# Suppressed Daytime Convection over the Amazon River

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**Key Points:**

- Daytime rainfall is suppressed over the Amazon River compared with surrounding forest.
- The reduction of daytime rainfall has a significantly negative linear relationship 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.

## 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 in the day and warmer at night. We analyzed twenty years of high-resolution satellite precipitation data and confirmed previous findings of daytime rainfall reduction over the river. This reduction is strongest during the dry-to-wet transition season. In addition, the reduction of each tributary is significantly correlated with a positive Laplacian of surface temperature, which causes thermally-driven surface divergence and suppresses local convection. Additionally, nighttime rainfall is enhanced over tributaries near the coast during the wet season. The local rainfall anomalies associated with the river is then simulated by a regional climate model. 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 important 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 source above the surface, whereas above the rainforest most moisture converges near the surface.


## 1 Introduction

Along with its vast tropical rainforest, Amazonia is a key area to study atmospheric convection for its unique convective characteristics. There are abundant maritime-like congestus clouds (Wall et al., 2013; D. Wang et al., 2018), 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 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). Modelling studies suggest that this relationship is achieved through 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 preconditioning between shallow and deep convection shows a larger 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 modify 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 surface temperature can induce boundary layer deepening and consequent convective initiation (Gentine et al., 2013). On a small spatial scale, heterogeneous surface temperature 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 important 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 surface temperature 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 surface temperature gradient during the daytime is reported to cause rainfall suppression over the Amazon River. 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 diurnal pattern of rainfall differences is consistent with the diurnal reversal of surface temperature gradient near the river and the river breeze circulation (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 (Nepstad et al., 1999; Lee et al., 2005), 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 surface temperature, which induces a local river breeze circulation (Dias et al., 2004).

In this study, we investigate 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 seasonality, the diurnal cycle of the river influence over convection and 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 are 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). Contributions from thermally-driven circulation is 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 to understand how the river breeze circulation affect precipitating convection. The paper is concluded 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, the effect of 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 fairly narrow. In addition, the Usina Hidrelétrica de Balbina (UHE Balbina; the Balbina Hydroelectric Dam) 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). Compared with the 0.25°×0.25° 3-hourly Tropical Rainfall Measuring Mission (TRMM) precipitation product used in Paiva et al. (2011) and the 0.25°×0.25° 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 Land Surface Temperature (LST)

Surface temperatures near the Amazon River are illustrated using the 8-day 0.05° Aqua MODIS land surface temperature 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 an equal weight to each month to avoid bias towards dry months. A root mean squared error of 4 – 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-day revisit period and the fixed daytime overpass at 1330 LT 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 typical cases of rainy cloud profiles to illustrate the cloud characteristics near the Amazon River instead of any quantitative analyses.

### 2.2.4 Weather Research and Forecasting (WRF) model

We performed a regional climate simulation from May 1st, 2007, to July 1st, 2010, using the WRF Advance Research WRF (ARW) version 3.6.1 (Skamarock et al., 2008). The first two months are excluded in 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 km × 10 km domain and 40-s time step. Model outputs are archived every 3 hours. There are 38 vertical layers in the atmosphere up to 10 mb and 4 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° × 0.3° National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSR) dataset (Saha et al., 2010). Particularly, the river and lake surface temperatures are specified using the previous 3-day average 2-m air temperatures from CFSR.

CFSR outperforms Modern Era Retrospective-Analysis for Research and Applications (MERRA) in simulating the South America water cycle (Quadro et al., 2013), but 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 the 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 as follows 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, while the baseline precipitation of the surroundings is estimated by the average rainfall of a buffer zone consisting of land 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 avoid too strong impacts of the local river breeze, as is suggested in 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, which is consistent with the diurnal cycle of river rainfall anomalies identified using CMORPH in Section 3. Although convection may initiate 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 also show little difference around 0800 LT between the moisture convergence profiles above the river and the surrounding forest (Figure S2). Similar to the precipitation comparison between the river and the surrounding forest, only the land 25 - 35 km away from the river are used to derive the average moisture convergence and compared against the average moisture convergence over the river.

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

$$\nabla_h \cdot (q\vec{u}) = q\nabla_h \cdot \vec{u} + \vec{u} \cdot \nabla_h q$$

where $q$ is specific humidity [g/kg], and $\vec{u}$ is the horizontal wind vector [m/s]. The subscript $h$ denotes horizontal divergence or horizontal gradient. The first term of this decomposition, or the convergence term, is proportional to horizontal wind divergence, while the second term, or the 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 surface temperature gradient has a component perpendicular to the river (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. The decomposition is fairly accurate with 3-hourly model outputsWe excluded when the residual of the decomposition is greater than 20% of the total moisture convergence (~XX% of the output).

2.3.3 Humidity change before strong daytime rainfall

Shallow convection is argued to help establish the precondition for deep convection by moistening and destabilizing the free atmosphere in Amazonia (Wright et al., 2017; Zhuang et al., 2017). This “shallow convection moisture pumping” hypothesis is investigated by computing the changes in atmospheric humidity before strong afternoon rain. Consecutive two 3-hourly model output intervals in the afternoon are selected if (1) there is at least 5-mm precipitation in the later interval, and (2) there is no precipitation in the earlier one. The conditions of the earlier interval are classified as shallow convection (SC), if the maximum cloud fraction between 850 mb and 700 mb is greater than 30%, or no convection (NC) otherwise. Here the cloudiness in the lower troposphere is considered as an indicator of preconditioning shallow convection. A comparison between these SC cases and NC cases help illustrate whether preexisting shallow convection favors deep convection in the afternoon.

# 3 Satellite observations of rainfall anomalies over the river

## 3.1 Overview of satellite observed rainfall pattern

Strong surface temperature 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 surface temperature gradient may induce local circulations that affect convection and rainfall characteristics, as is reported in a few studies (Cohen et al., 2014; Dias et al., 2004). The surface temperature 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 $\nabla^2$LST during the daytime is predominantly found along the river (Figure 1c). During the nighttime, the river also dominates the occurrence of large negative $\nabla^2$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 river influence is relatively smaller near the other narrower? 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 is reduced more significantly over the river (Figure 2b) compared with the total rainfall. Furthermore, the rainfall distribution becomes more asymmetrical on both sides of the Negro River and the Tapajós. Higher rainfall is higher to the east of the Tapajós River while lower rainfall occurs 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 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 both Figures 2b and 2c, but its location is further to the west during the nighttime.

The east-west gradient in precipitation and some orographic effects are also noticeable from Figure 2. The western side of the domain is relatively wetter than the eastern side. Remarkably high precipitation is found to the west of the Guiana Highlands (the northwest corner of the domain), which blocks eastward moisture transport and causes a local precipitation minimum to the east.

The rainfall reduction over the river mostly occurs during the daytime and the dry-to-wet transition season (August through October, in Figure 3b). We show the average diurnal and seasonal cycles of the river rainfall anomalies compared with the local surroundings (Figure 3a) and the rainfall percentage anomalies (Figure 3b) across the domain, and find negative values between approximately 1100 and 2300 LT. 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 (-24.6%) is seen in the afternoon of August – October during the dry-to-wet transition season, and there is a secondary peak in the afternoon of May (-22.6%) associated with the wet-to-dry transition (Figure 3b). 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) despite slight differences among tributaries. The daytime precipitation reduction and nighttime increase is consistent with the diurnal pattern of surface temperatures 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, rainfall is reduced over most of the rivers, and this reduction is stronger when only daytime 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 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. As relatively wider tributaries, the Negro, the Solimões and the Madeira have similar diurnal and seasonal cycles, with strong reduction in the afternoon and weaker yet mostly negative influences at night (Figures 3c, S3a and S3b).

Unlike the three tributaries mentioned above, the lower Amazon, the Tapajós, the UHE Balbina and the Purus are overall characterized by reduction during the daytime and increase at night (Figures 3d, 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, and there is no substantial difference in nighttime precipitation between the river and the surroundings in other months (Figure 3d). It also shows strongest rainfall reduction during the daytime and strongest increase at night. Over the Tapajós (Figure S3c), rainfall increase can even be found in the afternoon during the dry season (June - August). The hours of rainfall reduction over the UHE Balbina change throughout the year, ranging from about 8 hours in September to almost the entire day in January (Figure S3d). Nocturnal deep convection near the UHE 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 to be consistent with the location of these tributaries and the seasonality in Figure 3d. These squall lines have a strong influence on Amazonian rainfall at night during the wet and transitional seasons (Fitzjarrald et al., 2008; Schiro & Neelin, 2019), and the tributaries closer to the Atlantic coast, including the lower Amazon, the Tapajós and the UHE Balbina, have a smaller time delay due to inland propagation (Burleyson et al., 2016). This signal of coastal squall lines is absent in nearly all tributaries further away perhaps because the arrivals of these systems are more or less in phase with daytime heating (Burleyson et al., 2016).

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 2c, a typical cloud case on November 6, 2006 is plotted using the CloudSat CWC product (Figure 5). This case shows 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 (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; Dias et al., 2004; Lu et al., 2005). 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).

### 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). 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, 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 mostly from MCSs.

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

Except for the UHE Balbina and the lower Amazon, annual average rainfall anomalies of the other tributaries have a significant linear relationship with the climatological monthly average $\nabla^2$LST (Figure 6; -0.77±0.13 mm $hr^{-1}$ °$C^{-1}$ $km^2$; $r$ = -0.56, $p$ = 2.82e-7, $n$ = 72). A higher $\nabla^2$LST is associated with a stronger surface temperature gradient and consequently greater surface divergence over the river. Therefore, the negative slope in Figure 6 confirms more reduction of daytime precipitation 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), and their results suggest that the relationship could be even stronger when considering the boundary layer virtual temperature rather than surface temperature. Perhaps due to the size or the proximity to the Atlantic coast, the UHE Balbina and the lower Amazon do not follow this negative relationship well (Figure S5).

Despite the negative correlation with the surface temperature 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 is mentioned earlier, some tributaries like the Negro clearly shows 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 surface temperature 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 descrepancy may be small because modeled daytime or nighttime temperature is the average skin temperature over 12 hours centered at the satellite overpass (0200 and 1400 LT), while MODIS daytime or nighttime temperature is a composite average of Aqua swaths. MODIS surface temperatures in Amazonia also suffers the issue due to heavy cloudiness (Gomis-Cebolla et al., 2018). Additionally, the prescribed river temperature in WRF is cooler than MODIS during the day and warmer than MODIS during the night. As a result, the average surface temperature anomalies of the WRF river grid boxes relative to neighboring forest grid boxes 10 km away are exaggerated to -8.4 °C during the day and +6.6 °C at night. High values of modeled $\nabla^2$LST are also concentrated near the Amazon River (Figures 7c, d). 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 the lower Amazon. Despite the exaggerated surface temperature gradient near the river in the model results, the influence of surface temperature on convection and precipitation is expected to be qualitatively similar compared with observations.

The spatial distribution of surface energy fluxes corresponds with surface temperatures (Figure S7). During the daytime at 1400 LT, the cooler river has a sensible heat flux an order of magnitude lower than the rainforest. This difference in sensible heat flux is so strong that even some narrow tributaries, such as the upper part of the Tapajós, can be visually seen from Figure S7a. 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 both 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/m$^2$ 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 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 the unrealistically high nighttime rainfall in the southwest corner of the domain (Figures 8c and 8d). Daytime rainfall is substantially suppressed over the river in our simulation (Figure 8c), and the majority of this precipitation anomaly is attributed to convective rainfall rather than large-scale rainfall (Figure 8e). 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 8d).

Compared with the observations in Figure 2c, a zone of relatively higher nighttime rainfall extending northwards from the lower Amazon is successfully captured in our simulation (Figures 8c and 8d). As is discussed 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. A westward propagation of this high-rainfall zone from day to night can also be seen in Figure 8, 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 measurements.

### 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 9).

Here all the daytime rain events are categorized based on the total rainfall over the 12-hour 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 hr) over the river, the model simulation indicates moisture divergence near the surface and moisture convergence above up to approximately 750 mb (Figure 9a). 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 hr, 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 9b). When the rainfall exeeds 5 mm / 12 hr, 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.

The moisture convergence profiles for daytime rain events are then decomposed using the equation described in Section 2.3.2 (Figure 10). The moisture advection component ($\vec{u} \cdot \nabla_h q$) is insensitive to the amount of precipitation, and most changes in Figure 9 are contributed by the mass convergence component ($q\nabla_h \cdot \vec{u}$). 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 10a). The separate convergence and divergence layers are results of the separate 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 and reaches its peak near the boundary layer top, where is contributes to nearly half of the total moisture convergence. The shape of the wind convergence profile is associated with the river breeze circulation, the surface temperature gradient and subsidence in the lower troposphere over the cool river surface (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 10b). 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.

### 4.3 Role of shallow convection

The “shallow convection moisture pumping” mechanism is not explicitly supported in our model results, where shallow convection ahead of strong afternoon rainfall does not lead to more atmospheric moistening locally (Figure 11). Both the river and the surrounding forest show similar comparisons between the humidity changes in SC cases and in NC cases. The vertical profiles of specific humidity changes are characterized by an increase near the surface and a decrease above. However, for NC cases, the increasing specific humidity can be found util 800 mb, and the humidity decrease above is relatively small. The peak increase occurs around 900 mb, and is higher above the river than above the forest. By contrast, the humidity increase when there is shallow convection is limited below 900 mb and is small. The moisture divergence above reaches its peak near 800 mb and extends upwards until 500 mb. Particularly for the river, the preexisting shallow convection does not contribute to any significantly higher values across the troposphere. Despite a much lower humidity increase near the surface, the shallow convection above the forest reduce the humidity decrease above 700 mb, which may be favorable for deep convection to some extent when considering the lateral entrainment along the convecting path. To test the sensitivity of our results, we have also tried 10-mm precipitation as the threshold to select strong rainfall cases, and the result is very similar (Figure S10). Nevertheless, our results cannot exclude the possibility that shallow convection in earlier days or at locations nearby could contribute to a moistened atmosphere.

## 5 Synthesis and conclusions

Precipitating convection over the Amazon River and the surrounding forest is compared in this study. 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 surface temperatures, which suppress daytime convection over the river, interact with nighttime convection near the coast, and cause the double-layer moisture convergence/divergence structure.

Satellite-based analyses show rainfall reduction during the daytime across the domain and throughout the year, and substantial reduction only occurs in the afternoon in most tributaries when surface-induced convection is expected to reach its peak (Zipser et al., 2006). This reduction is particularly important during the dry-to-wet transition season, 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 significant linear relationship with the Laplacian of surface temperature. All 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 $\nabla^2$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). 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 show that moisture convergence before daytime rain above the surface is predominantly contributed by wind convergence as well as the humidity gradient near the boundary top. By contrast, the surrounding forest not far away gathers moisture primarily through convergence within the boundary layer or a little above, as is known from previous studies (Schiro & Neelin, 2019; Wu & Lee, 2019).

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 the interpretation of the GoAmazon datasets.

**Acknowledgments and Data**

Data is available through Amatulli et al. (2018), Austin et al. (2009) at http://www.cloudsat.cira.colostate.edu/data-products/level-2b/2b-cwc-ro/ (version P1_R05), Carroll et al. (2017), Joyce et al. (2004) at http://www.ftpstatus.com/dir_properties.php?sname=ftp.cpc.ncep.noaa.gov&did=8/, Mayorga et al. (2012), Saha et al. (2010), Wan et al. (2015) and Wu et al. (2020).

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**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.

**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.

**Figure 3**. Diurnal and seasonal cycle of the river precipitation anomalies relative to the forest. (**a**) Absolute anomalies of the entire river. (**b**) Percentage anomalies of the entire river. (**c**) Percentage anomalies of the Negro. (**d**) 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 (**c**) and (**d**) have the same color bar.

**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 UHE Balbina.

**Figure 5**. Afternoon CloudSat profiles (color contours) and average surface temperatures 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).

**Figure 6**. Linear relationship between the daytime river rainfall percentage anomalies and the Laplacian of surface temperature. Climatological monthly means of six selected tributaries are

plotted ($n$ = 72). The best linear fit derived from the ordinary least squares approach and its 99% confidence interval are also shown.

**Figure 7**. WRF 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) $\nabla^2$LST. (**d**) Nighttime (0200 LT) $\nabla^2$LST.

**Figure 8**. WRF 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.

**Figure 9**. 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 ($n$ = 1000). The horizontal lines and the grey shading indicate the mean planetary boundary top and its standard deviation.

**Figure 10**. 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 ($n$ = 1000). The horizontal lines and the grey shading indicate the mean planetary boundary top and its standard deviation.

**Figure 11**. Changes in atmospheric humidity three hours ahead of strong afternoon rainfall (> 5 mm / 3 hr). Cases are categorized into shallow convection (SC) or no convection (NC) before the rainfall occurs based on the maximum cloud fraction between 850 mb and 700 mb. Standard deviations are computed from bootstrap samples ($n$ = 1000).

**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 |