasslands, and 5% croplands. The remainder summed to roughly 3% of total coverage. By 2007, broadleaf evergreen forests accounted for 71% of land cover, while mixed forests decreased to a little more than 1% and the coverage of savannas increased to roughly 13% of the total area. While forested landscapes by and large refer to broadleaf evergreen forests, the variability of the physical properties across nonforested land covers is not trivial. In the most extreme case, compare the heating rate and energy flux properties of water bodies versus dry lands with shallow rooting depths; the partitioning of total net radiation into sensible, latent, and earthward energy flux components could differ significantly. We argue here that nonforested landscapes in this domain of study are strongly reflective of savanna-
grassland-type ecosystems, which in general have consistently higher albedo, lower leaf area index, lower surface layer roughness and drag coefficients, and shallower rooting depths than forests. While water bodies, permanent wetlands, and irrigated croplands may have higher potential evaporation rates and increased thermal inertia due to standing water, they only account for less than 10% of the total nonforested area and can only marginally influence statistics. Regarding terra firma, forests of the region typically have higher potential evaporation rates than grasslands, savannas, and croplands. There has been open discussion on how the evapotranspiration rates of the region’s forested and nonforest ecosystems respond to stomatal control; however, eddy covariance measurements indicate evapotranspiration rates for pastures (Fazenda Nossa Senhora) are, on average, lower than intact forests (Jaru) in both wet and dry seasons (Hasler and Avissar 2007).

The binary mapping of forest cover was then used as a common grid to georeference TRMM 2A25 precipitation measurements. The 2A25 is a swath-based near-instantaneous measurement of rainfall converted from backscattered reflectivity by the TRMM precipitation radar (Kummerow et al. 1998). The estimated rainfall is not without its uncertainties, considering, for example, its known biases over the region of interest (Rozante et al. 2010), patterned bias in sampling frequency, and its limited ability to measure the diurnal cycle or rainfall at fine scales (Negri et al. 2002). Likewise, with any remote sensing product, there are nonnegligible instances of missed detections, estimated at rates of 15% or less compared to validating rain gauges over 5-min integrations (Wang and Wolff 2010). As will be discussed in greater detail, the interest in this study lies in making relative comparisons of rainfall detection and in formulating its statistics irrespective of the swath footprint, swath coverage frequency or the accumulations, or temporal trends in rainfall. We do acknowledge, however, that the analysis of the TRMM PR data only reflects the statistics of the window of interest (afternoon) and not the whole diurnal spectrum of rainfall.

The orbital swaths of TRMM 2A25 precipitation that intersected the study domain were archived during an extended dry season (June–October) from 2001 through 2007, falling between 11 a.m. and 6 p.m. local time (LT); 199 rainfall-producing swaths were used. The rainfall estimate is a three-dimensional product, providing a ground resolution of 5 km in a 247-km swath width at a vertical-layering resolution of 250 m. Perhaps a TRMM product rendering surface rainfall alone would be simpler to use; however, the 2A25 product was already available in-house after an extensive preanalysis.
and comparison with other products, such as the TRMM 2A12 and Geostationary Operational Environmental Satellite (GOES) visible (VIS)/IR. The swath-based precipitation measurements were matched to the land-cover grid via the nearest-neighbor method. The study domain is 600 km wide north–south and 800 km east–west (150 \times 200 pixels; see Fig. 2a).

b. Data analysis framework

There was concern that multiple environmental covariates to precipitation were present in the area of interest, thus making it difficult to confidently discern how the linkage between land cover and precipitation exists in this area. Two obvious factors are topographic elevation and weather patterns. While the southwestern portion of the study domain does not quite reach the lower slopes of the Bolivian Andes, orographic weather effects and the persistent weather patterns associated with the South American low-level jet and South American circulation cannot be ignored. To neutralize the spatial biases imposed by topography or climate, the sampling strategy is randomized and the analysis is carried out over a series of smaller subdomains. More specifically, the statistical techniques (to be discussed) were applied to each subdomain independently, and then the average behavior across the subdomains was recorded for each event. Each subdomain is 50 pixels wide (200 km \times 200 km), and their locations were selected randomly by seeding an offset tiling the domain. An example of how the subdomains are tiled relative to an offset is shown in Fig. 2b. Notice that the subdomains are depicted with rounded corners in the figure; this is only to help the viewer differentiate subdomains and areas that were rejected. Subdomains were rejected from the analysis if both forested and deforested pixels did not each cover at least 10% of the total area. The number of subdomains varies from year to year as the land cover influences the balance of forested to nonforested pixels.

c. Experiment 1

Here we ask the question. Given a land cover—forest or nonforest—what is the likelihood precipitation will be detected above it? This is similar to and based on the

Fig. 2. (a) Binary mapping of the forested and nonforested grid converted from MODIS MCD12Q1 IGBP classes for the year 2001. (b) An example of subdomains that have been tiled out from a random offset. (c) The binary map with a 1-cell encroachment as used in experiment 2. (d) Mapping of the forested, nonforested, and an 8-km band on the forest-to-nonforest transition, as used in experiment 3.
Wang et al. (2009) question. Given a cloud, what is the likelihood it is found above a forest or pasture? During each TRMM overpass, we calculate the precipitation fraction for each forested $P_{F}^{\text{for}}$ and nonforested $P_{F}^{\text{nf}}$ land cover for each the subdomains. This is simply the number of pixels with precipitation $P$ above their respective land-cover type, normalized by the number of that land cover’s pixels $N$ contained in that subdomain, 

$$
P_{F}^{\text{nf}} = \frac{P_{nf}}{N_{nf}}, \quad P_{F}^{\text{for}} = \frac{P_{for}}{N_{for}}.
$$

In the same way, Chagnon and Bras (2005) used cloud fractions to calculate a binary exceedance ($e$) that describes the tendency of the cloud fractions over a series of events. In this case, if the subdomain precipitation fraction is greater over the nonforested areas, a binomial count of one is assigned; a zero is assigned for the alternative, as shown:

$$
e = \begin{cases} 
1 & \text{if } P_{F}^{\text{nf}} - P_{F}^{\text{for}} > 0, \\
0 & \text{if } P_{F}^{\text{nf}} - P_{F}^{\text{for}} < 0.
\end{cases}
$$

The event-based binary exceedance $e_{i}$ is simply the mode of the exceedance across each of the subdomains for that event. We then define an exceedance count (EC) as the sum of the event exceedances over $M$ total events, 

$$
EC = \sum_{i=1}^{M} e_{i}.
$$

This is analogous to a coin flip. If there is no tendency for either of the land covers to have higher precipitation fractions, then the expectancy of this counting statistic is half of the total number of swaths (events, coin flips, among others). We can then construct a posterior binomial counting distribution about the observed exceedance count ratio (Wang et al. 2009). If the expected random exceedance count ratio $=0.5$ lies outside the confidence interval of the posterior distribution, then it can be said with significance that the observed precipitation fractions differ. A leftward shift from center indicates precipitation fractions are generally greater over forested landscapes. The opposite is true for a rightward shift.

The natural first question is to identify if precipitation fractions tend to be greater over intact forests or nonforests. The satellite overpasses are grouped by month and the exceedance counts are calculated (see Fig. 3). Notice several features in the plots. The central vertical line is the expectancy. The dashed vertical lines are the two-sided 90% confidence boundaries on the posterior binomial distribution centered on the observed exceedance count ratio. Although there is some slight indication of precipitation favoring deforested areas in some months, the confidence range of the posterior distribution encompasses the expectancy; therefore, the precipitation fractions show no significant deviation from an unbiased binomial. Statistically, both forms of land cover have similar precipitation fractions.

d. Experiment 2

Our next objective was to identify if there were differences in precipitation fractions observed in the deep interior regions of nonforested landscapes, as compared to the remainder (forested lands and also those nonforested lands bordering forested lands). This was done by creating a modified land-cover map. Starting with the original binary forest coverage map, the nonforested pixels bordering the forest were incrementally changed into forested pixels. Each increment encroached on the nonforests by 4 km. After encroaching 5 times (20 km), there were too few nonforested pixels in the modified map to enable robust samples. The same binomial counting exercise carried out in experiment 1 was then applied to the modified maps for each succession of encroachment. An example of the binary forest map encroached 1 time is provided in Fig. 2c. It is apparent in results of this image that much of the deforestation in this region is fractionated, at least at averaging scales of 4 km.

The exceedance ratio is calculated in the same fashion as in the first experiment, using the modified land covers. Figure 4 presents the binomial counting statistics after three encroachments (12 km). These plots also show the posterior binomial counting distribution from the original map (dashed curved line) for reference against the distributions based on the encroached land cover (solid line). In each case, the distribution shifted to the left. The leftward shift indicates that the modified forest landscapes typically have higher precipitation fractions. The observed exceedance count ratios in the months of June–October are significantly different than the expectancy (0.5). In July, the 90% confidence interval still encompasses the expectancy.

The spectrum of observed exceedance count ratios for each level of encroachment is shown in Fig. 5. Results are broken down by month (line markers) and with the mean across months (solid dark line). For reference, the $y$ intercept reflects an exceedance ratio for an unmodified forest cover (forest versus nonforest; Fig. 3); the exceedance count ratios shown in Fig. 4 are reflected at $x = 12$. As the effective interior nonforest region is encroached upon, the mean observed exceedance count ratio decreases from the expected outcome (0.5) to roughly 0.30 at an encroachment of 16 km. This
indicates that relative precipitation fraction progressively decreases toward the center of the domain’s large deforestation structure.

e. Experiment 3

Given the first two exercises, it is still not clear how precipitation fraction changes on the forest edge. Results so far seem to indicate that the differentiation of precipitation fractions between forest and nonforest regions is accentuated as the transition areas between the two are reassigned to the forested region. In doing so, we realize that the interior deforested areas are drier. However, because the first experiment indicates that precipitation is balanced between the forested and nonforested land covers as a whole, there must be a compensatory effect. To elucidate this result, we simultaneously compare the precipitation fractions above (i) interior forests, (ii) forest edges (transition bands), and (iii) interior nonforests. A transition band is defined here as those locations where forested pixels adjoin nonforested pixels. Both forested and nonforested pixels on each side of the transition are considered part of the band and are therefore at least 8 km wide on the whole. Correspondingly, a 16-km transition band extends one more pixel on each side. An example of an 8-km transition band is shown in Fig. 2d.

A three-way comparison cannot be done with the binary exceedance statistic. Instead, for each event, the precipitation fractions above each of the three land covers are compared and the superlative is logged. The superlative counts using both 8- and 16-km transition bands are shown in Fig. 6. With the exception of July, precipitation fractions are highest above the 8-km transition band more times than compared to interior forests and interior nonforests. The precipitation fractions above the broader 16-km transition were much more likely to be higher than the interior forested and interior nonforested zones. In summary, precipitation fractions were greatest above the transition region the most number of times, as compared to the other two regions. In the same vein, interior forest regions typically had greater precipitation fractions than interior nonforest regions.

3. Discussion and conclusions

Consider a transect originating in the forest interior, crossing the transition region, and ending in the non-forest interior. Interpretations of the results from the
three exercises on this theoretical transect are provided in Fig. 7. Experiment 1 suggested that precipitation fractions were somewhat balanced, perhaps marginally biased toward the nonforested side of the transect (see upper left panel). Experiment 2 suggested that precipitation fractions were less over the interior nonforest regions, compared with all other landscapes (see upper right panel). Experiment 3 showed that the transition bands had the greatest precipitation fractions (see lower left panel), while the interior forested regions had greater precipitation fractions than the interior nonforests. The three experiments fit together as pieces of a puzzle, rendering a cohesive picture along this transect. Because precipitation fractions on each side of the forest edge balance, and because deep interior nonforests have low precipitation fraction, there must be a compensatory effect over the edge. The compensation is that precipitation fraction above the nonforest side of the forest edge must be high.

Nonforests (grasslands, savannas, croplands, among others) in the southwestern Amazon are typically associated with higher surface temperatures, rapidly developing atmospheric boundary layers, and subsequently lower convective inhibition (Wang et al. 2009). At certain heterogeneity scales, this convective focus can create convergence zones and solenoidal circulations (Atkinson 1981; Pielke 1984, 2001; Rennó and Ingersoll 1996).
Situated on the forest edges, there is corresponding subsidence over the forest canopies that serves as a source of moisture to the upwelling air on the nonforest edge. This moist static energy contributes to the convective available potential energy needed for deep convective precipitating clouds. The subsidence over the forested side of the transition band would inhibit precipitation at that location. The resulting precipitation trend along the transect from forest to nonforest features high precipitation fraction above the interior forest, lessened precipitation above the forest side of the transition, highest precipitation fractions over the nonforest side of the transition, and low precipitation fraction over the interior nonforest region. This synthesis is shown in the lower right panel of Fig. 7.

Mean areal precipitation fraction is synonymous with mean precipitation frequency at point locations within the statistically representative space and time. Shifting terminology, we can state that precipitation frequency shows a decline toward the interior of nonforests. In

**Fig. 7.** Diagram of a transect from the forest interior to the nonforest interior. A representation of (left) an intact forest stand and (right) nonforests. Raindrop size qualitatively represents the relative differences in precipitation fraction across the different land covers of interest.
cases where nonforests are the result of exogenous disturbance, there is potential for a drought-based feedback cycle of desertification. Our evidence also poses some questions as to ecosystem response on the forest edge. Two observations are possible. The subsidence-based decrease in precipitation frequency on the intact side poses a drying threat to forest ecosystem stability. Alternatively, the enhanced precipitation frequency on the nonforest side could conceivably stimulate forest regrowth by minimizing drought stress. These competing theories are dependent on many factors, including the holistic community responses to precipitation changes regarding growth rates, mortality rates, coupled effects with soil and nutrient composition, and endogenous disturbance. There is evidence, though, that the Amazon rain forest shows a basinwide general sensitivity to drought stress (Phillips et al. 2009).

While it is difficult to quantify the potential canopy biophysical effects of changes in precipitation frequency, the effects of forcibly excluding precipitation throughfall have been observed in the central-eastern Amazon. When precipitation throughfall was forcibly reduced by 50% of depth over the first half of the year, significant changes were seen in canopy openness, leaf area index, and aboveground biomass production (Nepstad et al. 2002). The results presented in this study cannot provide similar seasonal precipitation accumulations because of the inconsistent orbital nature of the satellite measurement system; however, they do indicate that existing large-scale Amazonian deforestation structures can modify precipitation fractions and frequency on the orders of ten(s) of a percent.

The generalized tendencies discussed here are applicable to afternoon dry-season events in southwestern Amazonia. However, there is no reason these results could not extrapolate to other regions of the world. The key for this to occur depends on the fact that precipitation is convectively driven and that there exists mesoscale land-cover heterogeneity (several to tens of kilometers) with associated differential heating rates. It is also clear that certain ambient conditions constrain the likelihood of stimulating land-surface-influenced precipitation. It was shown analytically through a stochastic analysis that the mesoscale circulations driven by heterogeneous land surface heating rates are strongest when ambient winds are at their lowest (Wang et al. 1996). Wet-season precipitation in Rondônia features frontal-based precipitation at their lowest (Wang et al. 1996). Wet-season surface heating rates are strongest when ambient winds drive the mesoscale circulations driven by heterogeneous land-cover phenomena are not insignificant among the whole.

In summary we found that the tendency of areal precipitation fractions in the southwestern Amazon is to (i) decrease over nonforested areas far removed from the forest edge and to (ii) increase over the forest edge, but that increase is focused over the nonforested side of the divide.

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