Observed Impacts of Aerosol Regimes on Energy and Carbon Fluxes in the Amazon Forest

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Abstract. Atmospheric aerosols play a crucial role in modulating the energy available to the Earth's surface, influencing the hydrological cycle, ecosystems, and climate. In the Amazon, previous studies have mainly examined how aerosols scatter and absorb radiation. However, little is known about their interactions with energy partitioning (i.e., sensible and latent heat fluxes). Here, we investigate how regimes of high ($AOD > 0.40$) and low ($AOD < 0.13$) aerosol optical depth (AOD) affect surface energy and carbon dioxide ($\mathrm{CO_2}$) fluxes in an undisturbed Amazon rainforest. For this, we used long-term meteorological measurements from the Amazon Tall Tower Observatory (ATTO) collected between 2016 and 2022. We find that enhanced aerosol presence reduces both sensible heat flux and energy available for evapotranspiration by approximately 13.5% and 2.1% respectively, while increasing $\mathrm{CO_2}$ uptake (i.e., $\mathrm{CO_2}$ flux becoming more negative) by about 39.5%. The impact of aerosols on turbulent surface fluxes is reflected in a cooling of approximately 0.9 °C at the canopy top, caused by a 2.8% reduction in incoming shortwave radiation. These results demonstrate that aerosols modify turbulent energy exchange, with consequences for the forest microclimate and the coupled carbon and water cycles.

1 Introduction

Atmospheric aerosols, which are defined as solid or liquid particles suspended in the air (Seinfeld and Pandis, 2006), play a multifaceted role in the Earth system. They influence the atmospheric cycle (Lohmann and Feichter, 2005; Rap et al., 2013; Gavrouzou et al., 2023), the hydrological cycle (Miller et al., 2004; Lau et al., 2005; Suzuki et al., 2017), and ecosystem processes (Kanakidou et al., 2018; Artaxo et al., 2022; Karthick Raja Namasivayam et al., 2024).

In the atmosphere, aerosols interact directly with solar radiation through scattering and absorption processes. These interactions influence the Earth's energy balance and, consequently, the climate (Liu et al., 2020). Aerosols also act indirectly by interacting with clouds, acting as cloud condensation nuclei. This interaction alters the albedo, formation, microphysics, and lifetime of clouds, thereby impacting global climate patterns (Andreae et al., 2004; Eltbaakh et al., 2012; Wang and Yi, 2024).

In the hydrological cycle, aerosols reduce the intensity of precipitation through complex, partially nonlinear processes that involve suppression of convection through mechanisms of aerosol-radiation interaction that stabilize the atmosphere, particularly at levels of aerosol optical depth (AOD) greater than 0.40 (Herbert and Stier, 2023). This results in a greater number of cloud droplets with a radius of less than 14 μm forming, which are insufficient for precipitation (Ramanathan et al., 2001; Gonçalves et al., 2015). In addition, they influence downdrafts, which alter the concentration of gases near the surface (D'Oliveira et al., 2022). Aerosols also reduce global evapotranspiration, which has a more significant impact on tropical forests (Palácios et al., 2024).

In forest ecosystems, high concentrations of aerosols can increase the intensity of diffuse radiation, which positively impacts photosynthetic rates (Li et al., 2025). This phenomenon, known as diffuse fertilization, mainly benefits shaded areas, allowing them to carry out photosynthesis more efficiently (Kanniah et al., 2012).

The Amazon region, home to the world's largest tropical rainforest, has been the site of significant research on the intricate relationship between aerosols, the biosphere, the atmosphere, and human activities. Since the 1980s, several scientific projects have been conducted in the region to better understand these interactions (Orsini et al., 1896; Artaxo and Orsini, 1987; Harriss et al., 1988; Avissar et al., 2002). Other studies have deepened our knowledge of the formation, transformation and impact of aerosols, particularly on clouds and precipitation (Yokelson et al., 2007; Martin et al., 2010; Brito et al., 2014; Machado et al., 2014; Martin et al., 2017; Machado et al., 2021; Franco et al., 2022). The Amazon Tall Tower Observatory (ATTO) project has recently played an instrumental role in monitoring long-term changes and in understanding the role of aerosols in global climate and the Amazon ecosystem (Andreae et al., 2015; Cecchini et al., 2025).

Aerosols in the Amazon are mainly composed of organic carbon, accounting for more than 80% of their mass (Artaxo et al., 2022). This proportion varies seasonally and can exceed 90% during the burning seasons. During the wet season, aerosol concentrations are low and similar to those of concentrations above the ocean (Pöhlker et al., 2018). However, in the dry season, fires drastically increase the aerosol load, which affects cloud formation and precipitation. These particles also alter the radiative balance, significantly affecting carbon absorption by the forest (Rodrigues et al., 2024). Changes in land use and an increase in fires not only lead to higher levels of pollution, but also reduce rainfall efficiency and modify the regional climate. This creates a positive feedback that can result in two different climatic states: one humid and sparsely Polluted and the other dry and highly Polluted (Andreae et al., 2004; Pöhlker et al., 2019).

Despite advances in understanding aerosol-biosphere-atmosphere interactions in the Amazon, the impact of these particles on energy and radiation partitioning and CO_2 fluxes is still unclear. Using numerical simulations for the Amazon basin, Braghiere et al. (2020) showed that there are considerable uncertainties about the influence of aerosols on the surface energy balance. Their simulations also revealed that, in a scenario without aerosols (AOD = 0), the sensible and latent heat fluxes were higher than those measured experimentally, resulting in higher surface temperatures. Furthermore, recent studies, such as those by Blichner et al. (2024), reveal that numerical models still fail to accurately portray the interaction between aerosols and thermal effects in the Amazon. This is mainly due to the models' inability to adequately capture the relationship between temperature and organic aerosol concentrations.

The aim of this study was to evaluate the influence of aerosols on energy and carbon fluxes, at the forest-atmosphere interface in an undisturbed region of the Amazon. Using in situ measurements, the study analyzed the period between 2016 and 2022, contributing to our understanding of processes involving the interaction between atmospheric aerosols and the energy balance in an area of pristine Amazon forest. To date, we are unaware of any studies that have used a long-term, purely observational approach to examine the relationship between aerosols and energy partitioning directly from surface-based measurements in the Amazon.

2 Material and Methods

2.1 Experimental site

The data used in this study were collected as part of the ATTO project, a bilateral initiative between Brazil and Germany. Since 2012, ATTO has carried out continuous measurements, as described by Andreae et al. (2015), located in an area of pristine tropical forests in the central Amazon (Figure 1), which contains the Instant Tower of 81 meters (-2.1441° S, -58.9999° W).

The Instant tower is located 150 km from the city of Manaus in the state of Amazonas, Brazil, at an altitude of 120 meters above sea level on a plateau covered by terra firme forests with an average crown height of 40 meters (Gomes Alves et al., 2023). In this landscape, wind speeds are relatively low, around 1 ms^{-1} immediately above the forest canopy, and above the canopy, the wind speed increases logarithmically with height (Santana et al., 2016). The main wind direction at the site is from the NE – E. It passes through areas of minimal anthropogenic influence in the northeast, a Clean fetch region covered by tropical forests (Pöhlker et al., 2019).

The climate is tropical humid and characterized by two seasons (wet and dry), driven by seasonal shifts of the Intertropical Convergence Zone over the Amazon Basin (Andreae et al., 2015). The wet season is characterized by more than 200 mm of rainfall per month and an average temperature of around 25 °C at the forest-atmosphere interface. In contrast, the dry season sees less than 100 mm of rainfall per month and an average temperature of around 27.7 °C (Schmitt et al., 2023).

2.2 Experimental data

The dataset used in this study was measured at the ATTO site from 2016 to 2022 (see Table 1). Wind speed, sensible heat flux (H), latent heat flux (LE), and carbon dioxide flux (FCO_2) data were calculated as 30-minute averages using EddyPro® software (LI-COR), as derived from fast-response sonic anemometers, according to Fratini and Mauder (2014). The other variables (radiation, thermodynamics and aerosols) were obtained as 30-minute averages, including net radiation (R_n) and its radiative components: incoming and outgoing shortwave radiation ($\mathrm{SW_{in}}$ and $\mathrm{SW_{out}}$), and atmospheric and terrestrial longwave radiation ($\mathrm{LW_{atm}}$ and $\mathrm{LW_{terr}}$), respectively. Additionally, diffuse shortwave radiation ($\mathrm{SW_d}$) was measured using a

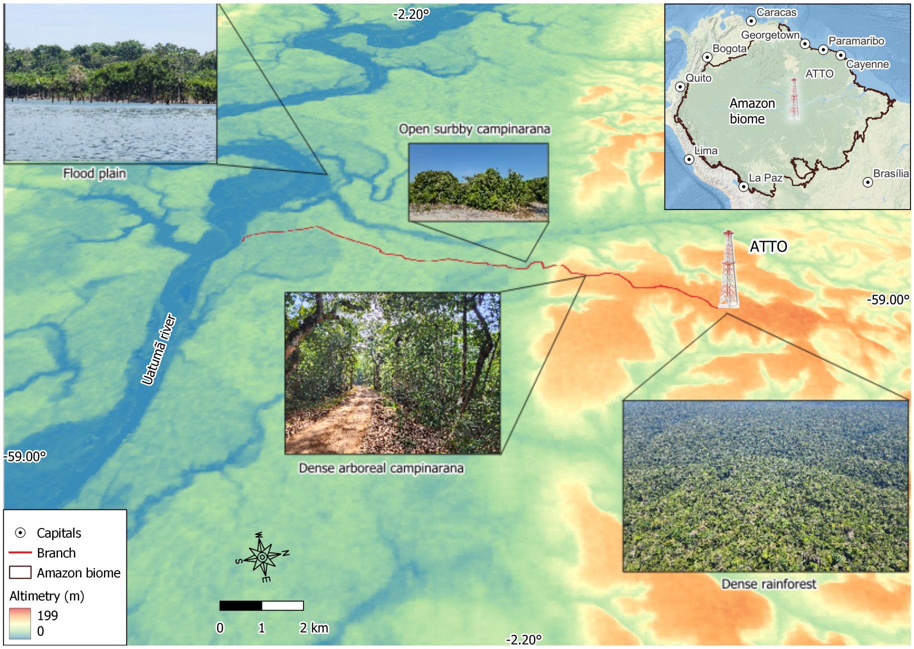

Figure 1. Amazon Tall Tower Observatory (ATTO) in central Amazonia, which has different landscapes along the topographic gradient, including floodplains, shrubby campinarana, dense arboreal campinarana, and dense ombrophilous forests. It is close to the Uatumã River, which runs in an NW-SE direction and is a tributary of the left bank of the Amazon River. Altimetry data by NASA JPL (2020) and vetorial data by RAISG (2023).

SPN1 Pyranometer (Delta-T Devices) installed at 75 m above ground level. However, $\mathrm{SW_d}$ data were available only for 2021, prior to this year, $\mathrm{SW_d}$ was not measured at the ATTO site, and data from 2022 were excluded due to technical issues with the sensor.

Based on Andreae et al. (2015) and Pöhlker et al. (2016), these data were organized by seasonality into four periods: (i) the wet season (February to May), which has a cleaner atmosphere, (ii) the wet-dry transition (June to July), (iii) the dry season (August to November), which has higher levels of pollution, and (iv) the dry-wet transition (December to January).

To eliminate cloud interference and investigate the role of aerosols in surface energy fluxes, the central objective of this study, we used data from the Aerosol Robotic Network (AERONET) at the ATTO site, specifically AOD (version 3, level 2). These data are free of cloud contamination due to pre and post-field calibration (Giles et al., 2019). Based on this, 30-minute averages were calculated between 2016 and 2022 for which AOD data from AERONET were available, the initial combined dataset comprised 10,890 observations, including all variables listed in Table 1. This matched dataset served as the starting point for the subsequent quality control and filtering procedures. First, the turbulent fluxes underwent quality control following Foken et al. (2004), who defined that only data with flags "0" (best quality) and "1" (acceptable for general analysis) should be used; data with flag "2" (poor quality) were discarded. Second, this study only considered the daytime period (from 07:00 to

Table 1. Variables and the methods used to obtain them.(*) Calculations according to Bolton (1980).

Type of Variable	Variable	Unit	Hight(m)	Method of production	Data sampling rate
Radiation	Short Wave Radiation (SW)	$\mathrm{W\,m^{-2}}$	75	Kipp&Zonen CMP21	1 min
	Long Wave Radiation (LW)	$\mathrm{W\,m^{-2}}$	75	Kipp&Zonen CGR4	1 min
	Net Radiation (R_n)	$\mathrm{W\,m^{-2}}$	75	Kipp & Zonen NR-LITE2	1 min
Thermodynamics	Air temperature (T)	°C	80	GALLTEC-MELA IAK I-Series	1 min
	Infrared surface temperature	°C	35	Campbell Scientific TIR radiometer (IR120)	1 min
	Relative humidity (RH)	%	80	GALLTEC MELA IAK I-Series	1 min
	Air Pressure (Patm)	hPa	80	YOUNG 61302V	1 min
	Wind speed	$\mathrm{m\,s^{-1}}$	80	CSAT3B & THIES 4.3830	1 min
	Vapor pressure deficit (VPD)	hPa	-	Calculation*	1 min
	Mixing ratio (r)	$\mathrm{g\ of\ vapor/kg\ of\ dry\ air}$	-	Calculation*	1 min
	Soil temperature (Ts)	°C	0.1	Campbell Thermistor 108	10 min
	Soil moisture (h)	$\mathrm{m^3\,m^{-3}}$	0.1	Campbell CS615	10 min
Flux	Sensible Heat (H)	$\mathrm{W\,m^{-2}}$	80	CSAT3B/LI-7200RS	10 Hz
	Latent Heat (LE)	$\mathrm{W\,m^{-2}}$	80	CSAT3B/LI-7200RS	10 Hz
	Carbon dioxide (FCO_2)	$\mathrm{\mu mol\,m^{-2}\,s^{-1}}$	80	CSAT3B/LI-7200RS	10 Hz
	Ground heat (G)	$\mathrm{W\,m^{-2}}$	0.05	Hukseflux HFP01	10 min
Aerosols	Aerosol Optical Depth 500 nm (AOD)	-	80	CIMEL Sun Photometer CE318-T	Variable rate

17:00 LT) because the highest R_n values occur during this time. After filtering, the resulting dataset is summarized in Table S1 and S2.

Using the values for humidity and temperature (variables shown in Table 1), it was possible to calculate the vapor pressure deficit (VPD) using Equations 1 to 3 according to Bolton (1980).

$$VPD = e_s - e_a \tag{1}$$

The water vapor saturation pressure (e_s) as a function of temperature (T) was calculated according to the equation Tetens (1930).

$$e_s(T) = 6.112 exp(\frac{17.67 \cdot T}{T + 243.5}) \tag{2}$$

The actual vapor pressure (e_a) was obtained by relating it to the relative humidity (RH).

$$e_a = RH \cdot e_s \tag{3}$$

2.3 Analysis methods

Daily averages of AOD values were obtained to investigate seasonal variability. Our analysis distinguishes two contrasting atmospheric conditions at the ATTO site, defined as “Clean” and “Polluted” using AOD thresholds derived from the dry-season distribution of AOD. The Clean and Polluted regimes correspond to the 10th ($AOD \leq$ 0.13) and 90th ($AOD \geq$ 0.40) percentiles, respectively. Further details on the seasonal aerosol analysis are provided in Section 3.1 and Table S3. Subsequently, 30-min AOD averages between 07:00 and 17:00 LT were computed to ensure temporal consistency with the surface flux data and enable direct comparisons. To improve the visualization of the mean diurnal patterns, a 4th-order polynomial curve was applied exclusively as a smoothing technique to the observational data. This curve fitting was used solely for graphical purposes and does not represent a physical or predictive model. All analyses were based on the measured data. For comparisons between Clean and Polluted regimes, only the interval from 10:00 to 14:00 local time was considered, as this period corresponds to the maximum net radiation at the study site and minimizes the influence of low solar elevation angles.

Statistical differences in meteorological variables and surface fluxes between the Clean and Polluted regimes were assessed using the Mann-Whitney U test. This non-parametric approach was selected because the observational data violated the assumption of normality, as confirmed by preliminary Shapiro-Wilk tests. The Mann-Whitney U test was used to determine whether the median values of the two independent regimes differed significantly ($p < 0.05$), offering a robust framework for analyzing non-normally distributed atmospheric data (Wilks, 2011).

3 Results and Discussion

3.1 Characteristics of seasonal aerosol variation

The distribution of atmospheric aerosols, expressed as AOD, exhibits a clear seasonal cycle at the ATTO site (Figure 2). The lowest values occur during the wet season, with an average of 0.07 in April, while the dry season is marked by higher AOD values, reaching an average of 0.28 in September. Furthermore, this seasonal variation in AOD values has previously been observed at other sites in the Amazon region (Artaxo et al., 2013; Cirino et al., 2014; Morais et al., 2022; Palácios et al., 2022). Cirino et al. (2014), for example, used data measured at the ZF2 site, located 60 km northwest of Manaus in central Amazonia, to show that AOD values were close to 0.4 (with peaks above 0.5) in the dry season and less than 0.2 in the wet season. Attention is drawn to the AOD values observed in the southern region of the Amazon basin, which is influenced by the arc of deforestation, an agricultural frontier zone with intense burning activity during the dry season (Davidson et al., 2012). Several studies in this region have shown that AOD values often exceed 4 in the dry season, whereas in the wet season they rarely exceed 0.2 (Fuzzi et al., 2007; Artaxo et al., 2013; Palácios et al., 2024).

The main distinction between the AOD values measured at the ATTO site and those measured in the southern Amazon is the magnitude of these values. In particular, the AOD values at the ATTO site are approximately 15 times lower than those in the region close to the arc of deforestation during the dry season (Sena et al., 2013; Palácios et al., 2020). Pöhlker et al. (2018) and Holanda et al. (2023) for example, investigated the seasonal contrast of aerosols at the ATTO site, highlighting that parts of the wet season resemble preindustrial conditions with minimal human impact.

Figure 3 shows the average daily AOD values for the dry and wet seasons, from 2016 to 2022. It is clear to see that the highest average AOD values were obtained during the dry season, with values reaching 1.5, while in the wet season these values did not exceed 0.5, a result similar to that already reported in Figure 2. It should also be noted that during the dry season, the 90th and 10th percentiles of the AOD values are 0.40 and 0.13, respectively. During the wet season, these percentiles were 0.13 and 0.04, respectively. In other words, the AOD values above the 90th percentile in the wet season are slightly higher than the values observed for the 10th percentile in the dry season. This reinforces what was already mentioned in Figure 2, that the

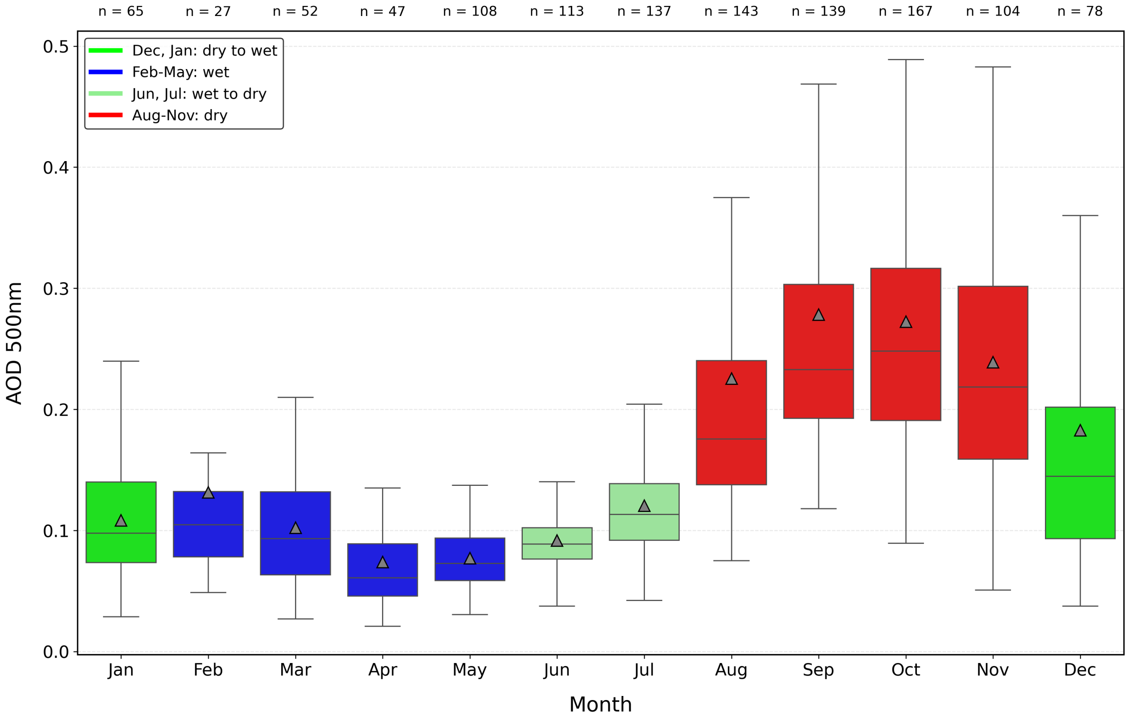

Figure 2. Box plot showing monthly AOD 500 nm values measured at the ATTO site between 2016 and 2022. The box represents the central 50 % of the data, the whiskers represent the smallest and largest non-outlier values, while the means are indicated by the green triangles and the medians are the lines inside the box. Numbers above each month indicate the sample size (n).

wet season in the ATTO region is quite ’Clean’ compared to the dry season. As the main goal of this work is to investigate the impact of aerosols on surface turbulent fluxes, the analysis focuses on data from the dry season. In addition, during the dry season there is more aerosol data since the could interference is much less pronounced than during the wet season. Two aerosol regimes were defined based on percentile thresholds of the dry-season AOD distribution. Several percentile combinations were tested to assess the robustness of the regime separation. Based on this analysis, the 10^{th} and 90^{th} percentiles were selected to define the Clean ($AOD \leq 0.13$) and Polluted ($AOD \geq 0.40$) regimes, respectively, as they preserve physically meaningful differences between aerosol regimes (See Table S1).

3.2 Relationship between AOD and surface turbulent fluxes

As described in Section 2.3, the comparisons between Clean and Polluted regimes were restricted to the 10:00–14:00 LT period, corresponding to the maximum net radiation. The full diurnal cycles of shortwave, longwave, and net radiation during the dry season (2016–2022) show that the maximum values occur between 10:00 and 14:00 LT (Figure 4), supporting the choice of this time window for the subsequent analyses. The average values of the radiation balance components during this period are summarized in Table 2. The negative sign in the difference between the Polluted and Clean regimes indicates that the radiative

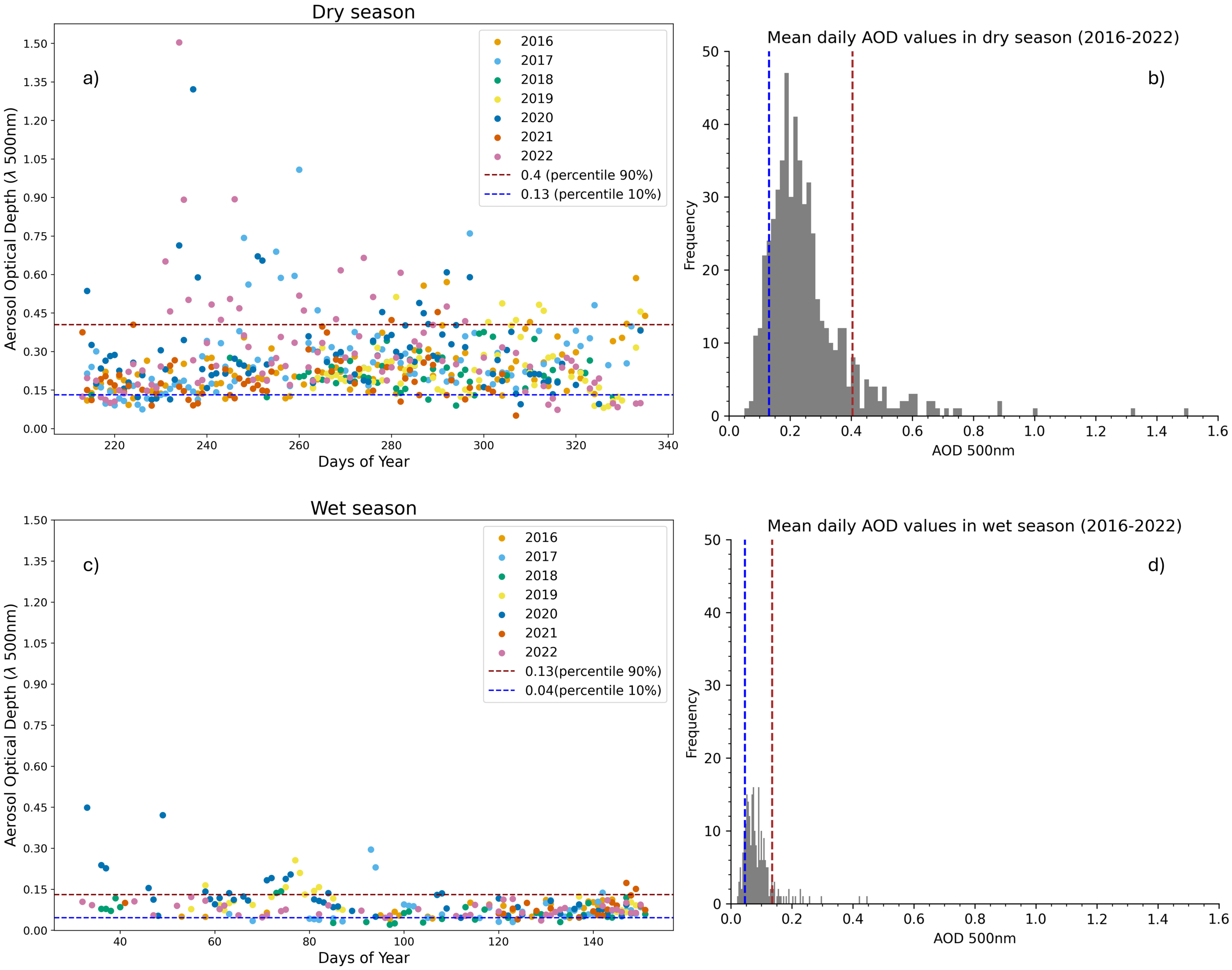

Figure 3. (a) and (c) Daily AOD averages (500 nm), (b) and (d) their respective histograms. Values above the red line indicate high aerosol concentration (above the 90$^{\text{th}}$ percentile), while values below the blue line indicate low aerosol concentration (below the 10$^{\text{th}}$ percentile).

components decrease during this period. The R_{n} fell the most in relative terms, by around -4%. Outgoing shortwave radiation (SW_{out}) showed a non-significant increase of 3.3% (p = 0.07). As is well known, the longwave balance is always negative during the daytime in the Amazon region (von Randow et al., 2004) since LW_{terr} is greater than LW_{atm}. However, pollution reduced the difference between LW_{atm} and LW_{terr} by around 2 Wm^{-2} compared to the Clean regime, indicating a slightly less radiative surface and a slightly warmer atmosphere.

Quantifying the impact of aerosols on radiative flux remains a significant challenge in climate system studies, with persistent uncertainties (Palácios et al., 2022). However, the relationship between aerosols and radiative flux has been investigated for decades in the Amazon region (Ross et al., 1998; Procopio et al., 2004; Rizzo et al., 2011; Artaxo et al., 2013; Palácios et al., 2022). There is a consensus in the literature that an increase in AOD reduces SW_{in}, which consequently also causes

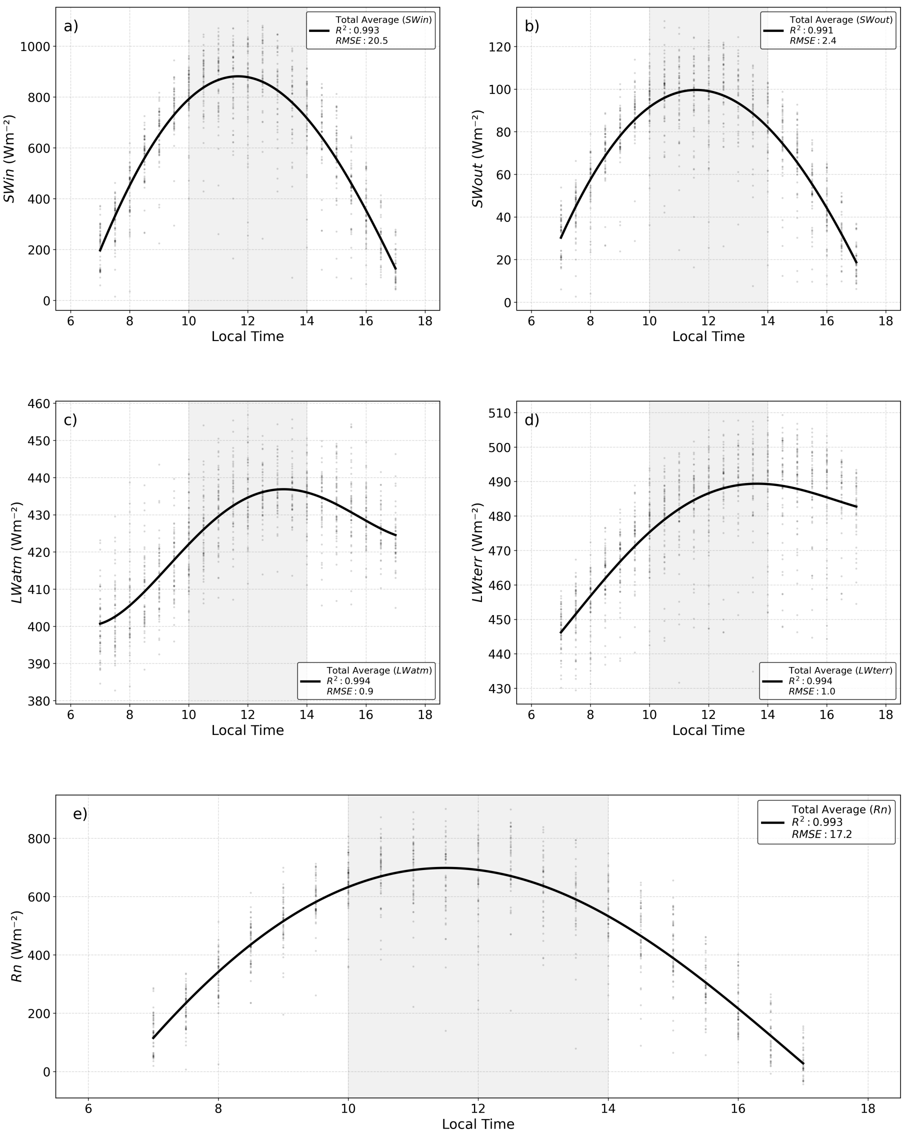

Figure 4. Diurnal cycles of radiative fluxes during the dry season from 2016 to 2022: (a) incoming ($\mathrm{SW_{in}}$) and (b) outgoing ($\mathrm{SW_{out}}$) shortwave radiation, (c) incoming atmospheric ($\mathrm{LW_{atm}}$) and (d) outgoing terrestrial ($\mathrm{LW_{terr}}$) longwave radiation, and (e) net radiation (R_n). Markers indicate observed data, and solid lines represent fourth-order polynomial fits, with the corresponding R^2 and RMSE

a reduction in R_n. However, the magnitude of these reductions varies considerably. Studies carried out during the dry season in the Amazon rainforest using different methods to estimate direct aerosol radiative forcing (ARF) illustrate this variability. For example, Ross et al. (1998) reported an average daily ARF of -20 ± 7 $\mathrm{Wm^{-2}}$ per unit of AOD at 550 nm in the Amazon rainforest. Consistent with these findings, Palácios et al. (2022) estimated an average ARF of -20.77 ± 5.04 $\mathrm{Wm^{-2}}$ for the dry season in the central Amazon. Procopio et al. (2004) found daily ARF values ranging from -21 to -74 $\mathrm{Wm^{-2}}$ in the

Table 2. Averages of the radiation components in the period from 10:00 to 14:00 LT, during the dry season from 2016 to 2022, with the respective relative difference between the Polluted and Clean regimes.

Means of radiation variables			
Variables	Polluted	Clean	Relative Difference
SWin ($\mathrm{W\,m^{-2}}$)	813.5 ±124.4	836.5 ±165.2	-2.8
SWout ($\mathrm{W\,m^{-2}}$)	95.9 ±15.1	92.8 ±19.7	3.3
LWatm ($\mathrm{W\,m^{-2}}$)	432.1 ±9.4	431.5 ±10.4	0.1
LWterr ($\mathrm{W\,m^{-2}}$)	483.6 ±10.8	484.7 ±14.0	-0.2
R_n($\mathrm{W\,m^{-2}}$)	632.8 ±100.8	659.3 ±137.8	-4.0

deforestation arc, an area with higher levels of pollution than the central Amazon. Rizzo et al. (2011) investigated this central region and reported a daily ARF value of -32 $\mathrm{Wm^{-2}}$.

Although these studies provide estimates of the reduction in surface radiation from aerosols in the Amazon, they do not converge on a single consensus value. This is because, in addition to the different methodologies used to obtain ARF values, Procopio et al. (2004), Sena et al. (2013) and Palácios et al. (2020, 2022) point out that uncertainties lie mainly in the complex interactions between types and concentrations of aerosols, surface characteristics, atmospheric conditions, and solar angle.

SW_{out} is directly related to surface albedo and the fact that it did not change significantly in our data between regimes (maintaining albedo at ~ 0.11) indicates that pollution has a secondary effect compared to the characteristics of the surface itself. There is a wide range of surface characteristics in the Amazon that directly influence albedo, as observed by von Randow et al. (2004) and Pareja-Quispe et al. (2021): i) degree of vegetation cover; ii) soil and vegetation water conditions; iii) solar elevation; iv) cloud cover and; v) wind speed and direction.

However, the behavior of longwave radiation was quite interesting. It shows that because of their interaction with the incident shortwaves, aerosols increase the emission of thermal energy toward the surface. At the same time, they act as a barrier to the total energy reaching the surface, thus impacting the amount of thermal energy emitted by the surface itself. The increase in LW_{atm} and the decrease in LW_{terr} in the Polluted regime result in a smaller longwave balance in this regime. de Menezes Neto et al. (2016) also observed this effect in their experiments involving biomass burning aerosols in South America: a subtle variation in longwave intensity attributed to the presence of aerosols.

With reduced solar energy input on the surface during the Polluted regime, cooling occurs at the forest-atmosphere interface, accompanied by a decrease in VPD compared to the Clean regime, as illustrated in Figure 5. The cooling between the 10:00 and 14:00 LT regimes implies an average reduction in canopy surface temperature of 0.9 °C, based on infrared surface temperature measurements, and a corresponding reduction in air temperature of 0.3 °C, resulting in a -2 hPa (13%) decrease in VPD.

As the curve for the Clean regime is consistently above that for the Polluted regime at all shown temperatures, it is suggested that the Clean regime will first achieve a reduction in evapotranspiration, given the approximately linear relationship between temperature and VPD.

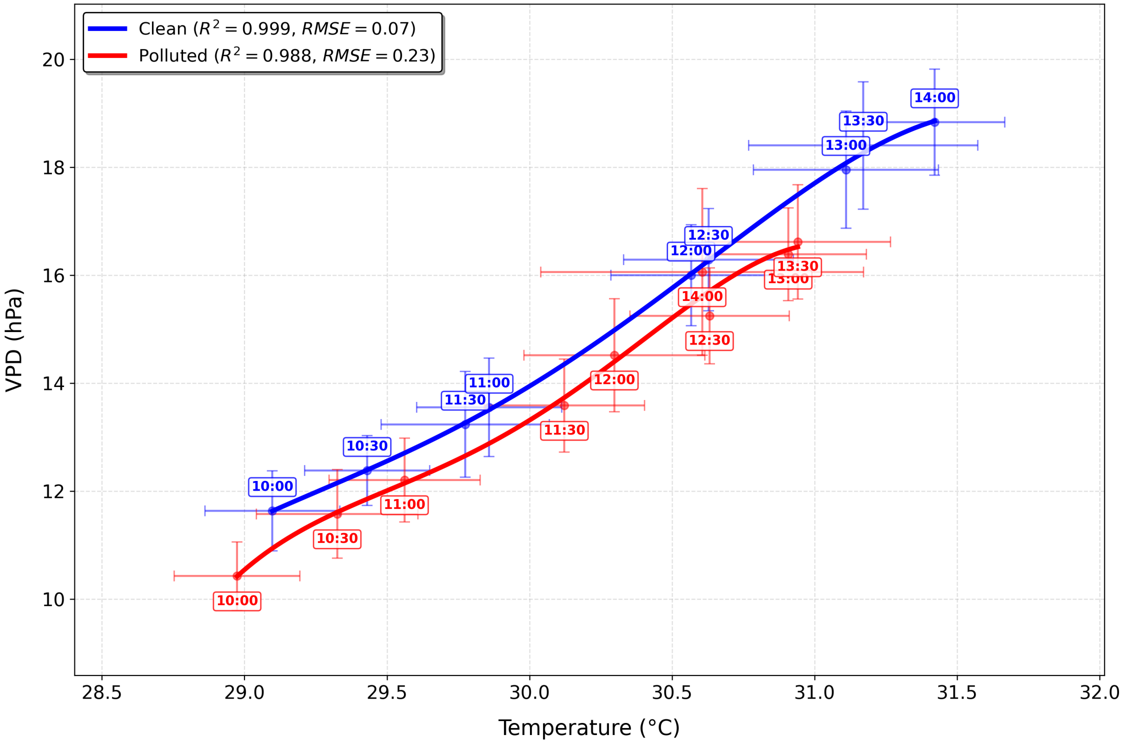

Figure 5. Relationship between temperature and vapor pressure deficit (VPD) above the forest canopy at the ATTO for Clean (blue) and Polluted (red) regimes during the dry season (2016-2022).

These cooling values are consistent with the effects documented in other studies. For example, Moreira et al. (2017) found a reduction in 1.2 °C above the Amazon region, while Cirino et al. (2014) identified a 1.8 °C and a decrease in 35% in VPD in the central Amazon. In the deforestation arc, Rodrigues et al. (2024) found an average cooling effect of between 3 °C and 4 °C, as well as reductions of between -2 and -3 hPa in VPD.

Braghiere et al. (2020) investigated temperature variations in the Amazon using a radiative transfer model. By simulating a scenario without aerosols (AOD = 0) and comparing it with real conditions, they observed an increase in temperature in the scenario without aerosols. They identified a correlation between relative irradiance, air temperature, and VPD. Meanwhile, Herbert and Stier (2023) and Palácios et al. (2024) reinforce the idea that AOD significantly influences temperature variations, particularly on a regional scale. For instance, Palácios et al. (2024) observed positive linear correlations between AOD and air temperature across distinct climatic phases, attributed to the absorption of solar radiation by biomass burning emissions resulting in atmospheric heating. Similarly, Herbert and Stier (2023) utilized reanalysis data to demonstrate that 2-meter air temperature increases as a function of AOD, consistent with localized heating of the smoke layer due to strong absorption of solar radiation.

Herbert and Stier (2023) and Palácios et al. (2024) also highlight that the physical characteristics of the aerosols present in the atmosphere, such as size, mixing state and presence of coatings, as well as the chemical characteristics, such as the ability to absorb or scatter light and hygroscopicity, determine their direct impact on temperature and VPD through radiative interaction, as well as their indirect impact by influencing cloud properties and evapotranspiration rates. These are essential components of the atmosphere's energy balance.

The interaction between aerosols, radiation, and evapotranspiration affects not only temperature and VPD, but also the fluxes of energy and matter on the surface. This has a direct impact on atmospheric and ecosystem processes. Figure 6 illustrates the impact of aerosols on these fluxes. It shows that for the Polluted regime, the values were lower than those observed during the Clean regime, especially during periods of high solar radiation, i.e. between 10:00 and 14:00 LT. The most significant reductions in the energy available to the surface occur during this period, with R_n falling by -4$\%$, as reflected in the energy partitions. The surface energy balance closure was 0.89 for the Clean regime and 0.88 for the Polluted regime, comparable to values reported in the literature (Mauder et al., 2024). The corresponding residuals were of similar magnitude (70 $\mathrm{Wm^{-2}}$ for Clean and 75 $\mathrm{Wm^{-2}}$ for Polluted), indicating that the observed differences in energy fluxes are not related to differences in energy balance closure.

Sensible heat decreased by an average of -21.7 $\mathrm{Wm^{-2}}$ (13.5$\%$), reflecting reduced energy transfer to the atmospheric boundary layer. Similarly, LE decreased by -8.9 $\mathrm{Wm^{-2}}$ (2$\%$), indicating limited evapotranspiration due to the reduced radiative energy available. The Bowen ratio, which relates H and LE, recorded 0.38 in the Clean regime and 0.33 in the Polluted regime, suggesting that a higher proportion of energy was allocated to latent processes, as expected in forest environments. The ground heat flux (G) also decreased by -1.0 $\mathrm{Wm^{-2}}$ (54.5$\%$), demonstrating its greater sensitivity to variations in R_n compared to turbulent fluxes.

In addition to their effect on energy fluxes, aerosols were found to have a significant influence on $\mathrm{CO_2}$ flux, becoming more negative by an average of 4.9 $\mu\mathrm{mol\,m^{-2}\,s^{-1}}$ (39.5%) in the Polluted regime compared to Clean conditions between 10:00 and 14:00 LT. This is when the difference between the Polluted and Clean regimes is most pronounced, indicating that the forest absorbs more $\mathrm{CO_2}$ in the Polluted regime (Figure 7). The reductions in H, LE, G, and FCO_2 shown in Figure 6 and Figure 7 were also observed across individual years (see Fig. S3).

In the Polluted regime, $\mathrm{CO_2}$ fluxes were more negative (Figure 7), indicating increased $\mathrm{CO_2}$ uptake by vegetation related to photosynthetic activity. Such enhanced photosynthesis may be linked to changes in stomatal regulation that allow greater $\mathrm{CO_2}$ uptake without a proportional increase in transpiration, reflecting higher stomatal conductance efficiency (Liu et al., 2022; Crous et al., 2025). However, analysis of the LE, which represents the fraction of available energy converted into evapotranspiration, shows a consistent decrease in the Polluted regime compared to the Clean regime (Figure 6).

The apparent paradox of an increase in $\mathrm{CO_2}$ absorption alongside a reduction in LE can be explained by water use efficiency (WUE). According to Dekker et al. (2016) and Yang et al. (2016), WUE is defined as the ratio of carbon assimilated to water transpired by vegetation. In this study, WUE was estimated using FCO_2/LE as a proxy. WUE was significantly higher under Polluted compared to Clean regime (mean values of 0.042 and 0.029, respectively, $p < 0.05$). This indicates that, under Polluted

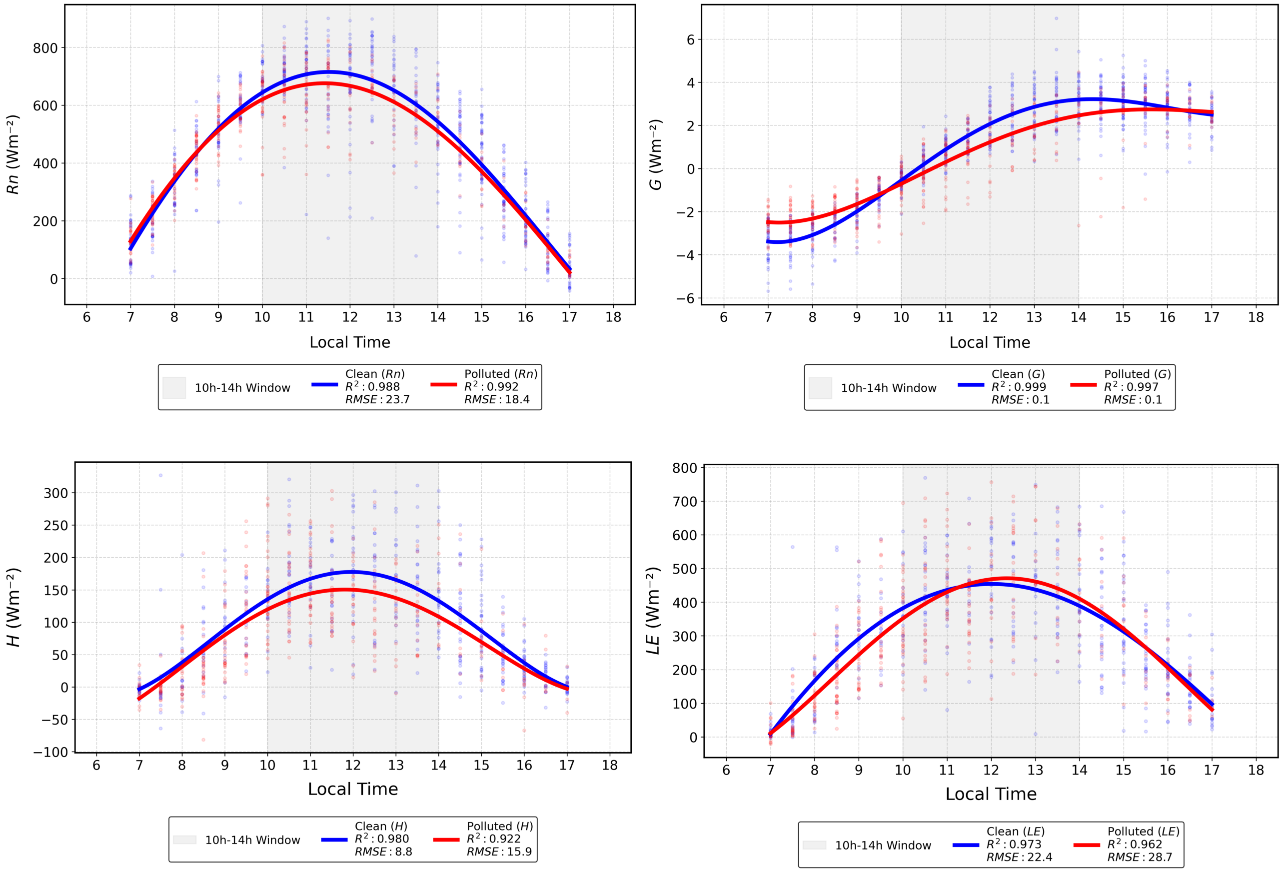

Figure 6. Diurnal cycle of surface fluxes during the dry season (2016-2022) under Clean (blue) and Polluted (red) regimes, highlighting the 10:00–14:00 LT period. R_n (net radiation), G (ground heat flux), H (sensible heat flux), and LE (latent heat flux).

regimes, vegetation assimilates more carbon per unit of water lost, consistent with the observed reduction in latent heat flux Figure 6 despite enhanced $\mathrm{CO_2}$ uptake Figure 7.

In forests in the USA, Steiner et al. (2013) conducted experiments to quantify the impact of aerosols on turbulent surface fluxes, observing reductions in H and LE ranging from 10% to 30%. Few studies have examined the relationship between H, LE and AOD in the Amazon region. Zhang et al. (2008), for example, used regional modeling with an AOD threshold of 0.3 to obtain a daily average reduction of -15 $\mathrm{Wm^{-2}}$ for H and -5 $\mathrm{Wm^{-2}}$ for LE. In the deforestation zone, Braghiere et al. (2020) observed a decrease of -67 $\mathrm{Wm^{-2}}$ (36%) for H and -4 $\mathrm{Wm^{-2}}$ (2%) for LE when simulating Clean conditions (AOD = 0) and comparing them with real conditions involving the presence of aerosols. These results suggest that regional climate models may underestimate the reduction in LE, highlighting the importance of biological processes, such as transpiration, in compensating for these effects.

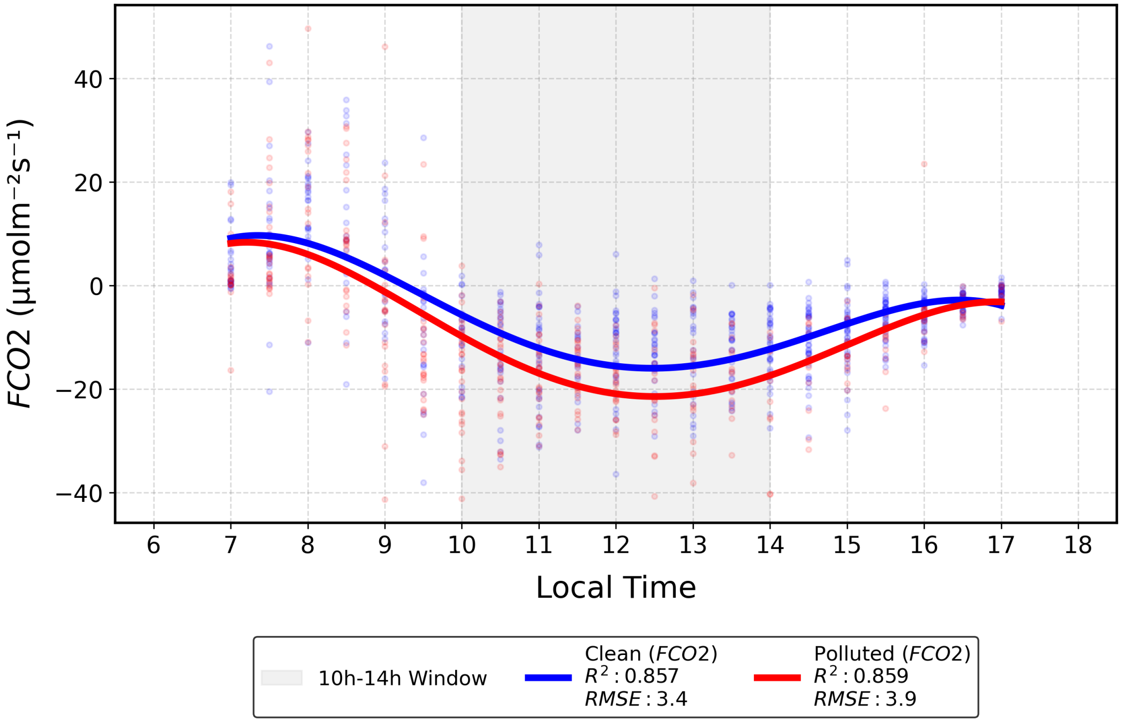

Figure 7. Diurnal cycle of CO_2 flux (FCO_2) during the dry season (2016–2022) under Clean (blue) and Polluted (red) regimes, highlighting the 10:00–14:00 LT period.

In contrast, numerous studies in the Amazon have demonstrated the significant impact of aerosols on CO_2 assimilation by forests. This occurs by increasing the diffuse fraction of photosynthetically active radiation reaching forest shade zones, thereby intensifying photosynthesis. Simultaneously, it reduces the net direct solar radiation reaching the canopy surface, thereby generating photosynthetic enhancement in this region (Doughty et al., 2010; Cirino et al., 2014; Rap et al., 2015; Moreira et al., 2017; Malavelle et al., 2019; Rodrigues et al., 2024). This diffuse fraction, which falls within the wavelengths of interest for vegetation (0.4 to 0.7 μm), can increase from around 19% (the typical value of a Clean atmosphere) to 80% under biomass burning conditions (Yamasoe et al., 2006).

We quantified the diffuse radiation fraction ($\mathrm{F_d} = \mathrm{SW_d}/\mathrm{SW_{in}}$) for the available period (2021) and compared $\mathrm{F_d}$ between Clean and Polluted aerosol regimes. Our results indicate higher $\mathrm{F_d}$ values under Polluted regime compared to Clean regime (Figure S1). Specifically for the 10:00 and 14:00 LT interval, the mean $\mathrm{F_d}$ values were 0.43 and 0.27 for Polluted and Clean regime, respectively, indicating an absolute difference of 0.16 between the two regimes ($p<0.05$). This is consistent with enhanced scattering of solar radiation associated with increased aerosol loading (Giorgi et al., 2002; Seinfeld and Pandis, 2016; Ezhova et al., 2018). Moreover, daytime CO_2 fluxes showed a non-linear dependence on $\mathrm{F_d}$, with net CO_2 uptake increasing up to an $\mathrm{F_d}$ threshold (≈ 0.6) and decreasing at higher $\mathrm{F_d}$ values (Figure S2). This behaviour was consistent with the response of net ecosystem exchange for diffuse radiation reported by Deng et al. (2022) for four forest sites in China and aligns with the global-scale mechanisms proposed by Mercado et al. (2009). These results provide observational support for the proposed mechanism linking aerosol loading, radiation partitioning, and ecosystem carbon exchange.

4 Conclusions

This study assessed, for the first time, the impact of aerosol regimes on the exchange of surface energy (net radiation - R_n, sensible heat - H and latent heat - LE) and mass (carbon dioxide flux - FCO_2) at the forest-atmosphere interface in the central Amazon, a region that experiences relatively pristine atmospheric conditions during part of the year. Based on long-term data collected between 2016 and 2022 at the ATTO site, our analysis provides clear and quantitative evidence that high aerosol loads (AOD > 0.40) reduced the magnitude of FCO_2, H, and LE fluxes compared to Clean conditions (AOD < 0.13).

During the peak radiation period (10:00-14:00 LT), the Polluted regime (AOD > 0.40) substantially reduces turbulent energy fluxes, decreasing H by 21.7 Wm^2 (13.5%) and LE by 8.9 Wm^2 (2.1%). Simultaneously, the forest's net CO_2 absorption increased, with FCO_2 decreasing by -4.9 $\mu mol\, m^{-2}\, s^{-1}$ (39.5%), indicating a significant increase in carbon assimilation. This biophysical response was accompanied by a cooling of the forest-atmosphere interface by 0.9°C and a reduction in the vapor pressure deficit (VPD) by 2.0 hPa (12.9%). Thus, aerosols also play an important role in modulating energy partitioning in the tropical forest ecosystem.

Our findings indicate that even in the relatively pristine central Amazon during the dry season, a threshold aerosol load (AOD 0.40) exists, above which significant impacts on energy fluxes occur. This suggests that in regions with higher aerosol loads, such as the southern Amazon's arc of deforestation, impacts on energy balance could be even more severe.

Our statistical analyses indicate that aerosols and surface turbulent fluxes interactions are predominantly indirect and non-linear, mediated by environmental variables like radiation, temperature, and humidity. Consequently, different inflection points likely exist across the Amazon, and the AOD threshold identified here cannot be applied to the entire region. Furthermore, isolating the aerosol effect from clouds requires rigorous filtering and a significant data collection effort, as cloud-free moments are scarce in long-term Amazonian time series.

Our work advances knowledge by quantifying the simultaneous effects of aerosol on energy and matter fluxes, bringing with it possibilities for improvements in climate models for the Amazon region and opening up the possibility of future work aimed at coupling the carbon and water cycles, mediated by aerosols, shedding light on the functioning of forest ecosystems. All of this is possible with the integrated analysis of diffuse radiation and the efficient use of water combined with the impact of aerosols on energy and matter fluxes.

In addition, future work involving remote sensing and data from micrometeorological towers throughout the Amazon is crucial in order to spatialize the results of all these dynamics between the forest-atmosphere interface, which is essential for quantifying the impact of aerosols on the Amazonian climate system.

Author contributions. Conceptualization: MABdR, CQDJ, JCPCand FAFDO. Data curation: CQDJ, ACdA, CP, SR and PA. Formal analysis: MABdR, CQDJ. Funding acquisition: CQDJ. Investigation: MABdR, CQDJ and FAFDO. Methodology: MABdR, CQDJ, FAFDO and RSP. Project administration: CAQ, CQDJ. Resources: CQDJ, ACdA, CP, SR and PA. Software: MABdR and FAFDO. Supervision: CQDJ and RSP. Validation: MABdR and FAFDO. Writing (original draft preparation): MABdR, CQDJ. Writing (review and editing): MABdR, CQDJ, JCPC, FAFDO, ACSM, CP, SR, ACdA, MAF, PA, CAQ, RSP.

Competing interests. The authors declare that they have no conflict of interest.

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