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Impacts of biomass burning smoke in clouds and rainfall in southern Brazil

Impacto dos aerossóis de fumaça das queimadas nas nuvens e chuva no Sul do Brasil

Fabiana Cruz de Araújo[1], *Renato Ramos da Silva*[1]

ABSTRACT

Biomass burning aerosols can spread over vast areas of South America. Recent findings indicate that the presence of these types of aerosols tend to affect cloud formation and rainfall. This research aimed to study the impacts of smoke aerosol emissions in southern Brazil, due to prolonged drought and dry events in the region. Initially, data on aerosol optical depth, precipitation, and clouds were collected to assess the influence of aerosols on the evolution of these meteorological processes. The data analysis focused on the study of the dry season in southern South America, which spans August, September, and October through the years of 2002 to 2022. Results obtained using the HYSPLIT model showed that black carbon transport during the study period originates from regions such as Paraguay, the Brazilian Midwest, and southern Amazonia. Monthly data analysis for the period of 2002 to 2022 revealed a negative Pearson correlation for August-September-October, respectively: -0.44, -0.35 and -0.37 between the aerosol optical depth (AOD) particles and precipitation; and -0.27, -0.39 and -0.22 between AOD and cloud formation. For Spearman correlations were obtained: -0.43, -0.29 and -0.21 between the aerosol optical depth (AOD) particles and precipitation; and -0.11, -0.26 and -0.23 between AOD and cloud formation. Although the results indicate a weak negative correlation, these results point to positive feedback where aerosols can negatively affect the formation of clouds and rain, causing dry periods with a greater probability of fires and smoke.

Keywords: aerosols; smoke; precipitation; clouds; biomass burning.

RESUMO

Aerossóis de queima de biomassa podem se espalhar por vastas áreas da América do Sul. Alguns resultados recentes mostram que a presença desses aerossóis tende a afetar a formação de nuvens e chuva. Esta pesquisa teve como objetivo estudar os impactos das emissões de aerossóis de fumaça na Região Sul do Brasil, em decorrência dos prolongados eventos de estiagem e seca ocorridos nesta região. Inicialmente, foram coletados dados de profundidade óptica de aerossóis, precipitação e nuvens para avaliar a influência dos aerossóis na evolução desses processos meteorológicos. A análise dos dados teve como foco o estudo do período seco na região sul da América do Sul, que compreendeu os meses de agosto, setembro e outubro dos anos de 2002 e 2022. Resultados obtidos com o auxílio do modelo HYSPLIT mostraram que o transporte de carbono negro no período estudado é proveniente de regiões como o Paraguai, o centro-oeste do Brasil e o sul da Amazônia. A análise dos resultados para dados mensais para o período entre 2002 e 2022 mostrou que há uma correlação de Pearson negativa de -0.44, -0.35 e -0.37 entre a profundidade óptica de aerossóis (AOD) e a precipitação; e de -0.27, -0.39 e -0.22 entre a AOD e a formação de nuvens. Foi também realizada a correlação de Spearman, por meio da qual foram obtidos os seguintes valores: -0.43, -0.29 e -0.21 entre a profundidade óptica de aerossol (AOD) e a precipitação; e -0.11, -0.26 e -0.23 entre a AOD e a formação de nuvens. Embora os resultados indiquem uma correlação negativa fraca, estes resultados apontam para uma retroalimentação positiva, em que os aerossóis podem afetar negativamente a formação de nuvens e chuva, provocando períodos de estiagem, com maior probabilidade de incêndios e fumaça.

Palavras-chave: aerossóis; fumaça; precipitação; nuvens; queima de biomassa.

[1]Universidade Federal de Santa Catarina – Florianópolis (SC), Brazil.

Corresponding author: Fabiana Cruz de Araújo – Universidade Federal de Santa Catarina, Departamento de Física – Campus Trindade – CEP: 88040-970 – Florianópolis (SC), Brazil. E-mail: fabiana.araujo06@gmail.com

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Introduction

A survey carried out in 2012 by the University Center for Studies and Research on Disasters (CEPED), at the Federal University of Santa Catarina (UFSC), resulted in the Brazilian Atlas of Natural Disasters (UFSC, 2013). This Atlas points out that the disasters that impacts the Brazilian territory the most are floods, windstorms, cyclones, hailstorms and droughts. Between 1991 and 2019, the Atlas reported 34,491 occurrences of droughts and forest fires, affecting approximately 164,022,085 people. On the other hand, events such as flooding accounted for 15,438 occurrences, affecting 47,659,661 people.

Drought, a persistent climatological event in which rainfall is reduced in relation to the average, triggers a shortage in local water supplies over the course of months or years (Gonçalves et al., 2021). They can be classified into types such as climatological, hydrological and edaphic droughts. A deficit of precipitation over time is a seasonal phenomenon that that can also be categorized as drought if chronically prolonged (Kobiyama et al., 2006). Unlike sudden disasters, drought occurs slowly and gradually, affecting vast areas and making it difficult to predict their onset and end.

The complexity of drought lies in its many contributing factors, including reduced precipitation, temperature, deforestation and global climate variability. Its recurring occurrence in Brazil generates widespread impacts, the severity of which depends on the exposure of the region, socioeconomic vulnerability of the affected population and precarious subsistence conditions. Consequences such as poverty, hunger, malnutrition, disease and migration can persist even after the drought is over (Salvador et al., 2022).

In addition to drought, wildfires play a significant role in the Brazilian region. The number of fires has increased mainly due to anthropogenic actions and prolonged droughts. Data obtained from Moderate Resolution Imaging Spectroradiometer (MODIS) on board the Aqua satellite for the period 2002–2021 shows about 300 thousand fires per year in South America (Bonilla et al., 2023). Brazil leads the number of fire outbreaks in South America, resulting in the spread of smoke and aerosol particles throughout the region (Fearnside, 2002; Oliveira-Júnior et al., 2020). Figure 1 presents a broad area of South America covered by smoke and many spot fires. In this context, the interaction between drought and fires amplifies the challenges faced by the country, demanding an integrated approach to mitigate the impacts of these climate events.

The influence of biomass burning aerosols concentration in the atmosphere has been the subject of recent studies, revealing significant impacts on the atmosphere. Investigating a specific case regarding large concentrations of smoke, Ramos-da-Silva et al. (2022) demonstrated that these aerosols can absorb radiation that induces a layer of atmospheric temperature inversion affecting cloud formation. Furthermore, other studies indicated that the presence of these aerosols can delay the formation of precipitation (Albrecht, 1989) and modify the precipitation rate by influencing the size of cloud droplets (Liu et al., 2020). A recent review on the impacts of biomass burning aerosols shows that several cases present a negative impact of these aerosols on the precipitation (Chang et al., 2024). The major mechanisms occur due to a large number of cloud condensation nuclei (CCN) that inhibit the onset of larger drops. Another effect is the surface decrease in radiation and the smoke level heating that causes a more stable atmosphere. However, in some cases the presence of these aerosols may increase precipitation due to changes in local atmospheric circulations. These studies suggest that high concentrations of aerosols can significantly affect the atmosphere, cloud formation and rainfall occurrence.

However, when analyzing the interaction of aerosol concentration, precipitation and other variables, the correlation between these elements still appears to be quite complex. This suggests that many atmospheric variables can influence the relationship between aerosols and precipitation, such as size distribution, composition and optical depth strength. The presence of aerosols from different sources in the atmosphere adds complexity to the understanding of how the optical property resulting from these particles interferes with the atmosphere and climate (Artaxo et al., 2006).

Cloud formation

Cloud formation plays a crucial role in understanding the impact of aerosols in this process. There are two main cloud formation initiation processes: homogeneous and heterogeneous nucleation. Homogeneous nucleation, idealized in conditions of total absence of particles in the atmosphere, demands high levels of supersaturation and is not observed under normal atmospheric conditions. Heterogeneous nucleation, on the other hand, involves the presence of aerosols which act as CCN. In a supersaturated environment, the aerosols present in the atmosphere can serve as a surface for water vapor diffusion and the deposition, facilitating the condensation process. This condition, which occurs in an environment with the presence of aerosols, allows cloud droplets to grow and develop through the condensation of water vapor in supersaturated conditions (Chang et al., 2024).

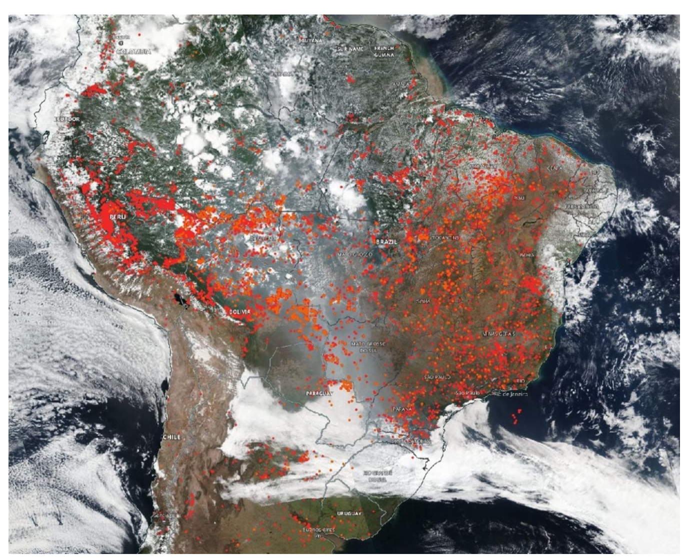

Figure 1 – Image from the Suomi satellite. A snapshot of aerosols biomass burning, on September 17, 2019. The red dots represent fire spots.
Source: Worldview NASA.

Therefore, aerosols are fundamental to the process of cloud formation as CCN. It is also important to mention that the highest concentration of these particles is found in the continental region, influencing cloud formation and resulting in smaller droplets. The hydrophobic or hygroscopic nature of aerosols is also relevant, where hygroscopic materials have a greater capacity to absorb moisture and promote condensation, without the need for an extremely high supersaturation environment.

After condensation, the growth of droplets that will eventually become raindrops occurs through the process of collision and coalescence. Larger and heavier droplets, formed by condensation, precipitate due to gravity and, during their fall, collide with smaller droplets. If the collision is effective, coalescence occurs, which is essential for the transformation of droplets into larger raindrops and precipitation.

A detailed understanding of these processes is fundamental, as it allows us to examine how the concentration of aerosols may influence cloud formation and, consequently, weather patterns in the study region. Climatological observations show that this region is undergoing extreme events in recent years (Ramos-da-Silva, 2023). The objective of this study is to evaluate the relationship between aerosol concentrations due to biomass burning and the formation of clouds and rainfall in the southern region of Brazil.

Material and methods

study area

The focus area for this study is the western region of the state of Santa Catarina (SC), located in southern Brazil (Figure 2). This region receives high concentrations of smoke and aerosols especially in the driest months (August, September and October) (Figure 1). However, nearby areas that also suffer from these events were explored as well, including the northeastern region of Argentina, Paraguay and other states in Brazil: Rio Grande do Sul, Paraná, São Paulo and Mato Grosso do Sul (Figure 2). Figure 2 highlights the area of study and the average intensity of aerosol optical depth for the month of September since it reaches the maximum of AOD, according to Figure 3a. Figure 3a shows a subset of 2 years (2020–2021) where the maximum black carbon column mass density and aerosol optical depth is reached in September.

Data

In order to evaluate the sources of aerosols transported into the study region, the Lagrangian model HYSPLIT (Hybrid Single-Particle Lagrangian Integrated Trajectory Model) was applied (Stein et al., 2015). This model can be freely accessed through the project portal NOAA (National Oceanic and Atmospheric Administration) (NOAA, 2026).

The data collection was carried out through the NASA database portal (https://giovanni.gsfc.nasa.gov/giovanni) that allows users to access and preview various global climate parameters. These parameters included reanalysis data from the MERRA2 project (*Modern-Era Retrospective analysis for Research and Applications, Version 2*), aerosol and cloud optical depth data, black carbon density and precipitation, for instance.

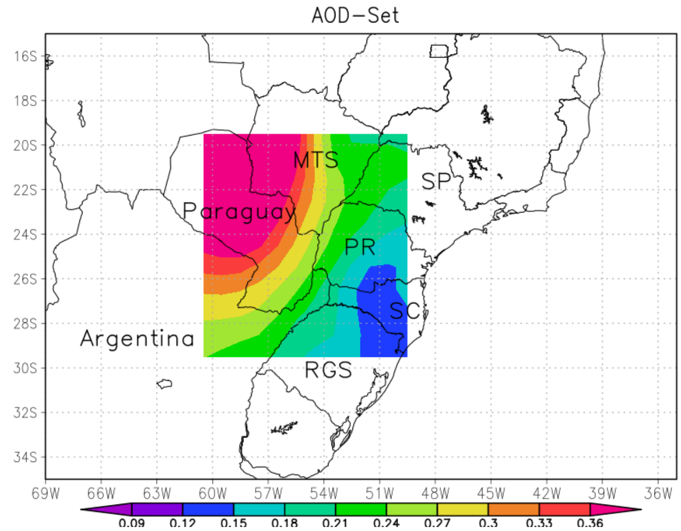

Figure 2 – Study area for analysis of aerosols and climatic variables. A subset is highlighted showing the focus area for the analysis and aerosol optical depth mean (unitless) for September (years 2002–2020).

The data analysis for the defined area included data for the period between the years 2002 up to 2022. The analyses focused on the period (August-September-October) when high concentrations of aerosols of burning biomass are transported over broader areas of South America. As seen in Figure 3a, during the years between 2020 and 2021, the peak values of aerosol optical depth coincide with the highest Black Carbon density column for the studied region. This preliminary analysis was used to determine the months selected and it also shows that the main aerosols present in the atmosphere come from the burning of biomass during this period of the year. This 3-month period corresponds to a transition from dry to wet regime (Figure 3b) and thus possible impacts on precipitation may affect the onset of the local rainy season.

In the NASA data portal, the monthly variable "*Aerosol Optical Depth 550 nm (Deep Blue, Land-only)*" was selected for analysis. This unitless variable is retrieved from the MODIS sensor of the Terra satellite, which has a spatial resolution of 1° latitude-longitude, and is available from the year 2002 up to present day (Hubanks et al., 2008).

For precipitation (mm/hr) data analysis, the GPM (Global Precipitation Measurement) project database was adopted. These precipitation fields are available with monthly temporal resolution for the entire globe with spatial resolution of 0.1 degrees of latitude and longitude for the period between June 2000 and October 2024 (Huffman, 2020).

For the cloud fields analysis, the selected monthly Cloud Optical Depth data available was the "Combined Cloud Optical Thickness"(COT) in the NASA portal. This data can be found at MODIS Terra sensor with the same spatial resolution of 1o latitude-longitude as seen at Platnick et al (2017).Cloud optical depth is a measure of the attenuation of light passing through the atmosphere mainly due to the scattering and absorption process of cloud droplets. Since most of the visible light that reaches the clouds ends up scattering and reflecting, a greater optical depth indicates greater amounts of cloud formation.

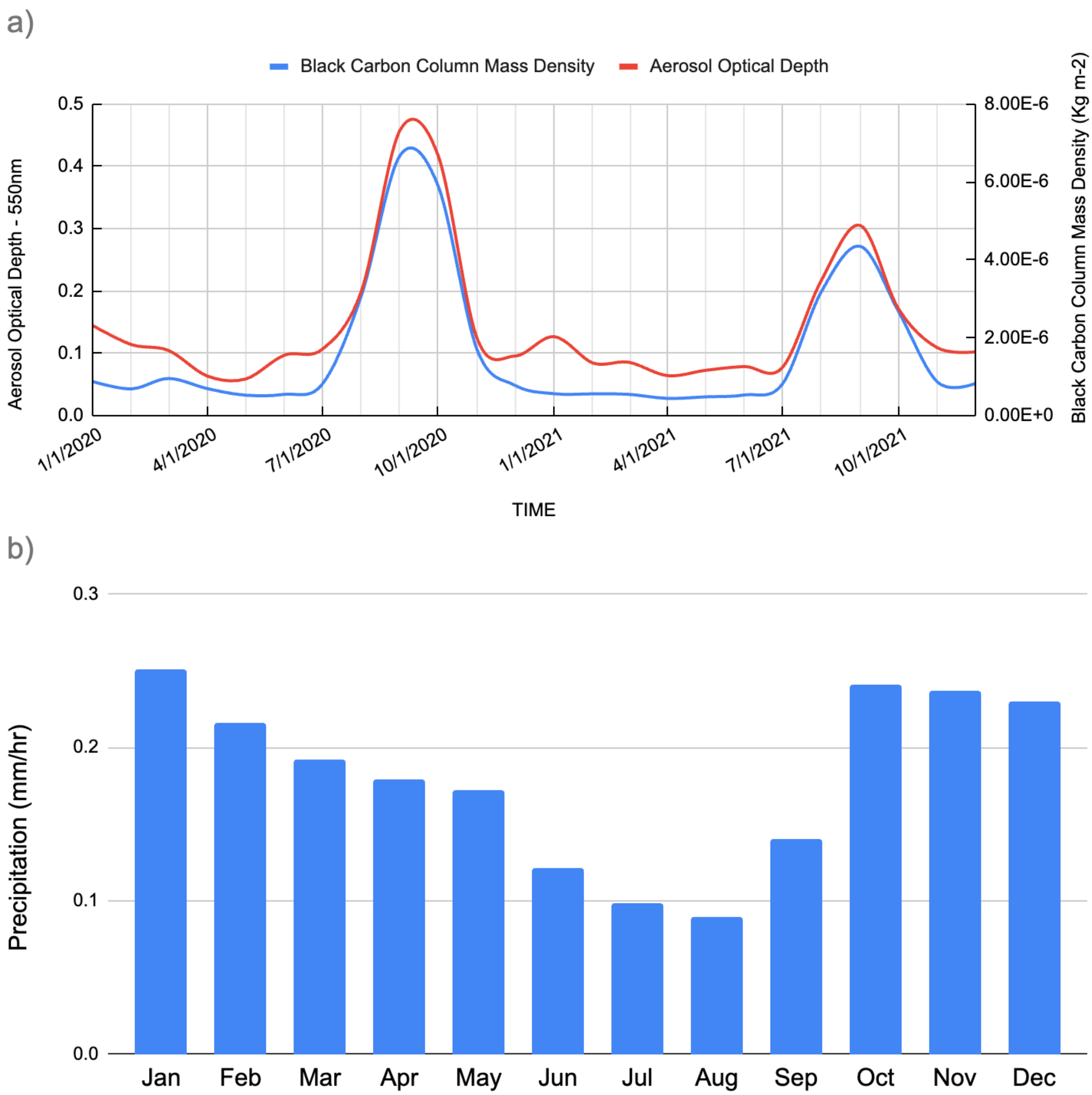

Figure 3 – (a) Space-averaged aerosol optical depth (60W-50W longitude, 29S-20S latitude) obtained by Terra satellite estimate and black carbon estimated by reanalysis (MERRA-2). (b) Precipitation historical average (GPM), years 2002–2022.

Analysis

Initially, monthly averaged time series were produced to evaluate the evolution of aerosols, clouds and precipitation variability over the studied region. Then, the Pearson and Spearman correlation statistical methods were applied to understand their common variability and the possible impacts of aerosols.

The monthly anomaly was calculated by taking an arithmetic average of the values available for each variable in that month (AOD and rainfall). The value provided by the database was then subtracted from the arithmetic mean. This made it possible to analyze how the value of each anomaly behaved through the years and was used to estimate the correlations.

Finally, the HYSPLIT maps trajectories were applied to identify the sources of high concentration of transport aerosols locally. Backward trajectories were applied to three smoky days of September (20th september 2019; 13th september 2020; 21st september 2021). These days were selected as they show local conditions with high aerosol concentrations. Meteorological 6-hourly data used in this model was adopted from the Global Data Assimilation System (GDAS) data set. Five trajectories were selected with a time span of 1 hour at the selected latitude of -26, longitude of -53 and altitudes of 2,000 meters. These coordinates were chosen to be at the central point of the study region. The altitude was chosen due to its troposphere height, where most of the meteorological phenomena and the smoke aerosols stay concentrated (Gonzalez-Alonso et al., 2019; Gammoudi et al., 2024). Other studies applied the HYSPLIT model to understand the smoke aerosols transport over South America (Jury and Pabón, 2021; Mulena et al., 2024).

Results

The analysis of the results included estimates of monthly data for the study area. The months selected for this study, August-September-October, present the period with the highest concentration of aerosols in the atmosphere throughout the year as shown in Figures 4a and 4b. The data shows that in some years there were higher concentrations of aerosols. For example, an aerosol optical depth greater than 0.4 occurred in the years 2002, 2004, 2007, 2010, and 2020.

Aerosols, precipitation and clouds

Figures 5a, 5b and 5c show the evolution of AOD concentrations, precipitation (based on GPM data) and COT, for the months of August, September and October, respectively. These data show that in various periods there is a decrease in precipitation associated with an increase in aerosols. In addition to the influence observed on precipitation, the results show that aerosols also may have effects on cloud formation.

As we have previously seen, the AOD and precipitation time series show that years that had a significant aerosol optical depth showed a drop in precipitation (Figures 5a, 5b and 5c). This corroborates the hypothesis raised that a greater amount of aerosols in the atmosphere has a negative influence on precipitation (Williams et al., 2002; Tao et al., 2012; Herbert and Stier, 2023; Zhao et al., 2025).

High aerosol concentrations can suppress precipitation through two main mechanisms: the albedo effect and the indirect effect. The albedo effect is the ability of a surface to reflect sunlight. In this case, a high concentration of aerosols acts as a layer that increases the scattering of solar radiation, reducing the energy reaching the layers below. This can stabilize the atmosphere below the aerosol layer by inhibiting convection and, consequently, inhibiting precipitation. In addition to the albedo effect, the indirect effect is a mechanism in which, in the presence of a high quantity of aerosols, they act as cloud condensation nuclei (CCN), leading to the formation of clouds with a higher amount of smaller droplets. This decrease in droplet size, in addition to increasing the cloud albedo effect, slows the collision-coalescence process, which hinders the formation of droplets large enough to produce precipitation (Chang et al., 2024).

Figures 5a, 5b and 5c, also show that during moments where a high concentration of aerosols occurs, there is a decrease in the cloud optical thickness. For example, in August of 2010, a very high AOD is observed, with a decrease in the COT. These results were also obtained by Herbert and Stier (2023), in their research carried out in the Amazon basin, where they concluded that AOD values greater than 0.4 were correlated with a reduction in cloud cover. This may be related to the reduction of convection due to the stabilization of the layer (albedo effect) and the excess CCNs that lead to a lower precipitation efficiency, in addition to reducing the vertical growth of clouds (Koren et al., 2014).

The results show also that most of the time, precipitation and COT values have a common variability. In general, precipitation peaks co-

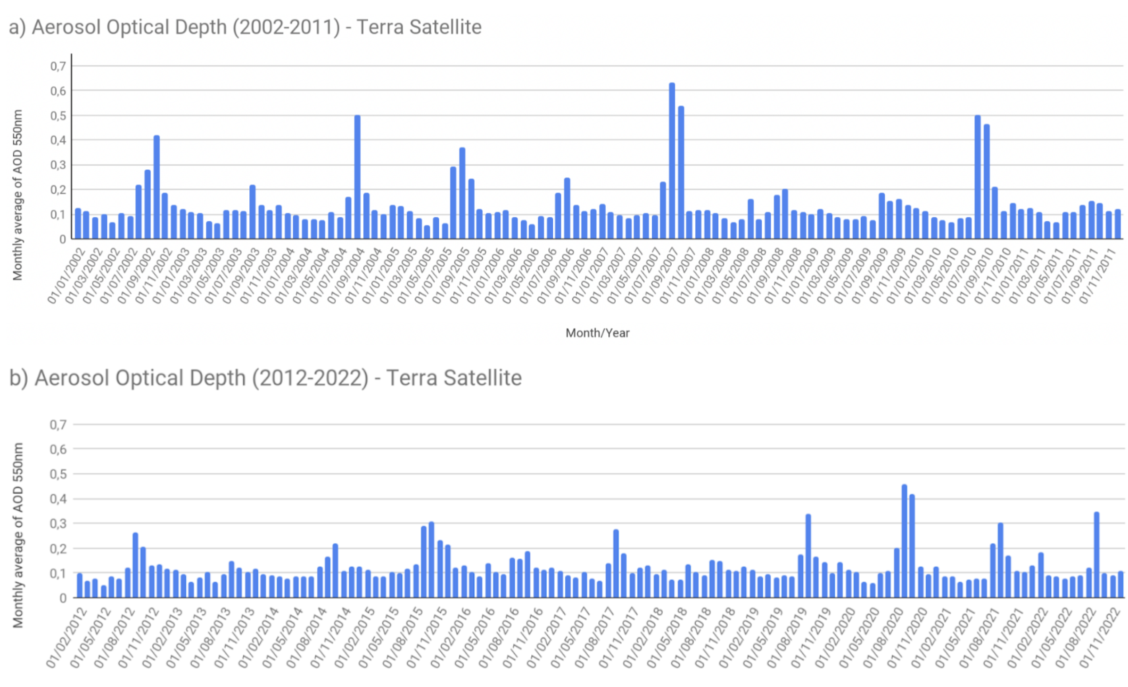

Figure 4 – Spatial monthly average of aerosol optical depth (60W-50W longitude, 29S-20S latitude) obtained by the MODIS sensor on the Terra satellite between: (a) 2002 to 2011 and (b) 2012 a 2022.

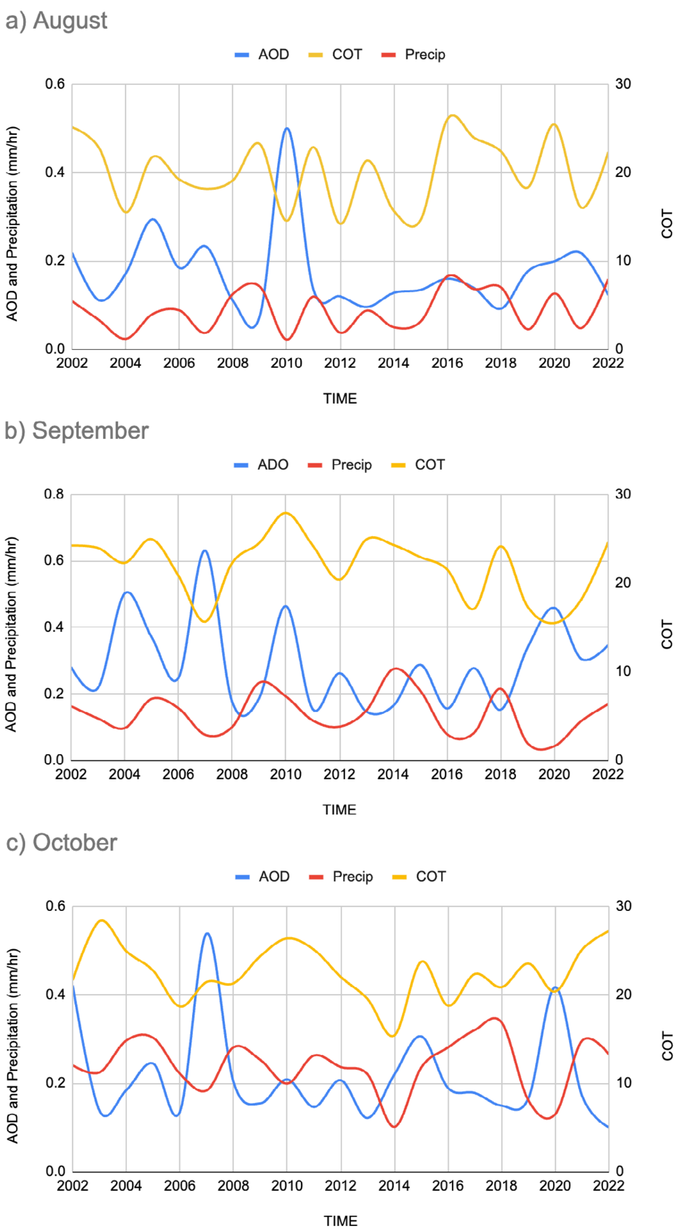

Figure 5 – Annual temporal evolution, between 2002 and 2022, of AOD, precipitation and COT in: (a) August; (b) September; (c) October.

incide with higher COT (Figure 5). This is expected, as thicker clouds can contain greater water content and vertical development, enabling intense precipitation events. However, in some cases COT peaks are also observed without significant precipitation, which may indicate the presence of clouds too instable to generate precipitation (Koren et al., 2014). Furthermore, a recent study used the Community Earth System Model version 1 Large Ensemble (CESM1-LENS) model to show that higher concentrations of biomass burning aerosol increase the concentration of cloud condensation nuclei (CCNs) and the amount of cloud droplets, leading to decreased cloud droplet size and precipitation formation (Magahey and Kooperman, 2023).

In these series results, it is observed that when an estimated quantity of aerosols is present in the atmosphere, it may have an impact in COT. However, it is also possible to observe that, at other times, with similar values of aerosols we have different results. This may occur since there are other variables that may interfere in this process of cloud and rain formation, such as, for example, air moisture. The availability of various amounts of water vapor in the atmosphere at the beginning of the formation process may also impact cloud formation.

Furthermore, it is not possible to state that there is a direct and clear correlation between the presence of aerosols and decreased precipitation. Some results show that the atmosphere is influenced by other effects that occur simultaneously and that also interfere with the cloud formation process, such as the moisture concentrations (Souza et al., 2021). Lin et al. (2006) considered the microphysical effect of CCNs as they can interfere both positively and negatively in the formation and evolution of clouds and, consequently, in precipitation.

In addition to the microphysical effect of droplet formation, there is also the effect of interaction with clouds that can affect the solar radiation balance. In this situation, the presence of clouds increases the fraction of solar radiation that is reflected into the atmosphere, while simultaneously increasing the greenhouse effect in the region. Therefore, at the surface, where cloud cover occurs, the absorption of solar radiation is prevented while receiving, locally, infrared radiation from the cloud. In this situation, it is possible to observe that the radiative effect can influence atmospheric circulation (Needham and Randall, 2021). Furthermore, smoke aerosols can absorb radiation and create a more stable atmosphere, inhibiting convection formation (Ramos-da-Silva et al., 2022).

Figures 6a, 6b and 6c show scatter plots between the AOD anomalies and precipitation (GPM) for all the months of August, September and October, respectively. The results show a generally negative correlation between precipitation and aerosols concentrations (Table 1). The results for Pearson and Spearman correlation coefficients of these scatter plots, along with their respective significance values (p) (where $p<=0.05$ is typically considered statistically significant) corroborates these results. For August, both methods show a moderate negative statistically significant correlation. For September, both methods show a weak negative non-significant correlation. For October the Pearson method shows a moderate negative non statistically significant correlation. In general, all the results show a negative correlation suggesting that there is a decrease in the precipitation as the aerosol concentration increases. Albeit not strong, these correlations estimate generally present negative values in their relationship, as obtained by other researchers (Rosenfeld et al., 2008; Rubin et al., 2023; Gulistan et al, 2024).

Table 1 also presents the correlation coefficients between COT and AOD, for August, September and October. For instance, August shows a non-significant negative correlation on both methods. September shows a Pearson stronger negative correlation indicating a possible decrease in clouds, as the smoke aerosols concentration increases. October also shows a negative non-significant correlation. In general, all the months show a non-significant negative correlation. Other studies show the same negative correlation. For instance, Koren et al. (2014) show that aerosols can suppress cloud formation. Thus, it is possible that other physical features may have an influence on cloud formation, but the occurrence of aerosols remains an important part of the processes.

Although the correlation between aerosols and clouds is negative, it is considered weak as it is below 0.5. The analysis was performed using monthly data and the local processes occur daily. Some studies show that this interaction between biomass burning aerosols, clouds and precipitation is still very complex (Rubin et al., 2023; Varble et al, 2023; Chang et al., 2024; Sands et al., 2024). Thus, a future analysis may be conducted on daily climate variables to improve our understanding of the interactions between high concentration of biomass burning aerosols and clouds and rainfall in this region.

The main results point to a negative correlation between aerosol concentrations and precipitation and clouds. In this south Brazil region, high concentrations occur due to transport from north to south. A few selected high aerosol concentration days were selected to verify the local transport of these particles with the HYSPLIT model. Figure 7 presents results of a sequence of aerosol transport maps chosen for the selected days with the highest AOD for the years 2019 to 2021. The results show that, for heights

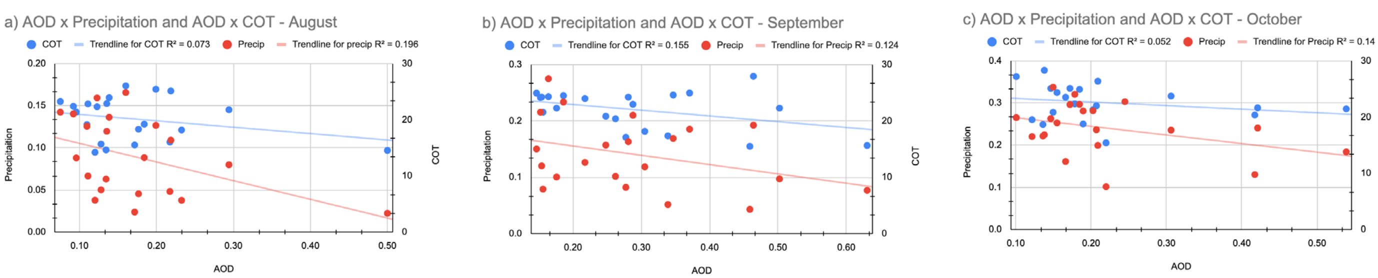

Figure 6 – Scatterplot between AOD x precipitation and AOD x COT for the month of: (a) August; (b) September and (c) October.

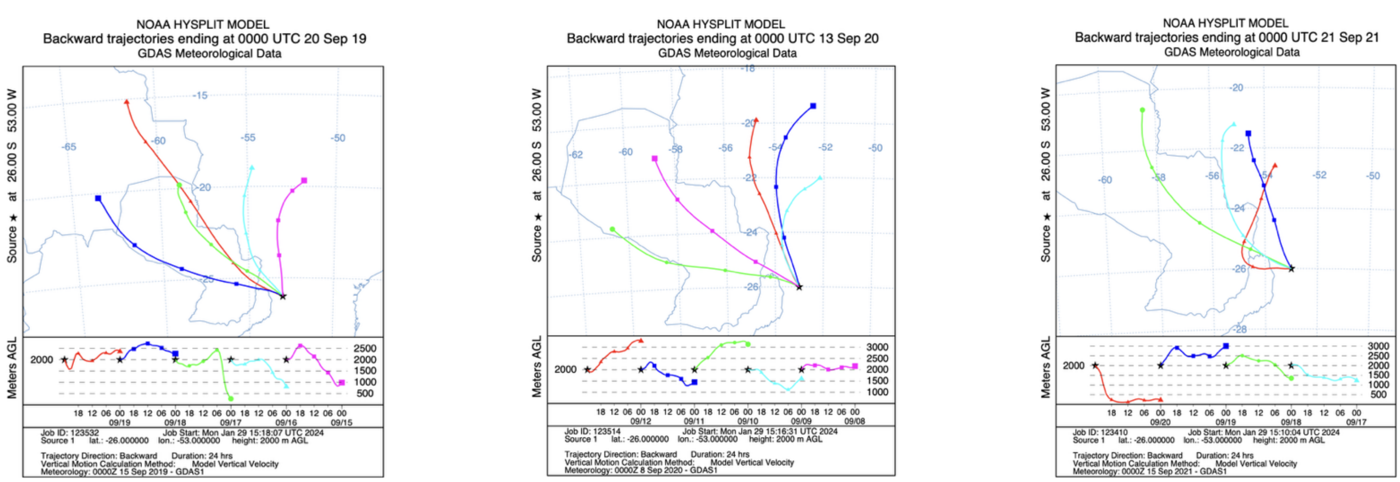

Figure 7 – Images of the HYSPLIT model for the peaks of aerosols (20th september 2019; 13th september 2020; 21st september 2021).

Table 1 – Correlation (corr) and significance (p) between AOD, precipitation and COT (years 2002–2022).

AOD x Precip	August		September		October	
	Pearson	Spearman	Pearson	Spearman	Pearson	Spearman
corr	-0.44	-0.43	-0.35	-0.29	-0.37	-0.21
p	0.044	0.051	0.118	0.2	0.094	0.34
AOD x COT	**August**		**September**		**October**	
	Pearson	**Spearman**	**Pearson**	**Spearman**	**Pearson**	**Spearman**
corr	-0.27	-0.11	-0.39	-0.26	-0.23	-0.23
p	0.23	0.63	0.071	0.25	0.32	0.32

of up to 2,000 meters, the aerosols are generally transported from the northern regions including Paraguay, Mato Grosso and the southern Amazon. Other studies show this transport from the north region to southern Brazil (Jury and Pabón, 2021; Rudke et al., 2025).

Conclusion

This research investigated the relationship between the varying concentrations of aerosols and the formation of clouds and rain in southern Brazil. The results indicated that the months of August, September and October record the aerosol peaks during the year that were transported from the north to the southern region of Brazil. Analyses demonstrated a relationship between increased optical depth of aerosols and the decrease in clouds and precipitation in these months, although with a negative and weak magnitude.

The possible negative impact on cloud formation and precipitation in conditions of high aerosol concentrations may intensify a dry period and thus cause drought in the region. In this location, smoke from burning biomass interacts with frontal systems affecting their evolution very often.

It is therefore recommended for future research to carry out additional observations to improve understanding of these processes, especially in the face of climate change and the increasing vulnerability of the tropical forest. Continuous monitoring of these climate variables is essential to assist decision makers and to society.

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Authors' Contributions

Araújo, F. C.: writing – original draft; validation; investigation; **Silva**, R. R.: supervision; writing – review & editing; investigation.

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