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Key Points:
- An exponential growth of precipitation occurs along wind streamlines passing over the Amazon forests and is reversed after the forests
- This pattern is consistent with multiple mechanisms through which forests can influence atmospheric moisture and precipitation production
- A critical implication is that forest loss may cause a shifting between patterns of exponential increase and decrease of precipitation

Supporting Information:
- Figure S1

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Forest-Induced Exponential Growth of Precipitation Along Climatological Wind Streamlines Over the Amazon

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Abstract The Amazon forests and climatological precipitation patterns in South America are interrelated. A fundamental question is how these patterns depend on the presence of forests. Here we investigate this relationship by studying how precipitation varies with distance from the ocean along wind streamlines linking the Atlantic Ocean to northwestern and southern South America through the Amazon forests. Through a robust observation-based analysis, we found that precipitation exponentially increases with distance from the ocean along wind streamlines flowing over forests, while it exponentially decreases downwind of the forests. These patterns are consistent with multiple mechanisms through which forests influence the transport of atmospheric moisture and precipitation production over the continent. We propose a conceptual explanation of this forest influence based on the atmospheric water balance. Our results imply that a major consequence of the degradation or loss of forests may be a disruption of these mechanisms, with widespread impacts on continental precipitation.

Plain Language Summary How and why precipitation varies within continents is fundamental for many natural and social phenomena and related decision making. Here we address these questions in South America, specifically studying the relationship between precipitation and the presence of the Amazon forests. We found that precipitation exponentially increases with distance following the direction of winds passing over the Amazon forests and transporting moisture from the Atlantic ocean. In contrast, precipitation decreases exponentially as these winds flow away from forests. We propose a conceptual explanation of this forests' influence, through multiple mechanisms, based on the atmospheric water balance. This implies that a major consequence of forest degradation or loss may be a disruption of these mechanisms, with widespread impacts on continental precipitation.

1. Introduction

The climatological spatial distribution of continental precipitation is determinant for many natural and social phenomena (Betts et al., 2008). Fundamental questions are whether and how the extensive forests of the world (including the Amazon) affect these precipitation patterns. Uncertainties and concerns about this issue are highlighted by these ecosystems being highly threatened worldwide (Hansen et al., 2013; Malhi et al., 2014; Potapov et al., 2017) and a growing body of evidence indicating how terrestrial precipitation regimes are related to the presence of forests, especially in the Amazon and neighboring continental areas (Boers et al., 2017; Davidson et al., 2012; Hirota et al., 2011; Khanna et al., 2017; Lawrence & Vandecar, 2015; Makarieva et al., 2013; Spracklen & Garcia-Carreras, 2015; Staal et al., 2018; Stickler et al., 2013; Weng et al., 2018; Zemp et al., 2017).

The maintenance of continental precipitation patterns depends on the transport of atmospheric water inland from the oceans (Arraut et al., 2012; Gimeno et al., 2010, 2012; Marengo et al., 2004; Staal et al., 2018; van der Ent et al., 2010; van der Ent & Savenije, 2013). This transport is critical for the terrestrial hydrological cycle because in the long term, all continental water comes from the ocean through the atmosphere. This is a consequence of the atmospheric fluxes of water being the only ones that flow upstream in river networks, whereas terrestrial fluxes are directed into the ocean by gravitational forces (i.e., water flows in the downstream direction in river networks due to its weight).

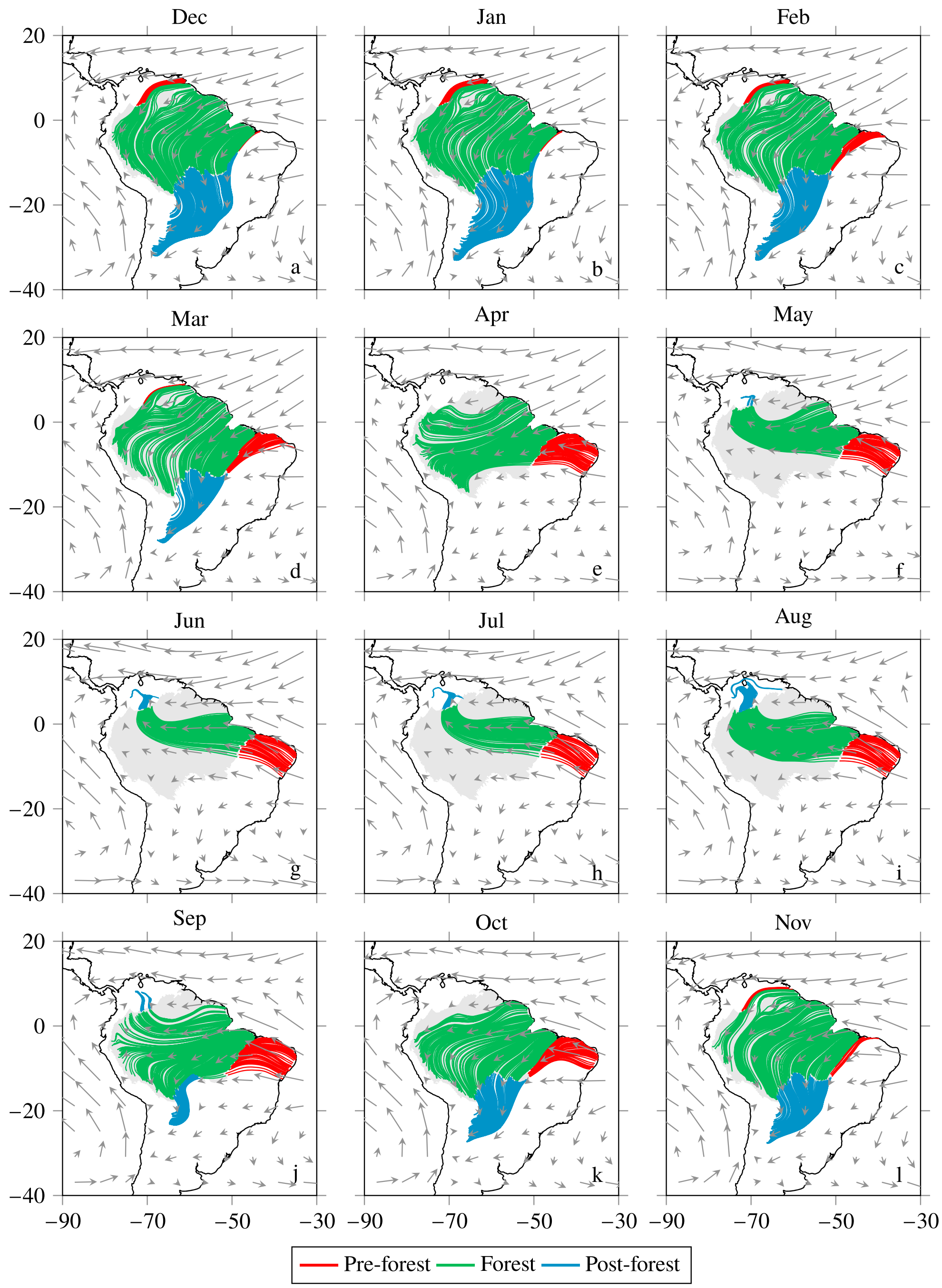

Figure 1. Transects for studying the P (precipitation) versus X (distance along a streamline) relationship. Each transect is defined along climatological monthly wind streamlines at 925 hPa using 1979–2016 European Centre for Medium-Range Weather Forecasts reanalysis-Interim data. Colors identify whether the streamline is directed toward the forest (red), pass over the forest (green), or flows away from the forest (blue). Figure S1 shows these same transects but for wind streamlines at 850 hPa.

Although the potential of the atmosphere to store water is relatively small, its capacity to transport water within or outside a continent is enormous (Trenberth et al., 2007).

In South America, the atmospheric moisture flowing over the Amazon forests exerts a strong influence on the continental distribution of precipitation (e.g., through the South American low-level jet; Vera et al., 2006). Depending on its seasonal variability, the moisture flows toward either northwestern or southern South America (Arraut et al., 2012; Berbery & Barros, 2002; Drumond et al., 2014; Marengo et al., 2004;

Martinez & Dominguez, 2014; Nieto et al., 2008). Thus, the Amazon basin connects the Atlantic ocean with other major basins and, therefore, it is an important source of moisture for precipitation in, for example, the La Plata (Martinez & Dominguez, 2014; Weng et al., 2018) and Orinoco (Drumond et al., 2014; Nieto et al., 2008; Weng et al., 2018) basins.

Here we use an observation-based analysis and model results to investigate whether and how the climatological patterns of continental precipitation distribution over South America are related to the presence of the Amazon forests. Further, we use the climatological atmospheric water balance to explain the potential mechanisms behind the observed forest-precipitation relationship.

2. Data and Methods

Our guiding questions are how climatological precipitation varies with distance from the ocean across South America and whether and how this variation is related to the presence of the Amazon forests. We investigate these questions through both an observation-based analysis (section 2.1) and modeling (section 2.2).

2.1. Observation-Based Analysis

We test whether the coast-to-interior distribution of climatological monthly precipitation (P) is represented by an exponential model of the form (suggested by Makarieva & Gorshkov, 2007)

$$\log(P) = \beta X + \alpha, \tag{1}$$

where α and β (slope) are empirical parameters and X is a measure of distance from the ocean along a given transect. Our analysis is constructed using observationally based streamlines and therefore does not address the *biotic pump* hypothesis, which concerns whether and how forests determine the wind distribution (Makarieva et al., 2013; Meesters et al., 2009). To avoid potential biases in the definition of these transects, we perform a statistical analysis for a large set of transects (Figures 1 and S1). Each of these transects has an origin point in the Atlantic coast of South America and is defined along climatological monthly wind streamlines (at 925 and 850 hPa) that pass over the Amazon forests. The analysis is performed using climatological monthly precipitation estimates from the Tropical Rainfall Measuring Mission (TRMM) 3B43 product (1998–2016 period; 0.25° × 0.25° resolution; Huffman et al., 2007, 2010) and wind fields from the European Centre for Medium-Range Weather Forecasts reanalysis (ERA)-Interim (1979–2016 period; 0.5° × 0.5° resolution; Dee et al., 2011). The studied wind streamlines (Figures 1 and S1) largely coincide with seasonal patterns of moisture transport over South America that are important for the continental distribution of precipitation (Berbery & Barros, 2002; Gimeno et al., 2012; Vera et al., 2006).

To test for the relationship between precipitation and forests, we divide each wind streamline in segments of at least 500-km length depending on land cover. Segments are classified as (1) *preforest* if there is no forest cover but the streamline is directed toward the forests, (2) *forest* if the land cover beneath the streamline is forest, or (3) *postforest* if there is no forest and the flow is moving away from the forest (Figure 1 and Figure S1 in the supporting information). To do this, we use a mask based on the Amazon Biome boundaries from the World Wide Fund for Nature (WWF)'s Global Observation and Biodiversity Information Portal (Olson & Dinerstein, 2002; Shapiro & Nijsten, 2015). We use this mask as an approximate description because land cover is not static; however, our approach is based on robust patterns (considering many segments of at least 500-km length) and, therefore, our results (statistical fittings over very long distances) are not highly sensitive to relatively small (compared to the size of segments) variations in the forest mask. For each type of segment, we test whether the exponential model equation (1) fits and how its parameters (especially β) are related to the presence or absence of forests.

2.2. Dynamic Recycling Model

Since precipitation recycling is a fundamental mechanism relating precipitation and the Amazon forests (Bosilovich & Chern, 2006; Burde et al., 2006; Eltahir & Bras, 1994; Satyamurty et al., 2012; Silva Dias et al., 2009), we use the Dynamic Recycling Model (DRM) to test for the role of recycling on the observed patterns. The DRM is a two-dimensional semi-Lagrangian model for estimating exchanges of atmospheric moisture between different regions (Dominguez et al., 2006; Martinez & Dominguez, 2014). Atmospheric moisture can reach a given target region after being evaporated from the surface from a given source region. Here we are especially interested in the atmospheric moisture contributed by source areas within the forest or the ocean to precipitable water over target areas representing preforest, forest, and postforest regions. The

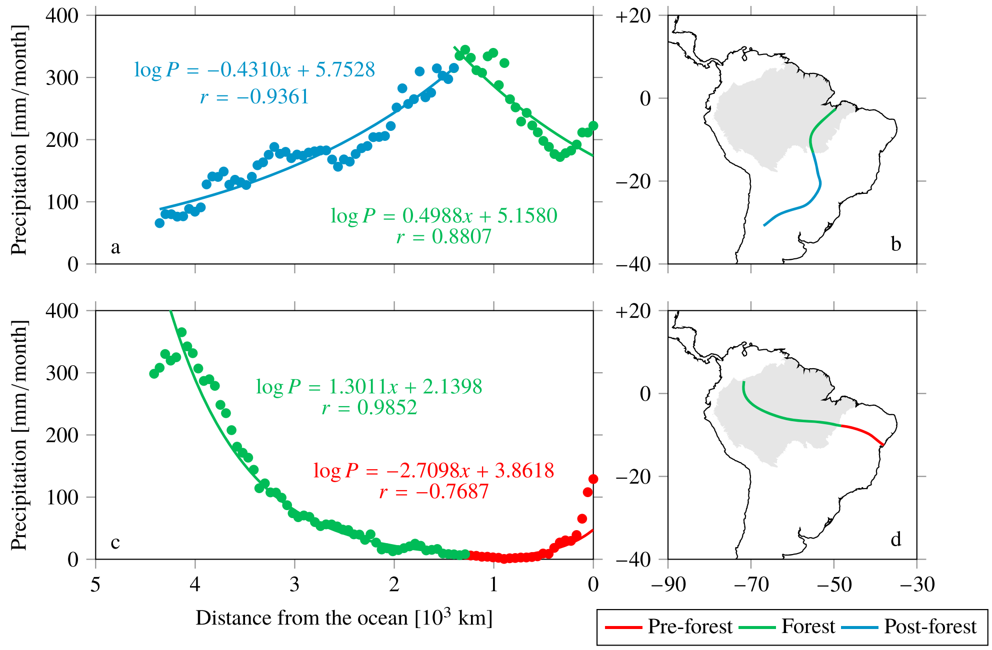

Figure 2. Climatological P versus X relationships along typical streamlines at 925 hPa during December–February (top) and June–August (bottom). P grows exponentially over forest (green) but not downwind (postforest, blue) or upwind (preforest, red) of the forest. Downwind of the forest, P decreases exponentially (blue). Figure S2 shows these same results but for wind streamlines at 850 hPa.

exchange of moisture estimated by the DRM is based on the equation of conservation of atmospheric moisture integrated in the vertical direction, assuming that the atmospheric column is well mixed. Inputs for the DRM include evaporation, precipitable water, and the vertical integral of horizontal moisture flux vector.

For the DRM experiments we focus on the seasons December–February (DJF) and June–August (JJA) because of the moisture transport patterns that are characteristic of each of these seasons (Figures 1 and S1): (i) northeasterly winds with preforest-to-forest transition during DJF and (ii) southeasterly winds with preforest-to-forest transition during JJA. We use daily and 6-hourly fields over a 0.75° grid; thus, the estimated transport includes the effect of variations at the synoptic scale.

As previous studies have pointed out, reanalyses have important biases in precipitation and evapotranspiration. In this paper, we use precipitable water instead of precipitation, in order to avoid the associated biases. However, we use evapotranspiration as provided by ERA-Interim directly. Despite their biases, all inputs for the DRM are obtained from the same reanalysis, in order to provide the model with fields that approximately close the water budget. The DRM is based on the conservation of moisture, which implies that we have to use a data set that is close to being internally consistent, as in the case of the reanalysis. The impacts of data assimilation on some moisture variables but not others mean that moisture is not strictly conserved in any reanalysis; however, ERA-Interim is one of the better data sets in this regard (Mueller et al., 2011; Pan et al., 2012; Trenberth et al., 2011). On the other hand, there is no best data set for large-scale land evapotranspiration, as found in different studies, for example, more recently Sörensson and Ruscica (2018) for South America. For a more detailed description of the model, we refer the reader to Dominguez et al. (2006) and Martinez and Dominguez (2014).

3. Results: Coast-to-Interior Variations of Precipitation

We found a clear-cut difference between P versus X over forest (pattern 1) and P versus X over nonforest covers (pattern 2; Figures 2 and S2). P exponentially increases with X over forest segments but not over postforest or preforest segments. Particularly important is that P exponentially decreases along the postforest region. These patterns are representative of the whole set of studied streamlines. Statistics (Figures 3–5 and S3–S5) indicate that the exponential model fits well (as evidenced by high correlation magnitudes and $p < 0.05$) over forest and postforest segments. A clear pattern of exponential growth over forest was

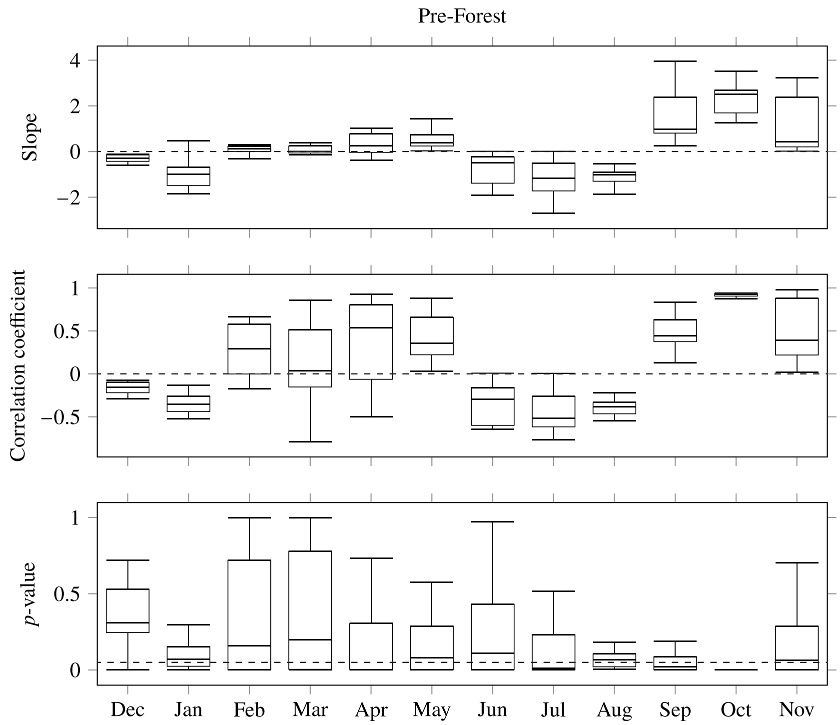

Figure 3. Statistics for the exponential fittings (equation (1)) corresponding to preforest segments for all the wind streamlines at 925 hPa. The slope (β) and correlation coefficients alternate between positive and negative values around the year. The p values and correlation coefficients show that the exponential model does not fit well in preforest segments. Figure S3 shows these same results but for wind streamlines at 850 hPa.

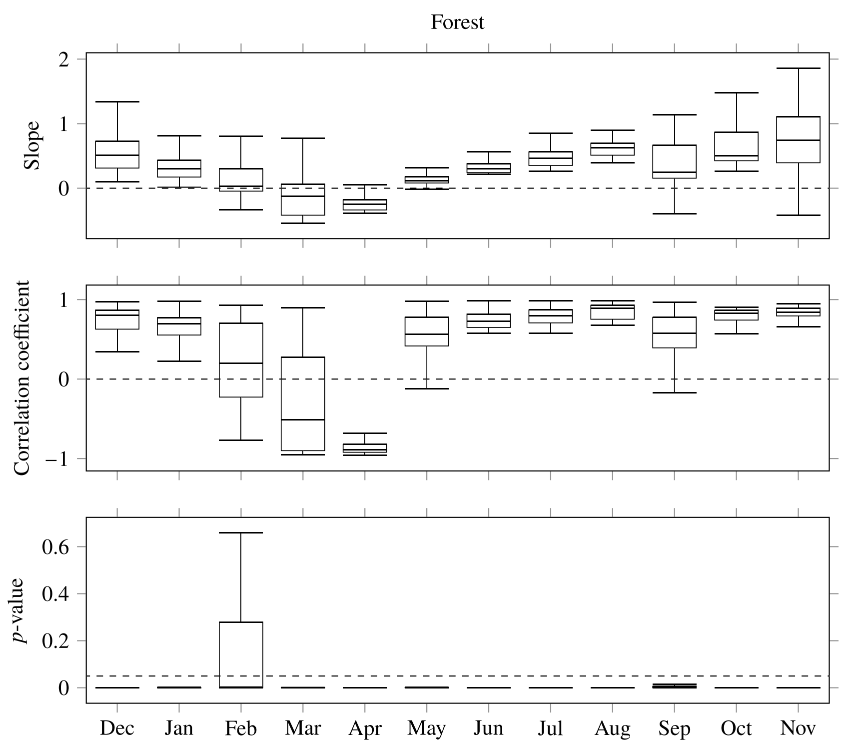

Figure 4. Statistics for the exponential fittings (equation (1)) corresponding to forest segments for all the wind streamlines at 925 hPa. The slope (β) and correlation coefficient are positive over most forest segments, and the p values are lower than 0.05 for all but 1 month. Figure S4 shows these same results but for wind streamlines at 850 hPa.

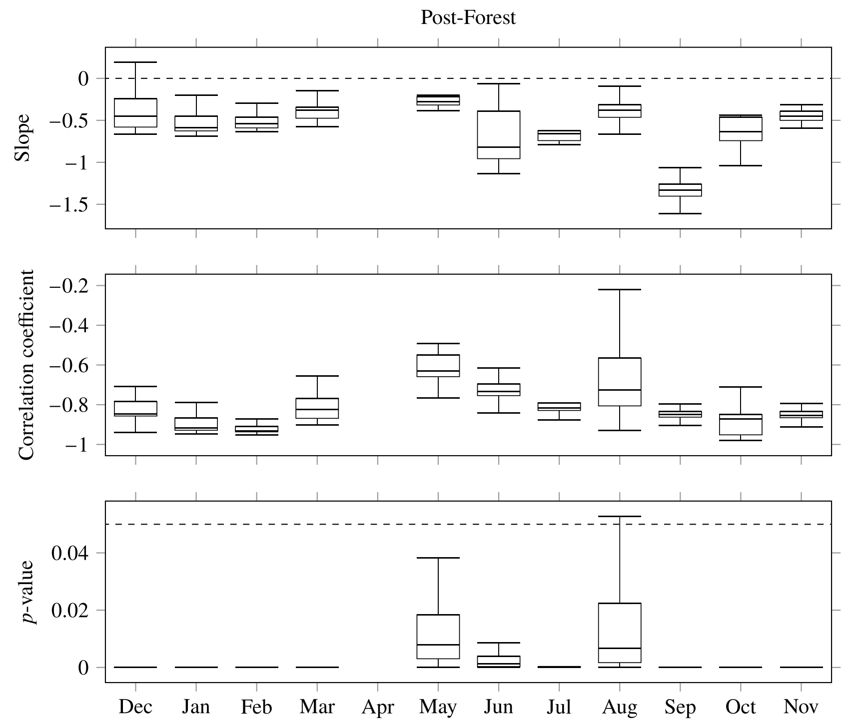

Figure 5. Statistics for the exponential fittings (equation (1)) corresponding to postforest segments for all the wind streamlines at 925 hPa. The slope (β) and correlation coefficient are clearly negative over postforest segments. The p values are all below 0.05. Figure S5 shows these same results but for wind streamlines at 850 hPa.

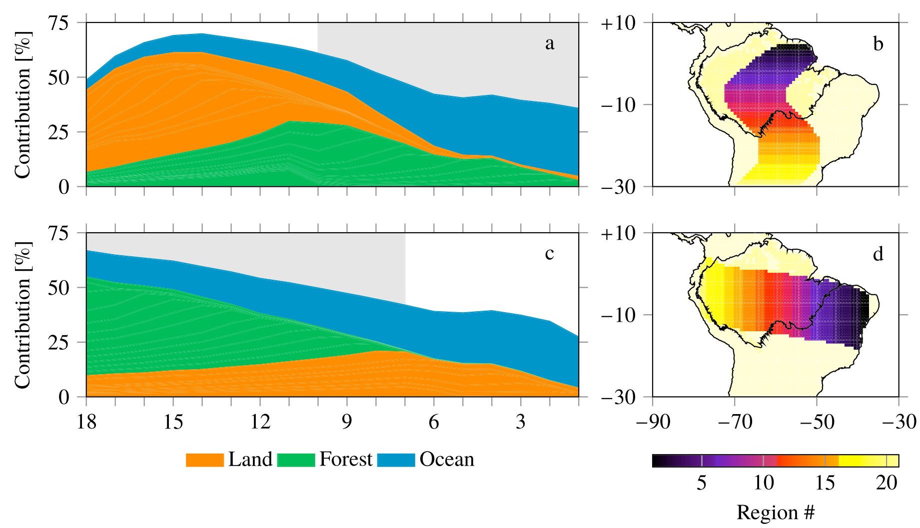

Figure 6. Dynamic Recycling Model results showing the relative contribution of ocean (blue), Amazon forests (green), or other land covers (orange) to precipitable water in consecutive boxes (right) defined along typical low-level wind streamlines during December–February (top) and June–August (bottom). Numbers in the x axis on the left identify boxes shown on the right. Gray areas in the left panels identify boxes where the land cover is forest. The Dynamic Recycling Model only accounts for atmospheric moisture from regions within its domain, but moisture from outside this domain can reach our study area. Therefore, the aggregated contribution of land, forest, and ocean do not add to 100% because some sources are outside the simulation domain shown on the right.

found for 9 out of 12 months (all except February–April), while a clear pattern of exponential decrease over postforest was found for 11 months (there are no postforest segments in April). Patterns of exponential decrease of P over forests during February–April are not related to low precipitation values in the tropical Andes. Instead, high precipitation rates are maintained along the whole forest segments, with a local maximum occurring near the coast (Figure S6). In the preforest segments, the exponential model's performance is weaker (as evidenced by correlation and p values) what shows that P does not exponentially decrease or increase with X.

Although latitudinal variations can affect precipitation, they cannot explain important features of the observed patterns. Notably, during DJF, the change of P with X exhibits an opposite behavior between forest (exponential increase) and postforest (exponential decrease) segments, despite an increase of latitude along both type of segments. Further, during JJA, latitudinal variations are much less pronounced (or even absent), while P exponentially grows with X over the forest but not over the preforest region.

Model results show that the contribution of Amazon forests to precipitable water progressively increases with X as the streamlines pass over the forest cover, progressively decreases along the postforest region, and is absent in the preforest region (Figure 6). In contrast to the behavior over forests, ocean contribution to precipitation progressively decreases with distance to the Atlantic coast. For trajectories over nonforest areas, there is also an increase in the moisture contributed by nonforest cover but not as pronounced as over the Amazon forests.

4. Discussion

The long-term water balance equation for an atmospheric control volume establishes a relation between climatological values of precipitation (P), evaporation (E), and moisture convergence (i.e., negative divergence $\nabla \cdot \vec{Q}$):

$$P = E - \nabla \cdot \vec{Q}. \tag{2}$$

Temporal variations of the atmospheric water storage tend to 0 in the long term. Hence, mass continuity implies that P is limited by the total atmospheric moisture supply given by the sum $E - \nabla \cdot \vec{Q}$. Exponential increase of P with X (i.e., $\mathrm{d}P/\mathrm{d}X \gg 0$) can occur only if a corresponding increase of $E - \nabla \cdot \vec{Q}$ occurs (i.e., $\mathrm{d}(E - \nabla \cdot \vec{Q})/\mathrm{d}X \gg 0$). Our empirical findings (Figures 1 –4) indicate that

$$\frac{\mathrm{d}P}{\mathrm{d}X}\begin{cases} \gg 0, \text{ if } & \frac{\mathrm{d}}{\mathrm{d}X}(E - \nabla \cdot \vec{Q}) \gg 0 \quad \text{(found over forests)} \\ = 0, \text{ if } & \frac{\mathrm{d}}{\mathrm{d}X}(E - \nabla \cdot \vec{Q}) = 0 \quad \text{(possible critical threshold)} \\ \ll 0, \text{ if } & \frac{\mathrm{d}}{\mathrm{d}X}(E - \nabla \cdot \vec{Q}) \ll 0 \quad \text{(found downwind of the forests).} \end{cases} \tag{3}$$

Increasing the atmospheric moisture supply with distance ($\mathrm{d}(E - \nabla \cdot \vec{Q})/\mathrm{d}X \gg 0$) can be a consequence of increasing both E and $-\nabla \cdot \vec{Q}$ (i.e., $\mathrm{d}E/\mathrm{d}X > 0$ and $\mathrm{d}(-\nabla \cdot \vec{Q})/\mathrm{d}X > 0$). However, depending on the magnitudes of $\mathrm{d}E/\mathrm{d}X$ and $\mathrm{d}(-\nabla \cdot \vec{Q})/\mathrm{d}X$, an increase of the atmospheric moisture supply along the streamline may result also from either increasing E while decreasing $-\nabla \cdot \vec{Q}$ or decreasing E while increasing $-\nabla \cdot \vec{Q}$. This has two important implications. First, the observed exponential growth of P does not require either $P < E$ or $P < -\nabla \cdot \vec{Q}$ along the streamline. Second, large E values do not imply the occurrence of large P values over the same region due to the possibility of large moisture divergence.

As a proof of concept, we examined two examples of these relations using data from ERA-Interim (Figures 7 and S7–S10). First, during DJF (Figure 7, left column), larger continental E occurs to the south of the Amazon (Figures S9a–S9c) in regions where P decreases with distance to the forests (Figures S8a–S8c) and $E - P$ is not always negative (Figures S7a–S7c). This is consistent with reduced $-\nabla \cdot \vec{Q}$ over the same regions (Figures S10a–S10c). In contrast, during the same season, large continental P occurs over the southern Amazon (Figure S8a–S8c) despite E being lower than P (Figures S7a–S7c). This is possible because of increased $-\nabla \cdot \vec{Q}$ over the same region (Figures S10a–S10c). Second, during JJA (Figure 7, right column), the growth of P across the continent (Figures S8g–S8i) coincides with $P < E$ over the southern Amazon (Figures S7g–S7i) and increased $-\nabla \cdot \vec{Q}$ over the northwestern Amazon (Figures S10g–S10i), which is consistent with an increased supply of atmospheric moisture over the forests.

Correlation does not imply causation. However, there are multiple mechanisms through which forests can influence precipitation and, hence, establish a nonspurious physically based relationship between the

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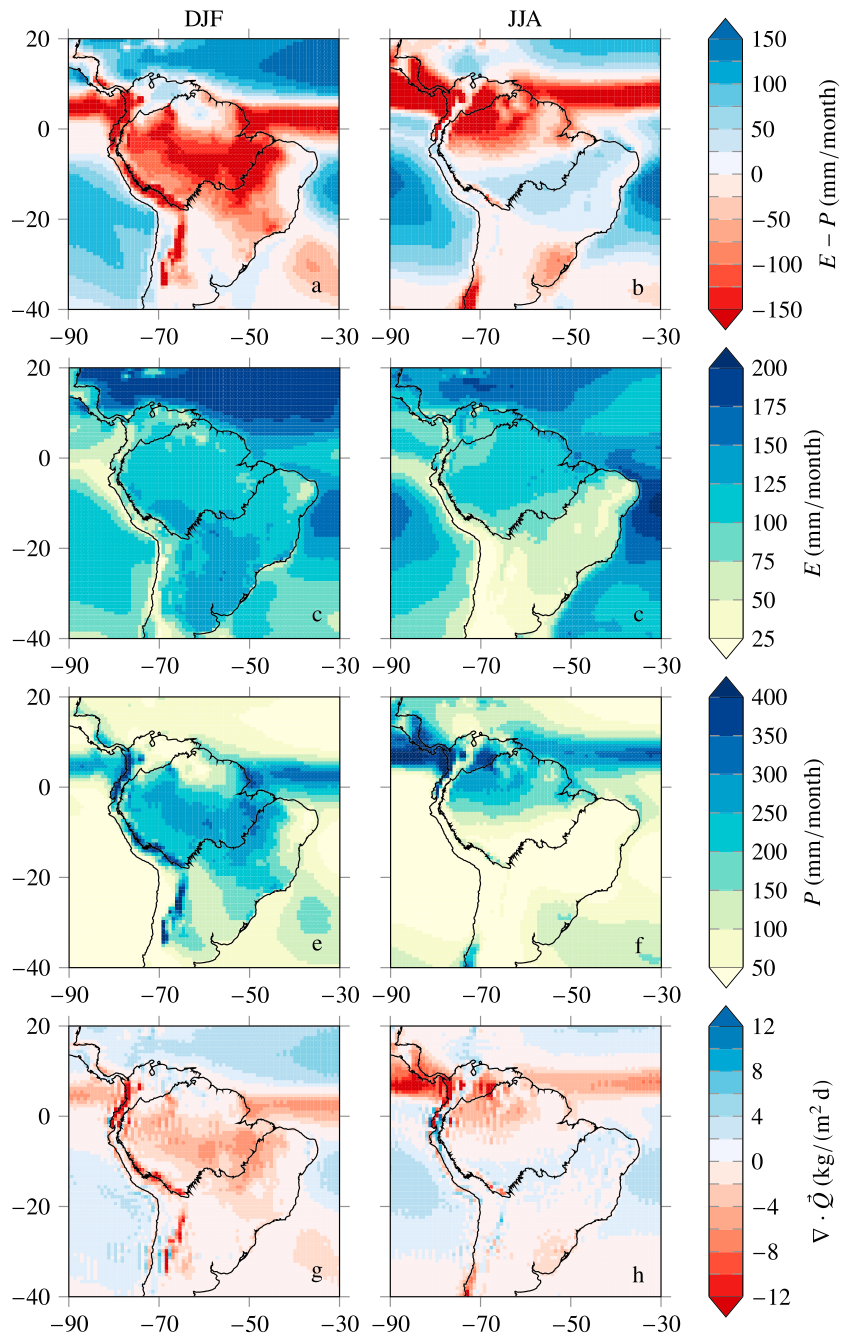

Figure 7. December–February (left column) and June–August (right column) trimester averages (1979–2017) of European Centre for Medium-Range Weather Forecasts reanalysis-Interim's difference between evaporation and precipitation (top row, $E - P$), evaporation (second row, E), precipitation (third row, P), and vertical integral of divergence of moisture flux (bottom row, $\nabla \cdot \vec{Q}$). Figures S7–S10 show the monthly averages for these same variables.

presence or absence of forests and the spatial variations of continental precipitation. There is increasing scientific evidence about forest-induced mechanisms, which affect land-atmosphere exchanges of water and precipitation production processes including accumulation and redistribution of soil moisture by root systems (Nadezhdina et al., 2010), long-term regulation of extreme river flows (Salazar et al., 2018), strong capacity for stomatal regulation due to the large cumulative surface area of leaves (Berry et al., 2010), triggering of shallow convection (Wright et al., 2017), production of biogenic cloud condensation nuclei (Poschl et al., 2010), and the surface drag that is caused by the large height of trees affecting the flow of air over the forests (Khanna et al., 2017). Further, transpiration from the Amazon forests has been identified

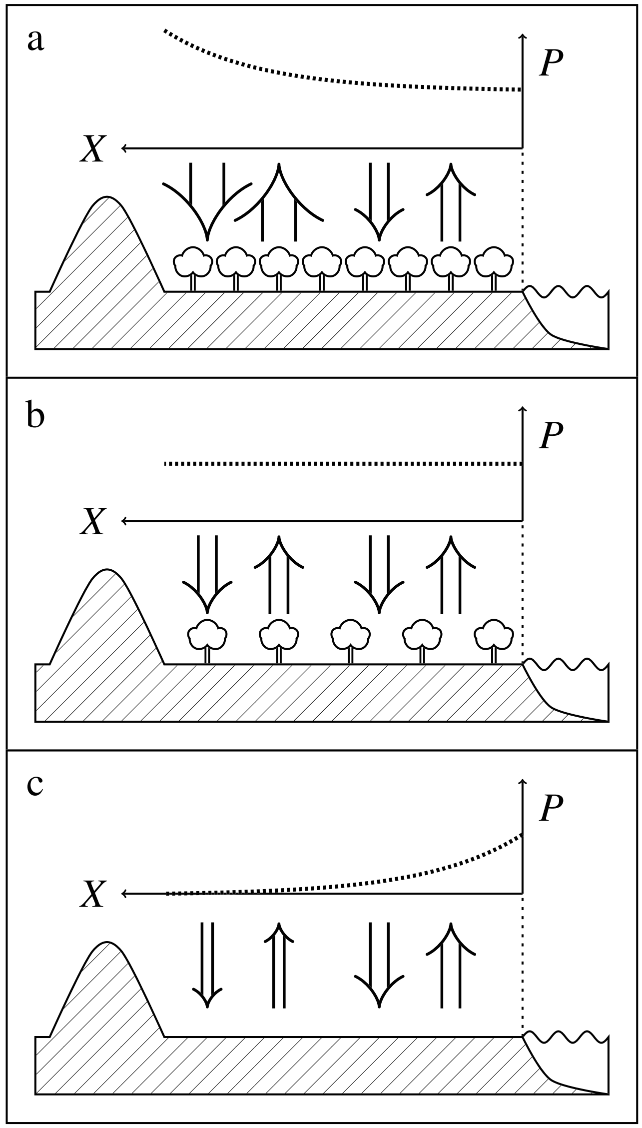

Figure 8. Schematic illustration of possible patterns of P versus X: (a) Exponential growth of P was found over forest cover and implies that the atmospheric water supply grows in the downwind direction. (b) P could be invariant with X (constant) if the atmospheric moisture supply remains constant as well. (c) Exponential decline of P was found over nonforest cover (postforest) and implies that the atmospheric water supply decreases in the downwind direction. In all cases, the downward arrow represents P, while the upward arrow represents the atmospheric moisture supply, that is, $E - \nabla \cdot \vec{Q}$.

as a large source for terrestrial precipitation (Gimeno et al., 2012; Schlesinger & Jasechko, 2014) through intense moisture recycling (Eltahir & Bras, 1994), which can lead to cascading effects affecting the distribution of continental precipitation (Staal et al., 2018; Weng et al., 2018; Zemp et al., 2017). Collectively, these mechanisms imply that forests have a strong potential to influence precipitation, consistent with converging research results that extensive forest loss can change precipitation patterns over extensive continental regions (including the Amazon; Lawrence & Vandecar, 2015; Mahmood et al., 2013; Spracklen & Garcia-Carreras, 2015).

Hence, our findings are consistent with the premise that the observed patterns of exponential increase or decrease of precipitation along streamlines in this region are at least partially dependent on the presence or absence of forests and may therefore reflect different alternative stable states of the climate-vegetation system (Figure 8). Although we did not find the state in which $dP/dX = 0$ (Figure 8b), it is theoretically possible and must exist between the two observed states (Figures 8a and 8c). Therefore, our results suggest that this intermediate state might be a critical threshold: the degradation or loss of forests could disrupt forest-induced mechanisms, thus inducing a shift between patterns of exponential increase (Figures 2a and 8a) and decrease (Figures 2c and 8c) along streamlines passing over the present-day forests. This would have tremendous implications for the hydrological cycle and related phenomena in the Amazon basin and other basins located downwind of the Amazon forests.

5. Conclusion

An observation-based analysis has revealed an exponential growth of precipitation that occurs along low-level wind streamlines passing over the Amazon forests. This pattern is reversed downwind of the forests, implying a rapid reduction of precipitation with distance to the forests. Our findings support previous hypotheses linking the increase or decrease of precipitation to the presence or absence of forests through mechanisms that invoke complex land-atmosphere interactions. Our streamline analyses and DRM simulations provide quantifiable evidence of how these mechanisms affect the atmospheric moisture supply and precipitation. Our results imply that the degradation or loss of forests may disrupt these mechanisms with strong effects on precipitation within and beyond the Amazon basin.

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