Impact of Aerosols on Brazil’s Solar Energy Potential

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Abstract

Given the significant impact of aerosols on downward solar irradiance, we analyzed aerosol optical depth data from multiple sources, including satellite-based, reanalysis, and ground-based observations. The goal was to assess the accuracy of these datasets to enhance atmospheric transmittance modeling for solar energy assessment in Brazil. The results indicate that the MODIS product is the most reliable and consistent for estimating aerosol optical properties, making it a preferred choice for large-scale solar energy resource mapping applications. The GOES-16 product offers high-frequency observations that can improve real-time monitoring of aerosol conditions. In contrast, CAMS reanalysis, while beneficial due to its continuous availability, demonstrated larger deviations from ground observations, suggesting the need for regional calibration adjustments.

Keywords: Atmospheric aerosols, Remote sensing, Aerosol optical depth, Surface downward solar irradiance, Radiative transfer modelling.

1. Introduction

Accurate solar irradiance mapping, particularly Direct Normal Irradiance (DNI), is fundamental for site selection, system design, and financial forecasting in solar energy projects. DNI is especially critical for concentrated solar power (CSP) and high-efficiency photovoltaic technologies, where errors in irradiance estimates can lead to energy yield deviations exceeding 15% in aerosol-rich regions (Blanc *et al.*, 2014). Atmospheric aerosols, varying widely in composition and optical properties, introduce uncertainties through wavelength-dependent scattering and absorption. Although long-term aerosol variations often induce only a few percent change in DNI, certain regions experience much larger reductions under heavy aerosol conditions; extreme dust storms or biomass-burning smoke can produce DNI drops comparable to those caused by major volcanic eruptions (Artaxo *et al.*, 2013). Accounting for aerosols is thus essential in solar energy modeling, especially in a country as geographically and climatically diverse as Brazil (Costa *et al.*, 2016).

Brazil’s aerosol environment is highly heterogeneous. In the Amazon Basin, massive biomass burning during the dry season (August–October) injects large amounts of smoke, dramatically increasing AOD and reducing surface irradiance. Field campaigns have documented significant reductions in total solar radiation (Schafer *et al.*, 2002). Regional modelling confirms that such smoke plumes cut surface short-wave fluxes and spread their effects far downwind (Rosário *et al.*, 2013). In Northeast Brazil, mineral dust is a dominant factor: Saharan plumes routinely cross the Atlantic during the austral summer, reaching the coast and depositing an estimated 10–15 Tg yr^{-1} of African dust over South America (Guedes *et al.*, 2018). This imported and local dust creates a seasonal haze that attenuates the region’s solar resource. In the large urban areas in the Southeastern region (e.g., São Paulo state), industrial and vehicular emissions, often mixed with advected biomass-burning smoke, produce complex aerosol plumes that measurably reduce surface solar radiation (Martins *et al.*, 2018); long time-series in São Paulo show that aerosol–cloud interactions drive significant variability in global irradiance (Yamasoe *et al.*, 2017).

Accurately modelling irradiance under these varying aerosol regimes remains challenging. The radiative transfer model Brazil-SR (Martins *et al.*, 2007), while validated for broadband clear-sky irradiance, requires spectral aerosol corrections to address systematic biases under high aerosol loads. Broadband models typically

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underestimate DNI in biomass-affected areas because they cannot resolve the strong spectral dependence of smoke aerosols (Gueymard and Yang, 2020). The research conducted under the Energy Security component of the INCT-MC2 (National Institute for Science and Technology – Climate Change phase II) project aimed to reduce uncertainties in estimating global and direct solar irradiation using the Brazil-SR model and several improvements were settled to enhance performance, particularly in integrating spectral DNI and Global Horizontal Irradiance (GHI) under clear-sky conditions and high aerosol load (Casagrande *et al.*, 2021).

Nevertheless, high-AOD scenarios, such as extreme smoke or dust, continue to challenge radiative transfer models, underscoring the need for improved aerosol inputs. Satellite AOD products (e.g., MODIS and GOES) and global reanalysis (e.g., CAMS) provide time-varying aerosol fields that improve DNI accuracy worldwide (Ruiz-Arias *et al.*, 2019). Yet their utility depends on AOD fidelity: errors propagate almost linearly into computed DNI (Boraiy *et al.*, 2017). Brazil's network of AERONET sun-photometers provides high-quality AOD (Holben et al., 1998), revealing biases in gridded products, while bias correction or assimilation can reduce clear-sky DNI errors by up to 20% (Boraiy *et al.*, 2017). This work aims to identify the best AOD product for solar resource assessment in Brazil's energy transition, where aerosol impacts account for up to 20% of the annual DNI variability (Ceballos *et al.*, 2022).

This study continues efforts to improve solar irradiation modeling in Brazil for regions with high aerosol loads but limited local observational data. To achieve this, aerosol optical depth (AOD) and Angström exponent (AE) data from satellite and reanalysis sources were compared with AERONET observations across different regions of the Brazilian territory, which have varying climates and data availability. The study aims to determine the most suitable input data and to propose modeling strategies for regional data, thereby enhancing model performance in national solar irradiance mapping.

2. Data and methods

The dataset used in this study comprises aerosol optical depth (AOD) observations compiled from various sources. These sources include satellite-based products (MODIS, GOES-R), reanalysis data (CAMS), and ground-based measurements (AERONET), which serve as the reference dataset. To enable a meaningful comparison across these varied data sources, all datasets were carefully processed and synchronized. This involved temporal alignment of time series data, including interpolation and averages. Spatial collocation was also performed, aligning satellite and reanalysis data with the geographical locations of the AERONET stations.

2.1 Ground measurements – AERONET data

The surface measurements dataset here was obtained from the AERONET network, which uses photometers to measure aerosol and other atmospheric properties. In this work, we utilized the AOD550 product to compare the modeled/satellite data with surface datasets and the 440-675 Ångström Exponent (α) for site-specific aerosol characterization. The surface stations used are spread across different regions of the Brazilian territory, with varying climate characteristics and differing data availability. Table 1 presents information about the sites, including their latitude and longitude, as well as the period of availability. All the data were downloaded from the AERONET website's Download Tool (https://aeronet.gsfc.nasa.gov/new_web/webtool_aod_v3.html).

2.2 Satellite products (GOES and MODIS)

Two satellite products were used in the study:

- GOES-16 ABI L2+ Aerosol Optical Depth (AOD) (Schmit et al., 2017) product provides high-frequency aerosol measurements derived from the Advanced Baseline Imager (ABI) onboard the GOES-16 satellite. This product estimates AOD using reflectance measurements in visible and near-infrared channels. It is generated using an operational retrieval algorithm that accounts for surface reflectance and atmospheric scattering, providing near-real-time data with high spatial and temporal resolutions.
- MODIS Aerosol Optical Depth (AOD) products are derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) sensors onboard NASA's Terra and Aqua satellites. These products provide global aerosol measurements by analyzing reflected sunlight in multiple spectral bands, allowing for the estimation of AOD over both land and ocean. MODIS aerosol retrievals are widely used for air quality monitoring, climate studies, and solar radiation modeling.

Table 1: AERONET site information.

Sites	Region	Latitude	Longitude	Time Availability
Amazon Tower – AMT	Amazon	2.1 S	59.0 W	01/2016 – 12/2024
Alta Floresta – AFL	Amazon	9.9 S	56.1 W	01/1993 – 12/2021
Ji-Paraná –JPR	Amazon	10.9 S	62.0 W	01/2002 – 12/2024
Brasília – BRB	Midwest - Cerrado	15.9 S	47.7 W	01/2015 – 12/2018
Campo Grande – CGR	Midwest-Cerrado	20.4 S	54.6 W	01/2003 – 12/2019
Natal – NTL	Northeast coast	5.8 S	35.2 W	01/2016 – 12/2019
Petrolina – PTR	Northeast semiarid	9.1 S	40.3 W	01/2004 – 12/2024
Cachoeira Paulista – CPA	Southeast	22.7 S	45.0 W	01/2016 – 12/2024
São Martinho Da Serra – SMS	South	29.4 S	58.8 W	01/2008 – 12/2024

The GOES-16 AOD product has been available since 2019 for the Brazilian territory, with continuous updates and improvements. It offers a temporal resolution of 10 to 15 minutes, covering the Western Hemisphere with a spatial resolution of approximately 2 km at the satellite's nadir. This capability for frequent observation is particularly valuable for tracking rapid aerosol changes, such as those caused by wildfire smoke and urban pollution events. However, retrieval accuracy may vary depending on cloud cover, surface properties, and aerosol type, necessitating validation against ground-based observations. A Python code using API call was developed in this work to download the full-disk image from GOES every 3 hours, cut it to the Brazilian territory, and save it. The data was downloaded for the period between 2019 and 2023.

MODIS aerosol products have been available since 2000 (Terra) and 2002 (Aqua), with continuous data coverage to the present. The MODIS Dark Target algorithm estimates AOD over dark vegetated surfaces using wavelengths ranging from 0.47 to 2.12 µm, assuming surface reflectance correlations (Levy et al., 2013). In contrast, the Deep Blue algorithm specializes in bright surfaces, such as deserts, by utilizing shorter wavelengths (0.412-0.65 µm) and precomputed reflectance databases (Hsu et al., 2013). Together, they provide complementary global aerosol coverage across diverse land surfaces.

These products offer daily observations with a spatial resolution of 10 km at nadir for standard AOD retrievals. The MODIS instruments provide valuable long-term aerosol records, which are essential for climate trend analysis and the validation of other aerosol datasets. However, retrievals may be affected by surface brightness, cloud contamination, and aerosol model assumptions. The data for this work were downloaded as daily averages from 2015 to 2023.

2.3 Reanalysis CAMS (Copernicus Atmosphere Monitoring Service)

The CAMS Aerosol Optical Depth (AOD) product provides global aerosol data through assimilation of satellite observations and numerical modeling (Inness, A. et al., 2019). Produced by the ECMWF (European Centre for Medium-Range Weather Forecasts), CAMS generates AOD estimates using the Integrated Forecasting System (IFS), which incorporates various aerosol species such as dust, sea salt, organic matter, black carbon, and sulfate. This dataset is widely used for atmospheric research, air quality forecasting, and climate studies due to its comprehensive coverage and data consistency.

CAMS aerosol products have been available since 2003 and are continuously being updated and improved. They offer a temporal resolution of three hours and a spatial resolution of approximately 0.75° × 0.75° (~80 km), making them suitable for regional and global-scale applications. The data for this work were downloaded for the period between 2015 and 2023.

2.4 Statistical Analysis

The statistical analysis focused on evaluating the consistency and behaviour of AOD data from satellite and reanalysis sources relative to AERONET observations. Different comparisons were conducted between the satellite-derived and CAMS reanalysis AOD values and the collocated AERONET measurements to assess the degree of agreement, using metrics such as bias and root mean square error (RMSE).

Intra-day variability of AOD was also examined to capture the diurnal patterns and assess whether satellite and reanalysis data adequately reflect short-term fluctuations observed in the ground-based measurements. Seasonal variations were further analyzed to explore how AOD levels change throughout the year and to identify any systematic biases associated with specific seasons or aerosol regimes.

Lastly, the study included aerosol characterization based on the observed patterns and magnitudes of the Ångström Exponent. This involved identifying dominant aerosol types and their likely sources by integrating the temporal and spatial behaviour of AOD across datasets. Through this multi-faceted analysis, the reliability and representativeness of satellite and model-derived AOD estimates were thoroughly evaluated

3. Results and Discussions

3.1. Evaluation and statistical analyses and correlation studies between satellite products and ground-based databases

Due to varying periods of available data from AERONET and satellite/reanalysis products, the comparisons differed by site. For instance, the GOES AOD product can only be compared among the selected sites at SMS, CPA, AFL, AMT, and JPR, as the remaining sites had high-quality data available only before 2019. Figure 1 presents a scatter plot of daily average AOD values from AERONET and GOES at 550 nm. In the figure, AERONET AOD values below 0.2 are marked in orange, while those above 0.2 appear in blue. This distinction was made because all products performed poorly when AOD values were below this threshold. Additionally, the impact of such low aerosol concentrations on solar irradiance is minimal. Since our primary interest lies in high aerosol concentrations, this separation allows for a more meaningful analysis. The Bias, RMSE, and number of samples (N) were only calculated for values above the 0.2 threshold. Figure 2 shows the same comparison for the MODIS AOD product and all sites, while Figure 3 does the same for the CAMS AOD product. In general, we observe better performance for both GOES and MODIS satellite products compared to the CAMS reanalysis. Notably, the poorest performance is observed at the PTR site, despite most of the site's values being below the 0.2 threshold.

Table 2 shows the Bias, RMSE, and number of samples N above the 0.2 threshold for a better comparison. In general, CAMS provides the most extensive time series because it is a modeled product, allowing interpolation even under cloudy conditions or when the satellite classifies the sky as cloudy. At the same time, the AERONET photometer can still occasionally record measurements. However, when sufficient data are available for all products, CAMS performs the worst. On the other hand, GOES had the smallest dataset for comparison, but demonstrated performance comparable to MODIS. Overall, MODIS products stand out as the most consistent and highest quality among the three options.

In some locations, there was insufficient data above the threshold of AOD 0.2 due to local conditions with low AOD, particularly in the Northeast region of Brazil, including Natal (NTL) and Petrolina (PTR). Another reason for the limited amount of data available, especially for the GOES comparison, is that AERONET data were available before AOD data from GOES-16.

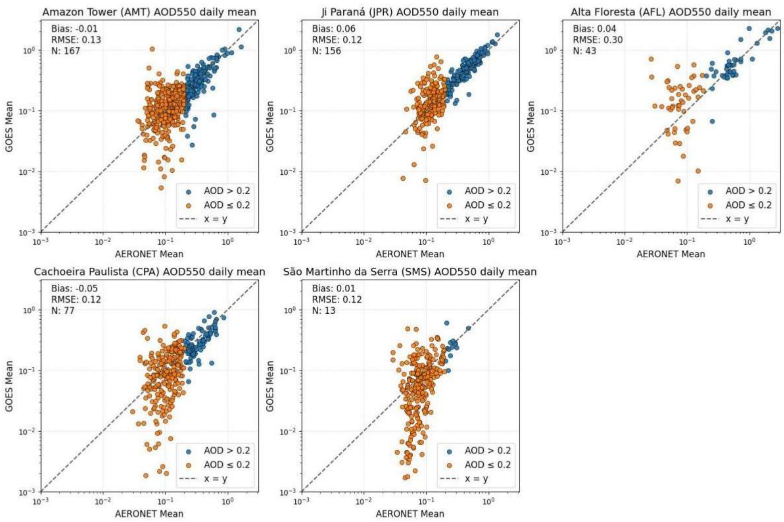

Figure 1: Comparison of daily average AOD values from AERONET and GOES at 550 nm. AERONET AOD data below 0.2 are marked in orange. The Bias, RMSE, and number of samples (N) were calculated only for values above the 0.2 threshold.

Table 2: Comparisons of AOD products assuming AERONET data as ground truth. Bold indicates the best values.

Region	Site	AOD Product	Nº of samples (N)	Bias	RMSE
Brazilian Amazon	Alta Floresta (AFL)	GOES	43	0.04	0.30
		MODIS	250	0.04	0.19
		CAMS	438	-0.09	0.32
	Amazon Tower (AMT)	GOES	167	-0.01	0.13
		MODIS	221	0.10	0.20
		CAMS	478	-0.09	0.20
	Ji-Paraná (JPR)	GOES	156	0.06	0.12
		MODIS	155	0.02	0.21
		CAMS	216	-0.06	0.25
Northeastern Coast	Natal (NTL)	MODIS	5	0.03	0.08
		CAMS	15	-0.04	0.07
Northeastern Semiarid	Petrolina (PTR)	MODIS	18	0.11	0.16
		CAMS	42	-0.16	0.17
Brazilian Cerrado	Brasilia (BRB)	MODIS	33	-0.15	0.18
		CAMS	45	-0.14	0.22
	Campo Grande (CGR)	MODIS	96	-0.10	0.15
		CAMS	120	-0.12	0.22
Southeast and South of Brazil	Cachoeira Paulista (CPA)	GOES	77	-0.05	0.12
		MODIS	145	-0.11	0.15
		CAMS	175	-0.09	0.22
	São Martinho da Serra (SMS)	GOES	13	0.01	0.12
		MODIS	39	0.05	0.31
		CAMS	55	-0.17	0.40

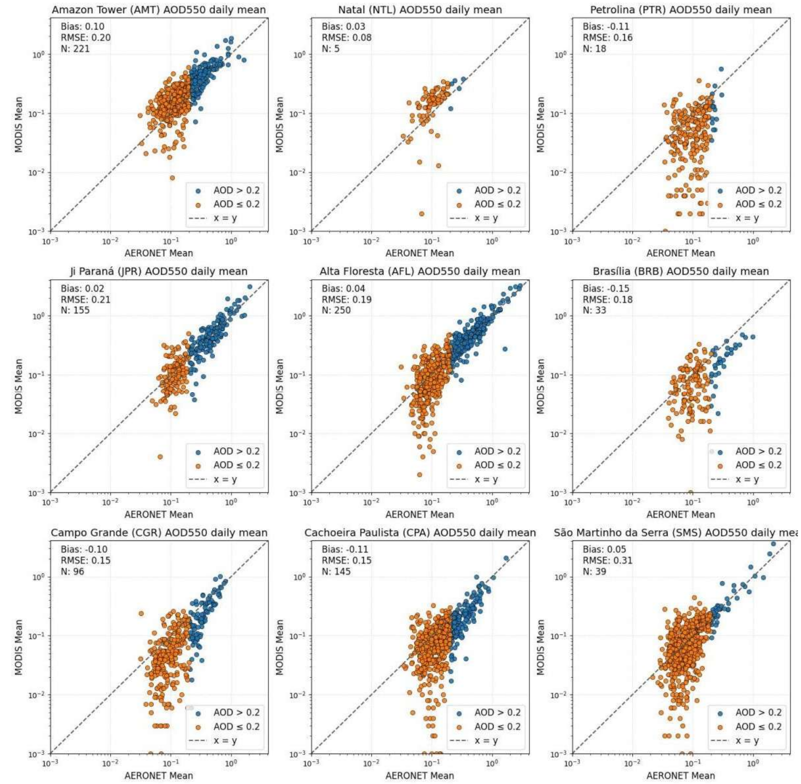

Figure 2: Comparison of daily average AOD values from AERONET and MODIS at 550 nm. AERONET AOD below 0.2 are marked in orange. The Bias, RMSE, and number of samples (N) were calculated only for values above the 0.2 threshold.

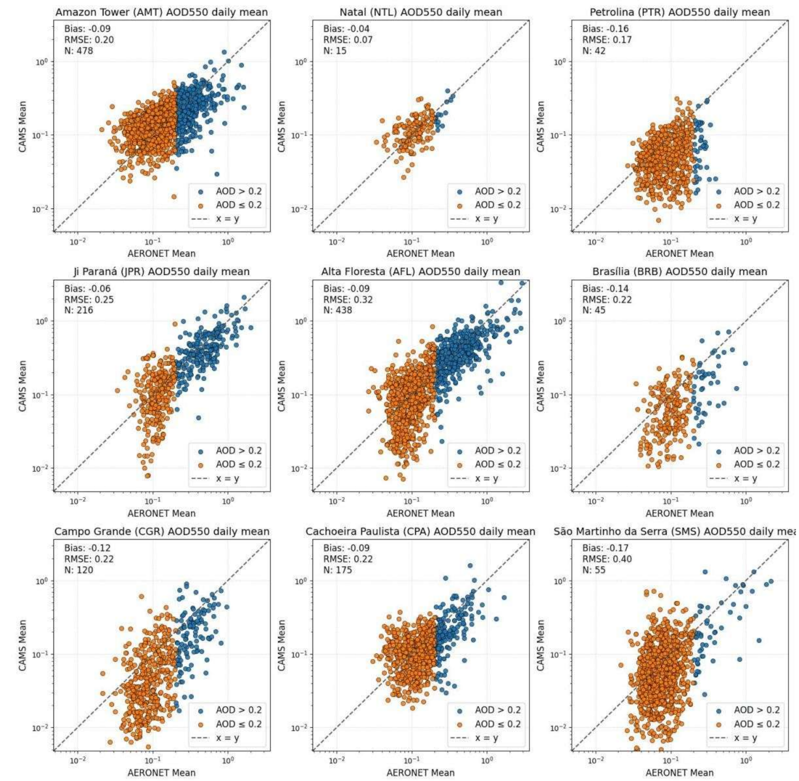

Figure 3: Comparison of daily average AOD values from AERONET and CAMS at 550 nm. AERONET AOD below 0.2 are marked in orange. The Bias, RMSE, and number of samples (N) were calculated only for values above the 0.2 threshold.

From the results, the MODIS product showed better correlation with surface measurements, at least for daily averages. However, it was not clear whether such low time resolution would be sufficient to account for situations with high aerosol concentrations and high variability. Figure 4 shows the higher resolution AOD concentrations from AERONET and CAMS compared to the MODIS daily average for September 2022 (a month with high aerosol concentration due to forest burns) at the Amazon Tower (AMT) measurement site. We can see that although MODIS showed the best agreement for averaged results, it lacks crucial AOD variability during the day. Similar results were observed at other sites.

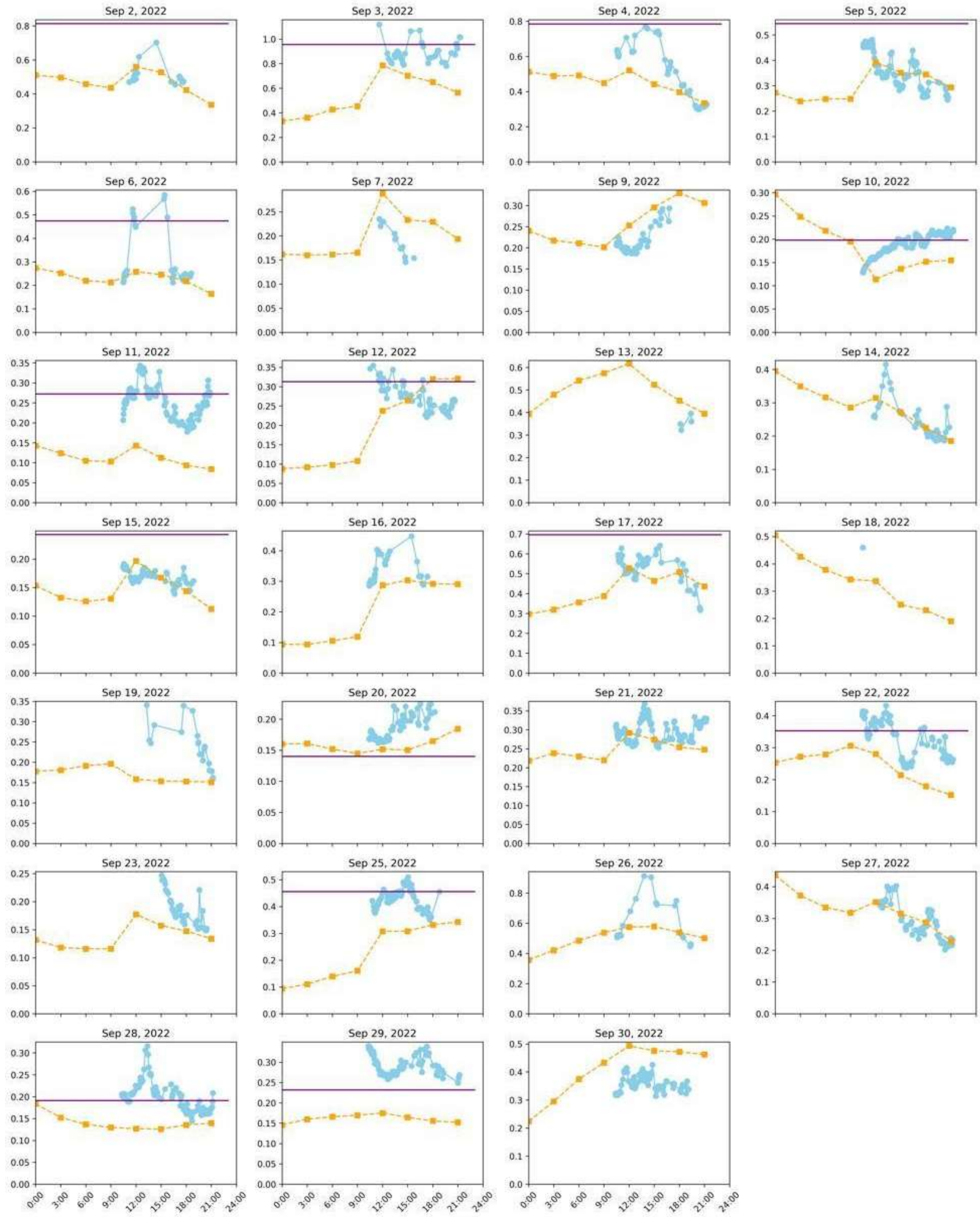

Figure 4 - Daily comparison of the aerosol AOD products from the AERONET (in blue), MODIS (in red), and CAMS (in yellow) for September 2022 in the Amazon Tower site.

Figure 5 shows the temporal variability of monthly averages at selected locations. Interestingly, the CAMS product presented the smallest deviations compared to the other two satellite products. This comparison shows the potential of CAMS, depending on the analysis goal; for example, climatologies can be better represented by such modeled data. Among the satellite products, MODIS demonstrated slightly better performance and more extended data availability. The advantage of GOES is that its temporal resolution is much higher (10-15 minutes) compared to MODIS's daily resolution.

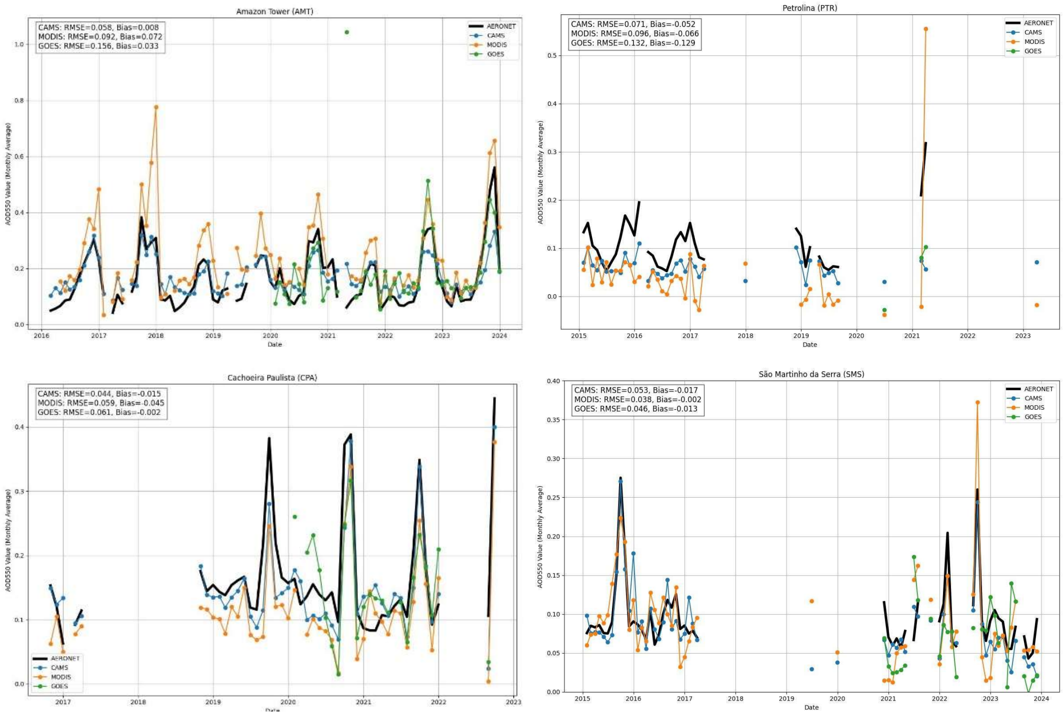

Figure 5: Time series of AOD550 monthly averages in four major Brazilian biomas: Amazon (left superior); Semiarid (right superior), Cachoeira Paulista (left inferior), and Pampa-South of Brazil (right inferior).

It is important to emphasize that the analyzed products have distinct spatial and temporal resolutions. However, Figure 4 demonstrates that each AOD product performs well under specific conditions that should be considered in regionalized studies. Our analysis revealed that MODIS AOD products generally provide the most consistent and reliable data for national-scale solar mapping. At the same time, GOES AOD offers advantages in temporal resolution despite a smaller dataset. Conversely, while providing broader coverage, CAMS reanalysis data exhibited higher errors when directly compared to ground-based measurements, highlighting the importance of regional calibration efforts. The findings also underscore the challenges of accurately estimating AOD under low-aerosol conditions, where all products exhibited performance limitations.

3.2. Physical characteristics of the aerosol particles

Differences in the physical characteristics of the aerosol particles can explain the regional patterns. Figure 6 shows histograms with the 440-675 Ångström Exponent (α) distribution for the nine measurement sites. The Ångström exponent is used to characterize aerosol size distribution. Low values ($\alpha < 1$) typically indicate larger particles, such as dust or sea salt. In contrast, moderate values ($1 \leq \alpha < 1.5$) indicate a mixture of coarse and fine particles, often originating from both urban pollution and natural sources. Higher values ($\alpha \geq 1.5$) are associated with smaller particles, such as those from biomass burning or industrial emissions. Each plot displays the density distribution of α, with the mean, median, and standard deviation annotated to highlight the central tendency and variability of each site. We can see that Natal (NTL) is the site with the largest particles, probably sea salt or even dust from the Sahara Desert. Petrolina (PTR) is the following site with the largest particles, despite having more mixed conditions. The Amazon Tower (AMT), Ji-Paraná (JPR), Alta Floresta

(AFL), and Campo Grande (CGR) show the smallest particles, very likely related to biomass burning in the Amazon and Cerrado regions. Cachoeira Paulista (CPA), in the central part of Brazil, can also be affected by the transport of biomass-burning aerosols from the Amazon and Midwest regions. São Martinho da Serra (SMS), located in southern Brazil, exhibits a broader range of aerosol conditions.

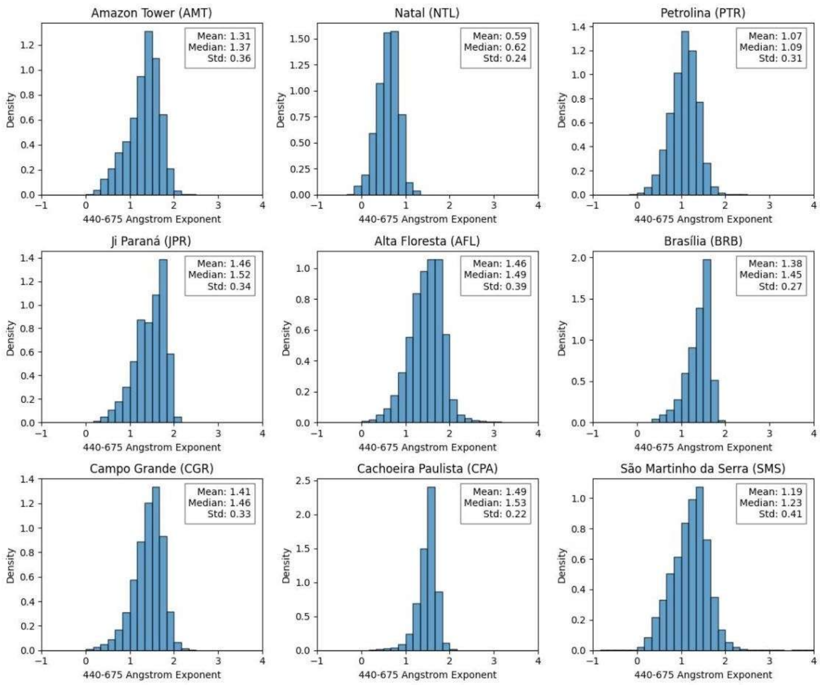

Figure 6: Histograms with the 440-675 Ångström Exponent (α) distribution for the nine AERONET sites. This exponent is used to characterize aerosol size distribution.

4. Conclusions

This study investigated the regional aerosol optical properties using publicly available datasets and compared them with satellite and reanalysis data. The multi-site evaluation demonstrated that the remote-sensing products present distinct advantages and disadvantages under moderate-to-high aerosol conditions. In particular, focusing on AOD values above ~0.2 (separating background haze from significant aerosol events) yields more robust comparisons, since low-AOD retrievals can be within the noise level of instruments and have smaller effects on solar radiation.

In the high-aerosol regime, the MODIS AOD retrievals showed the highest overall correlation and stability against AERONET, with the smallest Bias and RMSE across Brazilian biomes. MODIS provided the most self-consistent AOD record during the studied period, offering reliable data for national-scale solar mapping. At the same time, GOES AOD offers advantages in temporal resolution despite a smaller dataset. Conversely, while providing broader coverage, CAMS reanalysis data exhibited higher errors when directly compared to ground-based measurements, highlighting the importance of regional calibration efforts. The findings also underscore the challenges of accurately estimating AOD under low-aerosol conditions, where all products exhibited performance limitations.

MODIS consistently ranked highest in point-wise correlation and consistency with daily averages of ground data. By contrast, the CAMS reanalysis, while offering the longest continuous time series, achieved high correlation and demonstrated promising results, though biases were substantial in site-specific comparisons. These biases reflect limitations in the assimilation of regional fire and dust emissions into numerical parameterizations. GOES-ABI (geostationary) AOD offers the finest temporal sampling (5–10 min updates at 2 km resolution), enabling tracking of aerosol events. In summary, MODIS retrievals were most reliable for pointwise AOD, CAMS for long-term averages, and GOES for high-frequency event monitoring.

The comparison of monthly means showed that, despite its higher resolution errors, CAMS reproduces Brazil's aerosol climatology well. The reanalysis captured the seasonal peak in dry-season AOD in the Amazon and reductions during the wet season. In other words, CAMS AOD averages align with the seasonal and interannual trends observed in AERONET (and MODIS), even if individual days may be off. By contrast, MODIS's coarser temporal sampling missed sub-daily variability. When examined at high temporal resolution, the GOES data often revealed intraday peaks or minima in AOD that a once-daily MODIS overpass could not capture. This is expected since GOES delivers daytime observations with the highest temporal resolution, whereas MODIS samples only at fixed overpass times. In practice, our high-resolution comparison showed that MODIS may under- or overestimate actual daily AOD patterns when the satellite passes beyond the peak of an aerosol plume.

Aerosol type and size also played a role across regions. Coastal sites were dominated by large sea-salt particles, as evidenced by very low Ångström exponents and coarse-mode volume distributions. In contrast, Amazonian interior sites are heavily influenced by biomass-burning smoke during the dry season. Smoke aerosols are fine and highly variable, often leading to higher AOD variability and larger Ångström exponents. Land-cover and aerosol-type differences partly explain why retrieval performance varied by location.

In summary, no single AOD product consistently yields the best representation of ground observations across all time-scales or regional patterns. For event monitoring (e.g., tracking smoke plumes or dust outbreaks), GOES is most useful due to its minute-scale updates. For global or regional mapping of typical aerosol levels, MODIS offers broad coverage and generally reliable AOD. For climatological studies, trend analysis, and gap-filling under cloudy conditions, CAMS reanalysis can be valuable, as it robustly captures seasonal cycles. Users should also be aware of each product's limitations: GOES cannot retrieve data from over-bright surfaces or at night, MODIS has limited overpass times, and CAMS can exhibit regional biases during intense biomass burning or dust events. The insights gained from this research are instrumental in refining the Brazil-SR model, particularly in integrating spectral DNI and Global Horizontal Irradiance (GHI) under clear-sky conditions and high-aerosol-load conditions. Future work will focus on further improving calibration methods, incorporating additional observational datasets, and exploring machine learning approaches to enhance the predictive capabilities of solar irradiation models.

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