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Key Points:

- Daytime rainfall is suppressed over the Amazon River compared with the surrounding forest
- The reduction of daytime rainfall is inversely correlated with the Laplacian of surface temperature
- Daytime rain over the river needs moisture convergence above the surface, while above the forest, most moisture converges near the surface

Supporting Information:

Supporting Information may be found in the online version of this article.

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Suppressed Daytime Convection Over the Amazon River

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Abstract We investigated the interaction between surface conditions and precipitating convection by comparing the Amazon River against the surrounding forest. Despite similar synoptic conditions within a few tens of kilometers, the river surface is substantially cooler than the surrounding forest during the day and warmer at night. We analyzed 20 years of high-resolution satellite precipitation data and confirmed previous findings of daytime rainfall reduction over the river for the whole Amazon Basin. The percentage reduction is strongest during the dry-to-wet transition season. In addition, the percentage reduction of individual tributary is significantly correlated with the Laplacian of surface temperature, which causes thermally driven surface divergence and suppresses local convection. Additionally, nighttime rainfall is enhanced over tributaries near the Atlantic coast during the wet season. A regional climate model then simulates the local rainfall anomalies associated with the river. Above the river, moisture diverges near the surface and converges above the surface before the daytime rainfall, partially driven by the horizontal gradient of humidity. Unlike the river, moisture convergence within the boundary layer is more critical for the rainfall above the forest region. Our studies suggest that strong thermal contrast can be important in deriving heterogeneous convection in moist tropical regions.

Plain Language Summary To understand how surface types and surface conditions influence precipitation and cloud processes, we compared rainfall characteristics between the Amazon River and its surrounding rainforest using satellite observations and a regional climate model. With similar large-scale meteorological conditions, a much cooler river surface is shown to reduce daytime rainfall relative to the forest. By contrast, the warmer river surface at night contributes to higher nighttime rainfall in some tributaries near the coast. The climate model further suggests that daytime rain over the river relies on moisture sources above the surface, whereas above the rainforest most moisture converges near the surface.

1. Introduction

The unique land cover of the world's largest tropical rainforest in Amazonia creates unique convective characteristics, which makes it a key area to study atmospheric convection. There are abundant maritime-like congestus clouds (Wall et al., 2013; D. Wang et al., 2018), an intermediate intensity of thunderstorms (Zipser et al., 2006), more mature mesoscale convective systems (MCSs) relative to other continents (Bang & Zipser, 2016; D. Wang et al., 2019, 2020), and very low aerosol concentration during the wet season (Andreae et al., 2004; Williams et al., 2002).

Atmospheric moisture is one of the most important factors that determine the convective characteristics. Column-integrated water vapor (Bretherton et al., 2004; Neelin et al., 2009; Peters & Neelin, 2006), or more specifically, lower-tropospheric water vapor, has a robust relationship with deep convection either over the ocean (Holloway & Neelin, 2009; Schiro & Neelin, 2019) or over the land (Schiro & Neelin, 2019; Zhang & Klein, 2010; Zhuang et al., 2017). Modeling studies suggest that this relationship is achieved through the entrainment of convective updrafts in the lower troposphere (Kuo et al., 2017), which substantially reduces the buoyancy of rising air if the lower troposphere is dry (Schiro et al., 2018).

With different entrainment strength (Lucas et al., 1994; Takahashi et al., 2017), the oceanic convection is mostly associated with moisture in the lower free troposphere (Holloway & Neelin, 2009; Schiro & Neelin, 2019; Wu & Lee, 2019), while daytime continental convection in Amazonia is additionally linked to the boundary layer moisture considering both precipitation intensity (Schiro & Neelin, 2019) and cloud vertical



structures (Wu & Lee, 2019). Furthermore, the importance of boundary layer moisture may depend on seasons, as the differences in precondition between shallow and deep convection show a more significant signal in boundary layer moisture during the dry-to-wet transition (Zhuang et al., 2017). Climate model studies have shown that boundary layer humidity also lowers the convective inhibition (CIN), which modifies the spatial and temporal patterns of precipitation (Itterly et al., 2018).

In addition to atmospheric moisture, surface heterogeneity is also crucial to convection over land. Warm land surface temperature (LST) can induce boundary layer deepening and consequent convective initiation (Gentine et al., 2013). On a small spatial scale, heterogeneous LST and sensible heat flux can drive shallow circulations and induce convergence over the warm surface (Hohenegger & Stevens, 2018; Lindzen & Nigam, 1987; Taylor & Ellis, 2006). Studies (e.g., Taylor et al., 2012) have shown that thermally driven convergence may be more prominent in semi-arid regions and determines a negative soil moisture feedback for afternoon precipitation. In Amazonia, by contrast, researchers (Gentine et al., 2019; J. F. Wang et al., 2009) claim that the temperature effect is essential only for shallow convection instead of deep precipitating convection when comparing unperturbed rainforest against neighboring deforested pastures.

A possible explanation for the weak impact of LST gradient between the Amazonian forest and the pasture on precipitation may be the small magnitude of temperature contrast. For instance, the river breeze circulation driven by a much larger LST gradient during the daytime is reported to cause rainfall suppression over the Amazon River (Fitzjarrald et al., 2008). Station rain gauges, satellites, and ground-based radars all observe a noticeable reduction of rainfall over the river during the day and an increase at night at some locations (Cohen et al., 2014; Fitzjarrald et al., 2008; Paiva et al., 2011). This daily pattern of rainfall differences is consistent with the diurnal reversal of LST gradient near the river and the river breeze circulation (Silva Dias et al., 2004).

The distinct surface type within a short distance near the Amazon River is beneficial for understanding how temperature influences precipitating convection. Particularly, it provides a desirable condition for isolating the influence of the surface, as its proximity to the surrounding forest imply similar synoptic conditions. In addition, the deep roots of the rainforest lead to only moderate water stress in the dry season (Lee et al., 2005; Nepstad et al., 1994), and the surface latent heat flux and humidity are fairly high (Gentine et al., 2019; Wu & Lee, 2019). Thus, the differences between the river and the forest will predominantly be LST, which induces a local river breeze circulation (Silva Dias et al., 2004).

This study investigates the differences in rainfall between the Amazon River and the surrounding forest to understand the temperature effects on precipitation. Using the Climate Prediction Center morphing method (CMORPH), a high-resolution satellite precipitation product (Joyce et al., 2004), the seasonal and diurnal cycles of the river influence over convection, as well as the differences among tributaries, are discussed. We focus on the temperature effect in determining the temporal and spatial variability of rainfall. Further analysis of horizontal moisture convergence and its vertical structure is conducted with the Weather Research and Forecasting (WRF) model, which helps establish the mechanistic understanding of the temperature effect on convection in this region.

The remaining parts of the paper are organized as follows. Datasets and methods are described in Section 2. The diurnal cycle, seasonal cycle, and regional difference of the river-associated rainfall anomalies are analyzed in Section 3 using the CMORPH precipitation product (Joyce et al., 2004; Xie et al., 2019). Contributions from thermally-driven circulation are discussed in this section. Afterwards, we continue to discuss the vertical profile of moisture convergence simulated by the WRF model in Section 4. Distinct profiles over the river and the surrounding forest provide another aspect of understanding how the river breeze circulation affects precipitating convection. The paper concludes in Section 5 with a synthesis of our results and some implications.

2. Materials and Methods

2.1. Area of Interest

The area of interest is located in the lower part of the Amazon River near the mouth (Figure S1a). The northwest corner of the domain is wet all year round, while most of the rest area has a rainy season broadly



starting in October-December and ending in May-July (Marengo et al., 2001). The coastal regions are strongly influenced by sea breeze and squall lines, which decreases towards the inland region (Greco et al., 1994). Except for the southern extension of the Guiana Highlands in the northwest corner, the surface elevations within the domain are below 500 m and broadly rise from the west to the east (Figure S1b).

We identified seven major tributaries of the river within the domain: the Negro River, the Solimões River (the upper stretch of the Amazon, including the ends of the Japurá River and the Juruá River in our domain), the Amazon River (the lower stretch of the Amazon), the Madeira River, the Tapajós River, the Branco River and the Purus River (Figure S1a). The first five tributaries are relatively wider while the last two are relatively narrow. In addition, the Balbina reservoir is also clearly identified from the land water mask.

2.2. Datasets

2.2.1. Climate Prediction Center Morphing Method (CMORPH)

CMORPH is a high-resolution (8 km in space and 30 min in time) precipitation product retrieved from multiple polar-orbiting passive microwave sensors (Joyce et al., 2004; Xie et al., 2019). Compared with the $0.25^{\circ} \times 0.25^{\circ}$ 3-hourly Tropical Rainfall Measuring Mission (TRMM) precipitation product used in Paiva et al. (2011) and the $0.25^{\circ} \times 0.25^{\circ}$ CMORPH product used in Fitzjarrald et al. (2008), 8-km CMORPH has an improved ability to detect locally strong precipitation gradients over the Amazon River as well as the diurnal cycle. Although CMORPH is reported to overestimate rainfall near large water bodies in a light rain regime (Tian & Peters-Lidard, 2007), Fitzjarrald et al. (2008) showed a good agreement between CMORPH and station measurements near the Amazon-Tapajós confluence. We analyzed the CMORPH precipitation during 1998–2017.

2.2.2. MODIS/Aqua LST

LST near the Amazon River is illustrated using the 8-day 0.05° Aqua MODIS LST and emissivity product (MYD11C2) available during 2003–2019 (Wan et al., 2015). Retrievals flagged as low quality and cloudy pixels are excluded in the analysis. We assign equal weight to each month to avoid bias towards dry months. A root mean squared error of 4°C–5°C in the Amazon is reported due to deficient cloud detection (Gomis-Cebolla et al., 2018).

2.2.3. CloudSat Cloud Water Content (CWC)

CloudSat 2B-Cloud Water Content-Radar Only (2B-CWC-RO) P1_R05 product (Austin et al., 2009) provides the vertical cloud structure with a 485-m resolution using a 94-GHz cloud profiling radar (Stephens et al., 2002, 2018). Because of its 16-days revisit period and the fixed daytime overpass at 1330 LT (local time) in the tropics (Stephens et al., 2002, 2018), the afternoon clouds near the river cannot be fully sampled, and deep convection in the late afternoon will be missing. In addition, the liquid cloud water is underestimated during heavy precipitation. With these caveats in mind, we only use a typical case of rainy cloud profile across the Negro River on November 6, 2006, in Section 3.2 to illustrate the cloud characteristics near the river instead of any quantitative analyses.

2.2.4. Weather Research and Forecasting (WRF) Model

We performed a regional climate model simulation from May 1, 2007, to July 1, 2010, using the WRF Advance Research WRF (ARW) version 3.6.1 (Skamarock et al., 2008). The first two months are excluded from the analysis for the model spin-up. The applied parameterization schemes are summarized in Table 1. The single-moment cloud microphysics scheme used here is computationally cheaper than double-moment schemes yet performs reasonably well.

The simulation is conducted with a 10×10 km horizontal resolution and 40-s time step. Model outputs are archived every 3 h. There are 38 vertical layers in the atmosphere up to 10 mb and four soil layers. Land cover is identified using the modified IGBP MODIS 21-category data, and the model option of climatological albedo maps is chosen. Initial and boundary conditions are interpolated from the $0.3^{\circ} \times 0.3^{\circ}$ National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSR) dataset (Saha et al., 2010). Particularly, the river and lake LST are specified using the previous 3-days average 2-m air temperatures from CFSR.



Table 1		
Parameterization Schemes Used in the WRF Simulation		
Parameterization	Scheme	Reference
Land	Noah land scheme	Chen & Dudhia, 2001
Radiation	Community Atmosphere Model 3.0 scheme	Collins et al., 2004
Cumulus convection	Kain-Fritsch scheme	Kain, 2004
Planetary boundary layer	Yonsei University scheme	Hong et al., 2006
Cloud microphysics	WRF single-moment 5-class scheme	Hong et al., 2004

Abbreviation: WRF, Weather Research and Forecasting.

CFSR outperforms Modern Era Retrospective-Analysis for Research and Applications (MERRA) in simulating the South America water cycle (Quadro et al., 2013). Still, it overestimates the rainy season precipitation in the Amazon Basin (Blacutt et al., 2015) and underestimates precipitation near the northeastern coast and the Amazon river mouth (Silva et al., 2011). CFSR has also been used to analyze the wind and convergence in tropical and subtropical South America (Romatschke & Houze, 2013).

Other auxiliary datasets including the land water mask and the surface elevations are introduced in Text S1.

2.3. Methods

2.3.1. Local Rainfall Percentage Anomaly

Considering the northwest-southeast rainfall gradient in this region (Marengo et al., 2001), we defined the local rainfall anomalies to compensate for the large-scale pattern. For each 250-m MOD44W river pixel, the river precipitation is estimated by the average CMORPH rainfall within a 6-km neighborhood. In contrast, the baseline precipitation of the surroundings is estimated by the average rainfall of a buffer zone consisting of non-water pixels 25–35 km away from this river pixel. The rainfall percentage anomaly associated with this river pixel is then defined by the percentage difference of the river precipitation relative to the baseline precipitation. This river-forest difference is hereinafter abbreviated as "anomaly", which does not mean the difference from climatology in this paper. We define the land 25–35 km away from the rivers as the baseline to reduce impacts of the local river breeze, as is suggested in Silva Dias et al. (2004).

2.3.2. Horizontal Moisture Convergence

The horizontal moisture convergence at the model output time step just before 1100 LT is computed from the WRF outputs. We choose 1100 LT as the beginning of the daytime period, consistent with the diurnal cycle of river rainfall anomalies identified using CMORPH in Section 3. Similar to the precipitation comparison between the river and the surrounding forest using satellite data, only the land 25–35 km away from the river is used to derive the average moisture convergence compared against the average moisture convergence over the river. Although convection may be initiated earlier than 1100 LT, the previous model output time step around 0800 LT is too early when the daytime river breeze has not yet been established. Our model results show little difference around 0800 LT between the moisture convergence profiles above the river and the surrounding forest (Figure S2).

Moreover, we decompose the horizontal moisture divergence into two terms,

$$\nabla_{\rm h} \cdot \left(q \vec{V} \right) = q \nabla_{\rm h} \cdot \vec{V} + \vec{V} \cdot \nabla_{\rm h} q$$

where *q* is specific humidity [g/kg], and \overline{V} is the horizontal wind vector [m/s]. The subscript h denotes horizontal divergence or horizontal gradient. The first term of this decomposition, or the wind convergence term, is proportional to horizontal wind divergence, while the second term, or the moisture advection term, is proportional to the gradient of specific humidity. Thus, water vapor diverges when the wind diverges and/or the wind blows from regions of low humidity to regions of high humidity. When considering the Amazon River, the river breeze driven by the LST gradient has a component perpendicular to the river (Silva





Figure 1. MODIS annual average land surface temperature (LST) in 2003–2019. (a) Daytime LST. (b) Nighttime LST. The same color bar is used in top two panels. (c) Laplacian of daytime LST. Only large positive values are shown to highlight the cooler river surface. (d) Laplacian of nighttime LST. Only large negative values are shown to highlight the warmer river surface.

Dias et al., 2004). Therefore, moisture convergence associated with humidity gradient occurs if the specific humidity above the river is lower than the upwind forest. We excluded the data when the residual of the decomposition due to finite grid resolution and subgrid-scale moisture transport is greater than 20% of the total moisture convergence (\sim 5% of the model outputs).

3. Satellite Observations of Rainfall Anomalies Over the River

3.1. Overview of Satellite Observed Rainfall Pattern

Strong LST gradients near the Amazon River are confirmed by MODIS LST products (Figure 1). During the daytime, the annual average LST shows a cool anomaly along most parts of the river (Figure 1a). However, the river has a very small diurnal temperature range, and as a result, it is warmer than the surrounding forest during the nighttime (Figure 1b). This strong LST gradient may induce local circulations that affect convection and rainfall characteristics, as is reported in a few studies (Cohen et al., 2014; Silva Dias et al., 2004).





Figure 2. CMORPH annual average precipitation in 1998–2017 (a) throughout the day, (b) between 1100 and 2300 LT, and (c) between 2300 and 1100 LT. The same color bar is used.

The LST contrast can further be quantified by the Laplacian operator, and warm temperature anomalies are associated with a negative Laplacian (Protter & Weinberger, 2012), vice versa. Except for orographic effects, large positive ∇^2 LST during the daytime is predominantly found along the river (Figure 1c). During the nighttime, the river also dominates the occurrence of large negative ∇^2 LST (Figure 1d).

Figure 2a confirms the overall rainfall reduction along the Amazon River according to the 20-year CMORPH data, with different degrees among tributaries. The area with reduced rainfall extends up to several tens of kilometers away from the Negro River and the Solimões River, while the spatial range of the river influence is relatively narrower near the other tributaries. In addition, the gradient in rainfall appears more symmetric about the Solimões River on both sides but asymmetric about the Negro River, where the north side receives less rain than the south. Compared with similar results presented in Paiva et al. (2011), the spatial pattern of the river influence is better depicted because the CMORPH dataset has a higher resolution.



Daytime precipitation over the river is reduced to a larger magnitude (Figure 2b) compared with total precipitation. Furthermore, the rainfall distribution becomes more asymmetrical on the two sides of the Negro River and the Tapajós River. Rainfall is higher to the east of the Tapajós River while lower to the west, consistent with results from ground-based S-band radar measurements (Cohen et al., 2014).

In contrast to the strong gradients in daytime rainfall near the river, nighttime rainfall over the river does not substantially differ from the neighboring forests, except for the lower Amazon River near the coast (Figure 2c). The nighttime rainfall increase over the lower Amazon is likely to be associated with squall lines propagating towards the southwest overnight (Burleyson et al., 2016; Cohen et al., 1995), and it will be further discussed in Section 3.2. There is a high rainfall zone north of the lower Amazon in Figure 2b and 2c, but its location is further to the west during the nighttime.

We show the average diurnal and seasonal cycles of the river precipitation anomalies compared with the local surroundings and monthly average river precipitation anomalies during 1200–1800 LT (Figure 3a) across the domain. The rainfall reduction over the river mostly occurs during the daytime (termed the hours between 1100 and 2300 LT in this study). These negative precipitation anomalies usually occur in more than 70% of all the river grid cells during 1200–1800 LT (highlighted by the hatching). The peak percentage reduction (-19.1%) in afternoon precipitation during 1200–1800 LT is seen in September during the dry-to-wet transition, and there is a secondary peak in May (-18.7%) associated with the wet-to-dry transition (Figure 3a). By contrast, there are positive rainfall anomalies on average during the nighttime and early morning in December-July, which broadly corresponds to the wet season and the early dry season (Marengo et al., 2001; Zhuang et al., 2017). This nighttime rainfall increase is mainly contributed by the lower Amazon (Figure 3c). Over this tributary, the daytime precipitation reduction and nighttime increase are consistent with the diurnal pattern of LST and the river breeze circulation (dos Santos Pinheiro et al., 2014).

3.2. Spatial Variability in Individual Tributaries

The degree to which the rainfall is affected by the river differs among tributaries. This conclusion is further illustrated by comparing the 20-year average rainfall percentage anomalies among the selected tributaries in Figure 4. Overall, the rainfall is reduced in most tributaries, and this reduction is stronger when only day-time rainfall is considered. By contrast, the nighttime anomaly can be either positive or negative depending on the tributary, and the lower Amazon River shows the largest positive anomaly. Except for the Amazon, the nighttime percentage anomalies are close to 0 in all the other tributaries.

The diurnal and seasonal cycles of the rainfall anomalies also vary substantially among the tributaries. With relatively river channels, the Negro, the Solimões and the Madeira have similar diurnal and seasonal cycles, with a strong reduction in the afternoon and a weaker yet mostly negative influence at night (Figure 3b, Figures S3a and S3b).

Unlike the three tributaries mentioned above, the lower Amazon, the Tapajós, the Balbina and the Purus are overall characterized by reduction during the daytime and increase at night (Figure 3c, Figure S3). This type of rainfall anomalies was also reported for the Amazon-Tapajós confluence by Cohen et al. (2014). Strong positive anomalies at night only occur from December to August over the lower Amazon. There is no substantial difference in nighttime precipitation between the river and the surroundings in other months (Figure 3c). It also shows the strongest rainfall reduction during the daytime and the strongest increase at night. Over the Tapajós (Figure S3c), rainfall increase can be found in the afternoon during the dry season (June-August). The hours of rainfall reduction over the Balbina change throughout the year, ranging from about 8 h in September to almost the entire day in January (Figure S3d). Nocturnal deep convection near the Balbina was also observed by the Amazon Tall Tower Observatory (Oliveira et al., 2020).

We speculate that the nighttime rainfall increase over these tributaries may be related to squall lines which are generated along the sea-breeze front (Burleyson et al., 2016; Cohen et al., 1995; Cutrim et al., 2000; Garstang et al., 1994) and propagate further inland overnight. This is because the spatial and seasonal patterns for coastal squall lines seem consistent with the seasonality in Figure 3c. These squall lines strongly influ-





Figure 3. Diurnal and seasonal cycle of the river precipitation anomalies relative to the forest (top of each panel), and monthly average river precipitation anomalies during 1200–1800 LT (bottom of each panel). (a) Percentage anomalies of the entire river. (b) Percentage anomalies of the Negro. (c) Percentage anomalies of the Amazon. The hatching denotes that more than 70% of the river grid cells agree in the sign of precipitation anomalies. Panels (b and c) have the same color bar. The grey shading around the black solid curve represents the spatial variability among river pixels between the 25th and 75th percentiles.

ence Amazonian rainfall at night during the wet and transitional seasons (Fitzjarrald et al., 2008; Schiro & Neelin, 2019), and the nighttime rainfall percentage anomalies reach the peak during the same period. The tributaries with significant nighttime rainfall increase are also located closer to the coast, where the MCS influence is expected to be stronger (Greco et al., 1994).





Figure 4. River precipitation percentage anomalies of each tributary. Average percentage anomalies throughout the day are in blue; daytime average anomalies are in orange; and nighttime average anomalies are in purple. The box (quartiles) and whiskers (the minimum and the maximum) show the spatial variation of the percentage anomalies in each tributary. The tributaries are plotted in descending order of maximum channel width, except the Balbina reservoir.

Probably due to its narrow width, it is hard to identify a clear pattern in the diurnal cycle of the Branco River. Nonetheless, we tend to find stronger nighttime rainfall increase from October to February, and this positive anomaly extends to almost the whole day in February (Figure S3f).

To better illustrate the asymmetric river influence on both sides of the Negro shown in Figure 2, a typical cloud case on November 6, 2006 is plotted using the CloudSat CWC product (Figure 5). This case shows



Figure 5. Afternoon CloudSat profiles (color contours) and average land surface temperature (LST) along the swath (curve) near the Negro on November 6, 2006. The red line at the bottom denotes the location of the river, and the shaded area is possibly raining/drizzling (CloudSat radar reflectivity >-15 dbZ).

strong cloud development only to the south of the Negro River. Asymmetric rainfall anomalies were also reported near the Negro-Solimões confluence (Burleyson et al., 2016) and along the Tapajós River (Cohen et al., 2014), together with a single-cell river breeze circulation (Silva Dias et al., 2004). This phenomenon is probably associated with the orientation of the river, which is perpendicular to the prevailing winds. It generates convergence on one side of the river and divergence on the other side (Burleyson et al., 2016; Lu et al., 2005; Silva Dias et al., 2004). Dynamic effects due to surface roughness change can favor convection and precipitation on the downwind side of the river, similar to the roughness effects near the small-scale forest-pasture margin (Khanna et al., 2017). More about the dynamic effects of roughness will be discussed in the next section.

3.3. Suppressed Daytime Convection Due to Temperature Heterogeneity

We speculate that the daytime rainfall reduction over the rivers is mainly associated with suppressed local convection. This is because a strong reduction in the afternoon is consistent with the diurnal cycle of local surface heat fluxes, and smaller local convective cells are reported to be very common during the daytime in Amazonia (Schiro & Neelin, 2019). In addition, MCSs, broadly defined as precipitation cells around or greater than 100 km in at least one dimension (Houze, 2004), contribute substantially to Amazonian precipitation and may also be involved in the daytime rainfall



reduction. However, among the major MCS regimes, propagating systems from either the northeastern coast or the northern and eastern part of the Amazon Basin will precipitate at a wide range of local time depending on the location (Cutrim et al., 2000), unlike those fewer locally formed MCS which responds to diurnal heating (Greco et al., 1990). Indeed, a detailed examination of the 30-min precipitation maps during the dry-to-wet transition season (Figure S4, using September 8, 2007 as an example) and the wet season (Animation S1, using the first week of April 2007 as an example) suggests that nighttime rainfall is mainly from MCSs.

Suppressed daytime rainfall due to thermally driven circulation is supported by the close relationship between the Laplacian of LST (∇^2 LST) and river rainfall anomalies relative to the surrounding forest. The overlapping period 2003–2017 of available precipitation and LST data is chosen to conduct the statistical analysis between river rainfall anomalies and ∇^2 LST. Instead of absolute temperature, the gradient of temperature directly influences surface wind. Thus, surface convergence is linked to ∇^2 LST (Duffy et al., 2020; Lindzen & Nigam, 1987).

Except for the Balbina and the lower Amazon, monthly average rainfall anomalies of the other tributaries significantly correlate with the climatological monthly average $\nabla^2 \text{LST}$ (correlation coefficient r = -0.56, p = 2.82e-7, n = 72). A higher $\nabla^2 \text{LST}$ is associated with a stronger LST gradient and consequently greater surface divergence over the river. Therefore, the negative correlation indicates that daytime precipitation is reduced more where the temperature contrast between the river and the surroundings is stronger. This mechanism is similar to the "Laplacian-of-warming" mechanism in explaining tropical precipitation change under global warming (Duffy et al., 2020). Their results suggest that the relationship could be even stronger when considering the boundary layer virtual temperature rather than LST. This negative relationship could be largely related to the spatial variability among different tributaries since data points of an individual tributary tend to cluster in Figure S5. Perhaps due to the size or the proximity to the Atlantic coast, the Balbina and the lower Amazon do not follow this negative relationship and show an insignificant positive correlation instead (Figure S5).

Despite the significance of the negative correlation with the LST pattern, only 31% of the total variance of daytime rainfall reduction can be explained by this relationship. Therefore, other mechanisms also play significant roles in determining the river influence over convection. For example, the surface roughness is drastically different between the water surface and terrestrial vegetation. Although the roughness effects are likely to be minor on a large scale compared with energetics and thermodynamics (Zeng et al., 1996), small-scale heterogeneity of surface roughness between the forest and the pasture has been reported to have a strong dynamic impact over convection in Amazonia (Khanna et al., 2017). Similar impacts are expected for the roughness contrast between the river and the surrounding forest. Moreover, the dynamic effects of the surface roughness can have asymmetrical influence along the prevailing wind direction (Khanna et al., 2017). As mentioned earlier, some tributaries like the Negro clearly show convection preference on one side of the river than the other. The location shown in Figure 5 experiences a prevailing northerly wind during the rainy season. Consequently, the lower surface roughness of the Negro than the forest will favor convection on the downwind side, which is the southern bank. This explanation agrees with the annual daytime precipitation in Figure 2b and the cloud case presented in Figure 5.

4. Model Simulation of Rainfall Anomalies Over the River

4.1. Overview of Simulated Rainfall Pattern

The overall LST patterns simulated by WRF look similar to MODIS retrievals, but the absolute values are around 5°C too warm during the day and around 3°C too cold at night (Figure S6). The actual discrepancy between the model and observations may be smaller because MODIS LST in Amazonia suffers from the data quality issue due to heavy cloudiness (Gomis-Cebolla et al., 2018). Additionally, the prescribed river temperature from CFSR is cooler than MODIS during the day and warmer than MODIS at night. The average LST anomalies of the WRF river grid boxes relative to neighboring forest grid boxes are exaggerated to -8.4° C during the day and $+6.6^{\circ}$ C at night. High values of modeled ∇^2 LST are concentrated near the Amazon River (Figures 6c and 6d), consistent with MODIS (Figures 1c and 1d). The river grid cells are discontinuous or even completely missing for those tributaries narrower than the 10-km horizontal grid resolution, such as the Solimões, the Madeira, the Branco, and the Purus. Therefore, the following analyses will mainly focus on those wider tributaries resolved by the model grid, such as the Negro, the Tapajós, and





Figure 6. Weather Research and Forecasting annual average land surface temperature (LST) and Laplacians in July 2007-June 2010. (a) Daytime (1400 LT) LST. (b) Nighttime (0200 LT) LST. (c) Daytime (1400 LT) ∇^2 LST. (d) Nighttime (0200 LT) ∇^2 LST.

the lower Amazon. Despite the exaggerated LST gradient near the river in the model results, the influence of LST on convection and precipitation is expected to be qualitatively similar compared with observations.

The spatial distribution of surface energy fluxes corresponds with LST (Figure S7). During the daytime at 1400 LT, the cooler river has a sensible heat flux an order of magnitude lower than the rainforest. The sensible heat flux is proportional to the vertical temperature gradient between the surface and the air. Therefore, the much smaller sensible heat flux of the river surface is a consequence of less daytime heating and a small vertical temperature gradient. Although the daytime latent heat flux of the river is not as small as the sensible heat flux, it is still substantially lower than the surrounding forest. The river-forest contrast in surface energy fluxes is reversed at night when the river has higher sensible and latent heat fluxes. The forest has nearly zero or slightly negative sensible and latent heat fluxes at 0200 LT. The nighttime sensible heat flux of the river is also small, but the latent heat flux can reach around 100 W/m² in some tributaries. A higher surface flux helps destabilize the atmosphere and facilitates local deep convection (Wu & Lee, 2019; Zhuang et al., 2017), and it also has the potential to drive changes in the mesoscale and large-scale transport (Wright



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Figure 7. Weather Research and Forecasting annual average precipitation in July 2007–June 2010. (a) Average precipitation 1100–2300 LT. (b) Average precipitation 2300–1100 LT. (c) Average convective precipitation 1100–2300 LT.

et al., 2017). In addition to the absolute amount of surface energy fluxes, the Bowen ratio of sensible heat flux to latent heat flux is higher over the forest than the river. A higher daytime Bowen ratio is also found to favor deeper convective clouds in the Amazon region (Wu & Lee, 2019).

The modeled large-scale rainfall pattern resembles the observations, except for the unrealistically high nighttime rainfall in the southwest corner of the domain (Figures 7a and 7b). Daytime rainfall is substantially suppressed over the river in our simulation (Figure 7a), and the majority of this precipitation anomaly is attributed to convective rainfall rather than large-scale rainfall (Figure 7c). However, the absolute values of rainfall are about twice as high as the CMORPH data across the domain, and nighttime rainfall in the southern part of the domain is further overestimated compared with observations (Figure 7b).

Compared with the observations in Figures 2c and 2a zone of relatively higher nighttime rainfall extending northwards from the lower Amazon is successfully captured in our simulation (Figure 7b). As is discussed





Figure 8. Average horizontal moisture convergence profiles around 1100 LT before daytime rainfall (a) above the river, and (b) above the surrounding forest. Data are categorized by total daytime rainfall. Standard deviations are computed from bootstrap samples (n = 1,000). The horizontal lines and the grey shading indicate the mean planetary boundary top and its standard deviation.

in previous sections, this zone is associated with the observed positive nighttime rainfall anomalies over the lower Amazon during December to August, probably as a result of propagating squall lines. The nighttime propagation of squall lines is also simulated in the model (Figure S8). This zone of higher nighttime rainfall covering part of the lower Amazon is also a seasonal phenomenon in WRF results, which starts to appear in October and migrates northwards away from the river in April. Westward propagation of this high-rainfall zone from day to night can also be seen in Figure 7, but not as clear as in Figure 2. By contrast, the daytime rainfall suppression over the Amazon River in our simulation is noticeable every month (Figure S9), similar to CMORPH estimates.

4.2. Horizontal Moisture Convergence Before Daytime Rainfall

In addition to differences in rainfall amount, the river and its surrounding forest are characterized by distinct moisture convergence profiles before daytime rain events (Figure 8). Here all the daytime rain events are categorized based on the total rainfall over the 12-h period from 1100 to 2300 LT, and the convergence is computed for the closest model output time step before 1100 LT. For weaker to moderate rain (<20 mm/12 h) over the river, the model simulation indicates moisture divergence near the surface and moisture convergence above up to approximately 750 mb (Figure 8a). With increasing precipitation, changes occur below 850 mb where the divergence near the surface weakens and finally disappears and the convergence strengthens. When the rainfall exceeds 20 mm/12 h, moisture convergence extends from the surface up to 700 mb or even higher. Furthermore, together with higher and higher rainfall, the increase in moisture convergence extends above 850 mb.

In contrast to the separate convergence/divergence layers above the river, moisture convergence, if existing, is always highest near the surface over the surrounding forest (Figure 8b). When the rainfall exceeds 5 mm/12 h, the moisture convergence layer extends from the surface into the lower free troposphere, and this layer deepens with precipitation intensity. Similar to the river, the increase in moisture convergence first takes place below 850 mb, and the rises to higher levels. The deepening surface convergence layer may also relate to the rapid pickup of the well-known nonlinear precipitation-moisture curve (Bretherton et al., 2004; Neelin et al., 2009; Peters & Neelin, 2006; Schiro & Neelin, 2019), which may be worth further investigation in different environmental conditions.







Figure 9. Decomposition of average horizontal moisture convergence profiles around 1100 LT before daytime rainfall (a) above the river, and (b) above the surrounding forest. Standard deviations are computed from bootstrap samples (n = 1,000). The horizontal lines and the grey shading indicate the mean planetary boundary top and its standard deviation.

The moisture convergence profiles for daytime rain events are then decomposed into the convergence component $(q\nabla_h \cdot \vec{V})$ and the advection component $(\vec{V} \cdot \nabla_h q)$ using the equation described in Section 2.3.2 (Figure 9). Although the mass convergence term mainly controls the shape of the total moisture convergence profile, moisture convergence due to the specific humidity gradient and moisture advection is also important for the river (Figure 9a). The separate convergence and divergence layers result from the different layers of mass convergence above the surface and divergence near the surface. The total moisture convergence profile is further modulated by the moisture advection component. Because the specific humidity is lower above the river than the surrounding forest, the advection component is always converging below 850 mb. It reaches its peak near the boundary layer top, contributing to nearly half of the total moisture convergence. The shape of the wind convergence profile is associated with the river breeze circulation, the LST gradient and subsidence in the lower troposphere over the cool river surface (Silva Dias et al., 2004).

Over the surrounding forest, the total moisture convergence profile follows wind convergence and the advection component related to the specific humidity gradient is much smaller (Figure 9b). The average boundary layer top is higher above the forest (880 mb), and both moisture and wind convergence occur mostly within the boundary layer. There is weak and insignificant moisture or wind divergence above the boundary layer, indicating only a minor influence of the free-tropospheric moisture supply (Wu & Lee, 2019). The river breeze circulation during the daytime may strengthen this type of profile near the Amazon River. The advection component contributes to a significant but small moisture divergence below 800 mb.

For both the river and the forest, the moisture advection component is insensitive to the amount of precipitation, and most changes in Figure 8 are contributed by the mass convergence component (Figure S10).

5. Synthesis and Conclusions

In order to understand how the heterogeneity of surface temperature (LST) influences convection and precipitation, we compared precipitating convection between the Amazon River and the surrounding forest observed by satellites and simulated by the WRF model. The influence of synoptic conditions is



minimized in this comparison because of the short distance between the river and the forest, and hence the effects due to surface conditions can be isolated. Our results particularly highlight the role of LST, which suppresses daytime convection over the river, interact with nighttime convection near the coast (Figure 4), and cause the double-layer moisture convergence/divergence structure (Figure 8). Nonetheless, other processes could also be involved in this convection contrast between the river and the forest. For instance, shallow convection could help establish the precondition for deep convection by moistening and destabilizing the free atmosphere in Amazonia (Wright et al., 2017; Zhuang et al., 2017), and different surface types may cause differences in lower-troposphere moistening before deep convection (Text S2 and Figure S11).

Satellite-based analyses show rainfall reduction during the daytime across the domain and throughout the year. However, substantial reduction only occurs in the afternoon in most tributaries when surface-induced convection is expected to reach its peak (Zipser et al., 2006). The percentage reduction is particularly important during the dry-to-wet transition season (Figure 3a) when large-scale moisture supply has not yet started to increase (Fu & Li, 2004; Wright et al., 2017) and the average convective intensity is highest in a year (D. Wang et al., 2018; Wu & Lee, 2019). The uniqueness of the dry-to-wet transition season could come from a combination of increasing humidity and yet elevated instability during the daytime (Wu & Lee, 2019; Zhuang et al., 2017), as well as enhanced wind shear (Giangrande et al., 2020). Terrestrial evapotranspiration is reported to be responsible for the early increase in atmospheric moisture (Wright et al., 2017), and the developing deep convection further triggers large-scale moisture advection from the ocean (Fu et al., 1999).

The magnitude of daytime reduction has a significantly negative correlation with the Laplacian of LST. These characteristics support the daytime suppression of local convection above the river due to thermally driven divergence (Duffy et al., 2020; Lindzen & Nigam, 1987). The "Laplacian-of-warming" mechanism is reported to be important in oceanic precipitation responses to climate change (Duffy et al., 2020), and this study also confirms the close connection between ∇^2 LST and precipitation near the Amazon River on land.

The river also increases rainfall at night but only in a few tributaries, such as the Amazon-Tapajós confluence (Cohen et al., 2014). The strongest nighttime signal is found in the lower Amazon River near the Atlantic coast, which forms the southern end of a high-rainfall corridor associated with propagating squall lines (Burleyson et al., 2016; Cohen et al., 1995).

The WRF model further shows that moisture convergence before daytime rain above the river is predominantly contributed by wind convergence and the humidity gradient near the boundary top. By contrast, the surrounding forest not far away gathers moisture primarily through convergence within the boundary layer.

In addition to the knowledge of surface-convection interaction, this study also has implications on the Observations and Modeling of the Green Ocean Amazon (GoAmazon2014/5) Experiment (Martin et al., 2016). The T3 site of GoAmazon2014/5 is reported to be slightly suppressed by the river breeze of the Negro (Burleyson et al., 2016). Our results regarding the unique convective characteristics near the Amazon River may further help interpret of the GoAmazon datasets.

Data Availability Statement

The topography data used in the study is available at Amatulli et al. (2018). The CloudSat 2B-CWC-RO cloud water content data is introduced in Austin et al. (2009) and the web page at http://www.cloudsat.cira. colostate.edu/data-products/level-2b/2b-cwc-ro/ (data description, version P1_R05), and it is available at ftp://ftp1.cloudsat.cira.colostate.edu/2B-CWC-RO.P1_R05/ (ftp server) after registration at CloudSat Data Processing Center (http://www.cloudsat.cira.colostate.edu/). The MODIS land water mask is available at Carroll et al. (2017). The Amazon River stream map is available at Mayorga et al. (2012). The NCEP CFSR used for the WRF boundary conditions is available at Saha et al. (2010), reproduced by Research Data Archive (RDA) at the National Center for Atmospheric Research (NCAR). The MODIS LST is available at Wan et al. (2015). The WRF outputs are available at Wu et al. (2020). The CMORPH dataset is available at Xie et al. (2019).



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