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Assessment of aerosol remote sensing uncertainty in urban centers of Latin America

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RESUMEN

La profundidad óptica de aerosoles (AOD) derivada de satélites es un indicador clave para ampliar la cobertura espacial en estudios de calidad del aire, particularmente para estimar concentraciones de $PM_{2.5}$. Sin embargo, la validación de productos AOD de alta resolución sigue siendo limitada en entornos urbanos de América Latina, que se caracterizan por una dinámica compleja de aerosoles y una escasa cobertura de monitoreo terrestre. En este estudio, evaluamos el desempeño del producto MAIAC C6.1 AOD en seis ciudades latinoamericanas densamente pobladas (São Paulo, Santiago, Buenos Aires, Medellín, La Paz y Ciudad de México) entre 2015 y 2022, utilizando como referencia la red AERONET. El desempeño de MAIAC C6.1 también se comparó con su versión anterior (C6.0) y con MODIS DT, para analizar diferencias en la resolución espacial y evaluar mejoras en el rendimiento. Se observó una falta de datos AOD a nivel de superficie, especialmente en Medellín y São Paulo, junto con niveles promedio bajos (AOD < 0.2) en La Paz y Buenos Aires. El rendimiento de MAIAC C6.1 mostró una variabilidad notable según el tamaño de la ventana espacial, aunque la ventana temporal no tuvo un impacto considerable. Se identificaron dos grupos de sitios: (*i*) La Paz y Buenos Aires, con menores niveles de AOD, menor desempeño y sesgo positivo; y (*ii*) São Paulo, Santiago y Ciudad de México, con mayores niveles de AOD, mejor desempeño y sesgo negativo. MAIAC C6.1 mostró una mejora en la reducción del sesgo, aunque sin cambios significativos en R^2 o RMSE respecto de C6.0. En comparación con MODIS DT, MAIAC C6.1 presentó mayor precisión y menor sesgo, ya que MODIS sobreestimó la AOD en todos los sitios. A pesar de los avances en productos de alta resolución, persisten limitaciones en la cobertura de datos e incertidumbres, especialmente en áreas urbanas de América Latina.

ABSTRACT

Satellite-derived aerosol optical depth (AOD) is a key indicator for expanding spatial coverage in air quality studies, particularly for estimating $PM_{2.5}$ concentrations. However, validation of high-resolution AOD products remains limited in Latin American urban environments, which are characterized by complex aerosol dynamics and sparse ground-based monitoring. In this study, we evaluated the performance of MAIAC C6.1 AOD in six densely populated Latin American cities (São Paulo, Santiago, Buenos Aires, Medellín, La Paz, and Mexico City) from 2015 to 2022, using the AERONET network as a reference. MAIAC C6.1 performance was also compared with the previous version (C6.0) and MODIS DT to analyze differences in spatial resolution and assess performance improvements. A lack of ground-level AOD was observed, especially in Medellín and São Paulo, along with low average levels (AOD < 0.2) in La Paz and Buenos Aires. MAIAC

C6.1 performance showed notable variability depending on the spatial window size, although no considerable impact was seen in the temporal window. Two site groups were identified: (*i*) La Paz and Buenos Aires, with lower AOD levels, lower performance, and positive bias; and (*ii*) São Paulo, Santiago, and Mexico City, with higher AOD levels, better performance, and negative bias. MAIAC C6.1 showed improvement in bias reduction, but no significant changes in R^2 or RMSE compared to C6.0. Compared to MODIS DT, MAIAC C6.1 exhibited greater accuracy and lower bias, with MODIS overestimating AOD across all sites. Despite advances with high-resolution products, limitations in data coverage and uncertainty persist, especially in urban Latin American areas.

Keywords: aerosol optical depth (AOD), AERONET, satellite products, MODIS, MAIAC.

1. Introduction

Aerosol optical depth (AOD) is a key measure of the amount of direct solar radiation that is blocked on its way to the Earth's surface due to scattering and/or absorption by atmospheric aerosols. As an indicator of aerosol, AOD plays a crucial role in understanding air quality, climate change, and human health (Kaufman et al., 2005; Kloog et al., 2015). The most reliable method for monitoring AOD is through solar photometers situated at the surface, such as those in the AErosol RObotic NETwork (AERONET), which provides measurements every 15 min (Holben et al., 2001; Liu et al., 2019). However, its spatial coverage is limited, especially in urban centers across Latin America, where reliable ground-based aerosol monitoring remains scarce. In contrast, satellite remote sensing allows for global monitoring of AOD, providing broader spatial coverage, although with a lower temporal resolution (1-2 daily overpasses) (Martins et al., 2017).

Among the available open-access satellite products, the MODIS instrument on board the Terra and Aqua satellites provides AOD products such as Dark Target (DT) and Deep Blue (DB), with resolutions of 3 and 10 km. Although suitable for regional studies, these spatial resolutions are insufficient for detecting aerosol variability within urban areas (Kaufman et al., 1997; Levy et al., 2013; Remer et al., 2013). To overcome these limitations, the MODIS Multi-Angle Implementation of Atmospheric Correction (MAIAC) algorithm was developed, providing AOD data with a spatial resolution of 1 km and daily frequency (Lyapustin et al., 2018). Since 2018, MAIAC Collection C6.0 has been available and widely adopted. More recently, in June 2023, the updated Collection 6.1 was released. It incorporates key improvements such as enhanced aerosol absorption retrievals at high AOD levels and particle size adjustments based on seasonal behavior (Lyapustin and Wang, 2022; Ye et al., 2022).

MAIAC has been used globally for a variety of applications, including serving as a key predictor of particulate matter (PM), validating air quality models and emission inventories, supporting epidemiological studies, and in spatio-temporal aerosol trend analysis (Li et al., 2018; Hammer et al., 2020; Pashayi et al., 2023). The MAIAC performance has been evaluated both globally and regionally, generally showing good agreement with AERONET. However, studies have shown that its accuracy depends on soil type and aerosol load (Superczynski et al., 2017; Lyapustin et al., 2018; Falah et al., 2021; Jiang et al., 2023). In Latin America, performance varies notably across sites. Martins et al. (2017) in South America, and Della Ceca et al. (2018) in Argentina found a high agreement with AERONET, although performance was lower in urban areas. Lyapustin et al. (2018) showed a low-moderate correlation for South America due to the low values and AOD limited variability. Qin et al. (2021) pointed out that the presence of clouds and rainfall affects the accuracy of MAIAC in South America, where AOD values are generally low. However, in São Paulo (Brazil), Damascena et al. (2021) found weak to moderate correlations, partly attributed to differences between the MAIAC aerosol model and aerosol properties. These results demonstrate promising performance; however, some uncertainties remain due to differences between satellite and surface measurements, as both rely on distinct assumptions to characterize aerosol properties in the region (Levy et al., 2007; Li et al., 2015).

Despite the growing use of MAIAC, there is currently a lack of systematic evaluation of the newest version (C6.1) in Latin American urban areas, particularly in cities where monitoring is essential for public health and environmental policy. Moreover, validation methodologies vary considerably across studies, and there is no uniform criterion for their application. Different spatial windows (e.g., 3 × 3, 5 × 5, × x 9, or 25 × 25 km grids) and temporal windows (e.g., intervals of ±15, ±30, ±60, ±90, or ±120 min) are employed, which could affect the interpretation of the results and the conclusions (Martins et al., 2017; Falah et al., 2021; Shaylor et al., 2022). Addressing these uncertainties through specific validation analyses would improve the reliability of satellite-derived AOD and expand its application in air quality studies. In addition, the scarcity of surface measurements limits the understanding of aerosol and pollutant distribution, increasing the vulnerability of many countries in the region (Carmona et al., 2021; Sawant et al., 2024).

To address these issues in the region, we evaluated the performance and assessed the uncertainty of satellite-derived AOD in Latin American urban centers, with emphasis on the MAIAC C6.1 product due to its spatial resolution. The analysis includes six sites in densely populated cities across Latin America (São Paulo, Santiago, Buenos Aires, Medellín, La Paz, and Mexico City) from 2015 to 2022. Additionally, the MAIAC and MODIS DT 3 km products are compared to assess differences in spatial resolution, and the previous version of MAIAC (C6.0) is examined to identify the improvements introduced. From this comparative approach, we seek to answer: how does the performance of satellite-derived AOD vary according to product, version, and resolution?

2. Methodology

2.1 Study sites

Level 2.0 (L2.0) data from AERONET network (Holben et al., 1998), available at https://aeronet.gsfc.nasa.gov/ (accessed on June 23, 2024), were used to evaluate the performance of the satellite-derived AOD products. The L2.0 data correspond to quality-assured and cloud-screened measurements, which are manually processed to remove outliers and instrumental errors, ensuring high accuracy and reliability for validation. Since AERONET does not provide AOD at 550 nm, the products were interpolated using the Ångström exponent (Ångström, 1929; Eck et al., 1999). As inclusion criteria for the study, each station was located in urban agglomerations with populations exceeding two million inhabitants, which must have L2 data records available to provide a basis for extended temporal analysis. Initially, an attempt was made to cover a 10-year analysis period. However, limitations in data continuity restricted the period to 2015-2022. Table I presents relevant information about the stations used.

The six cities are not only important economic, industrial, and transportation centers, but they also present unique challenges due to their demographic, topographic, and climatic characteristics, which

Table I. AERONET sites.

AERONET station	Code	Latitude	Longitu de	Elevation (masl)	Available period (L2)	Number of observations
Sao_Paulo (Brazil)	SP	23.56º S	46.73ºW	865	2000-2022	29 429
Santiago_Beauchef (Chile)	ST	33.45º S	70.66º W	560	2014-2022	48 397
CEILAP-Buenos ires (Argentina)	BA	34.56º S	58.51º W	10	1999-2022	78 711
Medellin (Colombia)	MD	6.261º N	75.578º W	1471	2012-2022	21 542
La_Paz (Bolivia)	LP	16.539º S	68.066º W	3439	2006-2022	79 720
Mexico_City (Mexico)	MX	19.33º N	99.182º W	2268	1991-2022	34 299

directly influence the dispersion and sources of atmospheric pollution. Mexico City, with a population exceeding 24 million, is located in a high-altitude valley (~2200 masl), surrounded by mountains that restrict air circulation, exacerbating the effects of heavy traffic and industrial activity (Soto-Coloballes, 2020; Baca-López et al., 2021). São Paulo, with over 23 million inhabitants, is located on a plateau and is partially surrounded by mountains to the north and northwest. Its subtropical climate, characterized by heavy rainfall, facilitates the deposition of pollutants, while frequent thermal inversions limit their dispersion, exacerbating air quality issues caused by vehicle and industrial emissions (Rangel and Tomé, 2022). Buenos Aires, with ~16 million inhabitants, is located in an extensive plain at the mouth of the Río de la Plata, where it flows into the Atlantic, which naturally facilitates the dispersion of atmospheric pollutants. However, intense vehicular and industrial activity, along with its proximity to agricultural areas with seasonal burning, contribute to the degradation of air quality (Diaz et al., 2018). Santiago, with ~8 million inhabitants, is situated between the Los Andes Mountains to the east and the Coastal Mountains to the west, which often limits ventilation and contributes to the accumulation of pollutants (Pérez and Menares, 2018). The primary sources of emissions are mobile and stationary, with notable contributions from industry and residential heating. Medellín, with a population of ~4 million, is located in the Aburrá Valley, a deep valley that restricts air circulation (Velásquez et al., 2021). The city's extensive vehicle fleet is a major contributor to air pollution. The La Paz-El Alto metropolitan area, with ~2 million inhabitants, has complex topography, with El Alto on the Altiplano plateau and La Paz extending across valleys. The region experiences alternating dry and wet seasons (Mardoñez-Balderrama et al., 2024).

2.2 Performance assessment

Two satellite-derived AOD products were evaluated: MAIAC 1 km (MCD19A2, C6.0 and C6.1) and MODIS DT 3 km (MOD04_3K and MYD04_3K). The evaluation was carried out using five spatial windows (1, 3, 5, 15, and 25 km) centered on each AERONET site, along with four temporal windows (±30, ±60, ±90, and ±120 min) centered on the satellite overpass time. All available overpass times from both Aqua and Terra satellites within the study period were considered. For MAIAC, a quality assurance (QA) filter was applied to retain observations classified with the highest quality (QA = 0000) (Martins et al., 2017). For MODIS DT, the Optical_Depth_Land_And_Ocean subset was used, selecting only pixels with a QA = 3 over land surfaces (Levy et al., 2013). Figure 1 illustrates the selected sites and the corresponding area of interest (25 km buffer).

The evaluation methods used were: (*i*) linear regression, (*ii*) coefficient of determination (R^2), (*iii*) root mean square error (RMSE), (*iv*) bias, and (v) number of matchups (n). The metrics were calculated using Eqs. [1-3].

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(AOD_{Satellite} - AOD_{AERONET})^2}{\sum_{i=1}^{n}(AOD_{AERONET} - \overline{AOD_{AERONET}})^2} \quad (1)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(AOD_{Satellite} - AOD_{AERONET})^2}{N}} \quad (2)$$

$$Bias = \frac{\sum_{i=1}^{n}(AOD_{Satellite} - AOD_{AERONET})}{N} \quad (3)$$

where $AOD_{Satellite}$ and $AOD_{AERONET}$ refer to satellite-derived and measurements, respectively. $\overline{AOD_{AERONET}}$ is AERONET daily averages.

3. Results and discussion

3.1 AOD variability and missing data

Figure 2 shows a histogram of AOD550 for the period 2015-2022, based on daily averages recorded at each AERONET station. As observed, AOD levels were generally low at all sites (AOD < 0.2). The lowest levels were observed in La Paz (LP, average = 0.09), followed by Buenos Aires (BA, average = 0.10). Meanwhile, Mexico City (MX) showed the highest average levels (average = 0.29), followed by Medellín (MD, average = 0.20). Papachristopoulou et al. (2022) reported similar findings, highlighting that in several cities across America and Europe, AOD levels ranged between 0.08 and 0.20, representing some of the lowest levels observed worldwide. The standard deviation (SD) at each site was comparable in magnitude to the mean, indicating a significant relative variation. In absolute terms, MX exhibited the highest variability (SD = 0.19), whereas LP, conversely, showed the lowest variation (SD = 0.05).

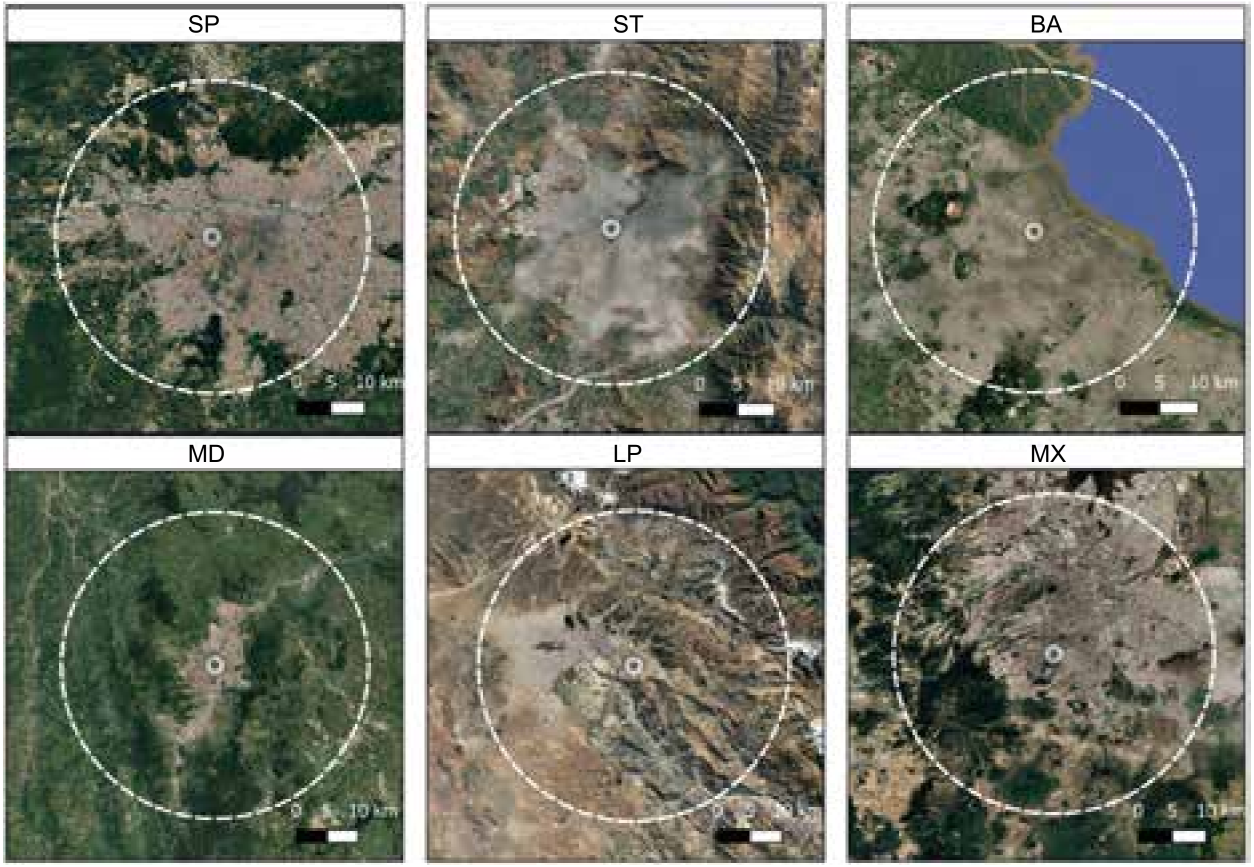

Fig. 1. AERONET stations in six Latin American cities and their area of interest (25-km window).

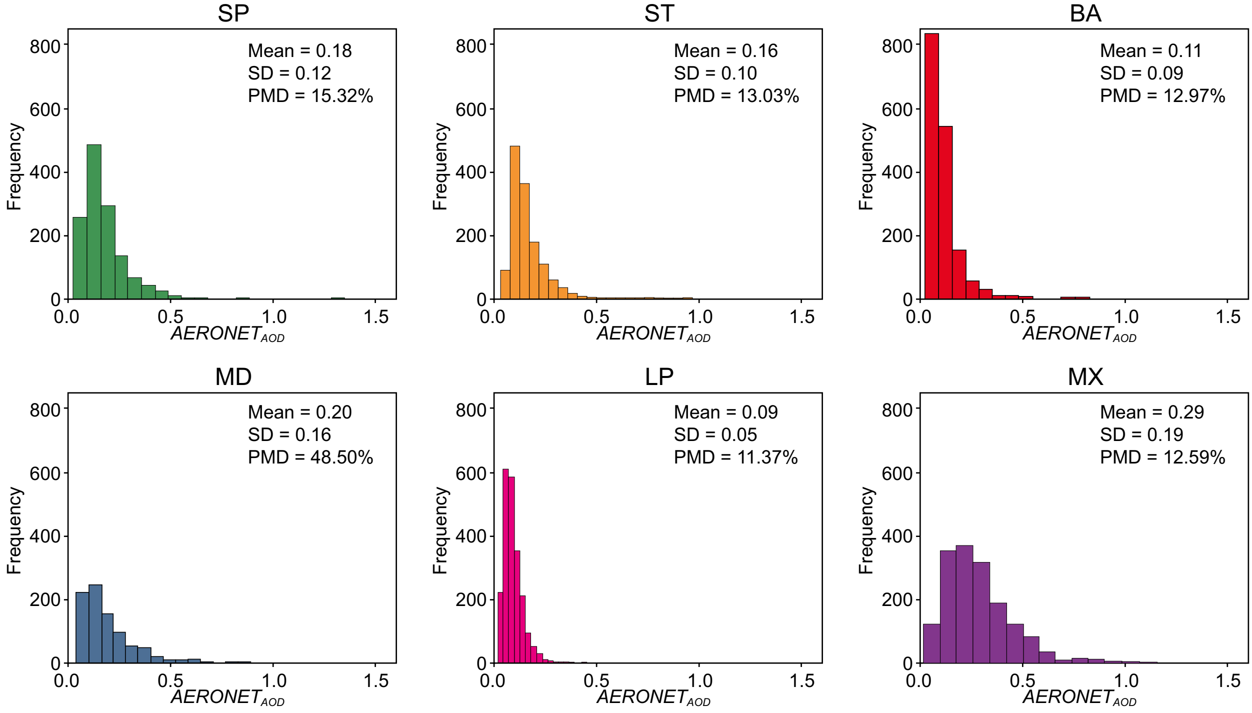

Fig. 2. Histogram of daily $\mathrm{AOD}_{\mathrm{AERONET}}$ averages. PMD represents the percentage of missing data.

Several extreme AOD events observed during the study period coincided with biomass burning episodes, particularly in SP, LP, and MD (Bencherif et al., 2020; Cazorla et al., 2024). These episodes, along with cloud cover and other meteorological conditions, contribute to data availability discontinuities and pose challenges for model validation and trend analysis, particularly when traditional metrics that require consistent data are used (Chudnovsky et al., 2013; Ștefănie et al., 2023). This issue was particularly relevant at the analyzed sites. For example, in MD, the percentage of missing data amounted to 48.50%, while in SP it was 15.32%. At the other sites, this was below 13.03%, with LP having the most complete time series, although it had 11.37% of missing data. Despite this, MD was retained in the analysis due to its representativeness as a high-density urban area, environmental diversity, and the scarcity of monitoring stations, making it a relevant site for evaluating the satellite product's performance.

3.2 Overall performance of MAIAC C6.1

Figure 3 presents a comparative evaluation of the MAIAC C6.1 algorithm's performance across Latin American sites, using R^2, RMSE, and bias metrics for five spatial and four temporal windows (a total of 20 combinations per site). The R^2 values ranged from low to moderate (< 0.8), with the lowest values in LP and the highest in SP, showing high variability among the different window combinations within each site. The RMSE varied between 0.05 (BA) and 0.11 (MX), while the bias ranged from –0.05 (Santiago [ST]) to +0.06 (LP). The SP, ST, and MX sites showed a tendency for underestimation, whereas LP, MD, and

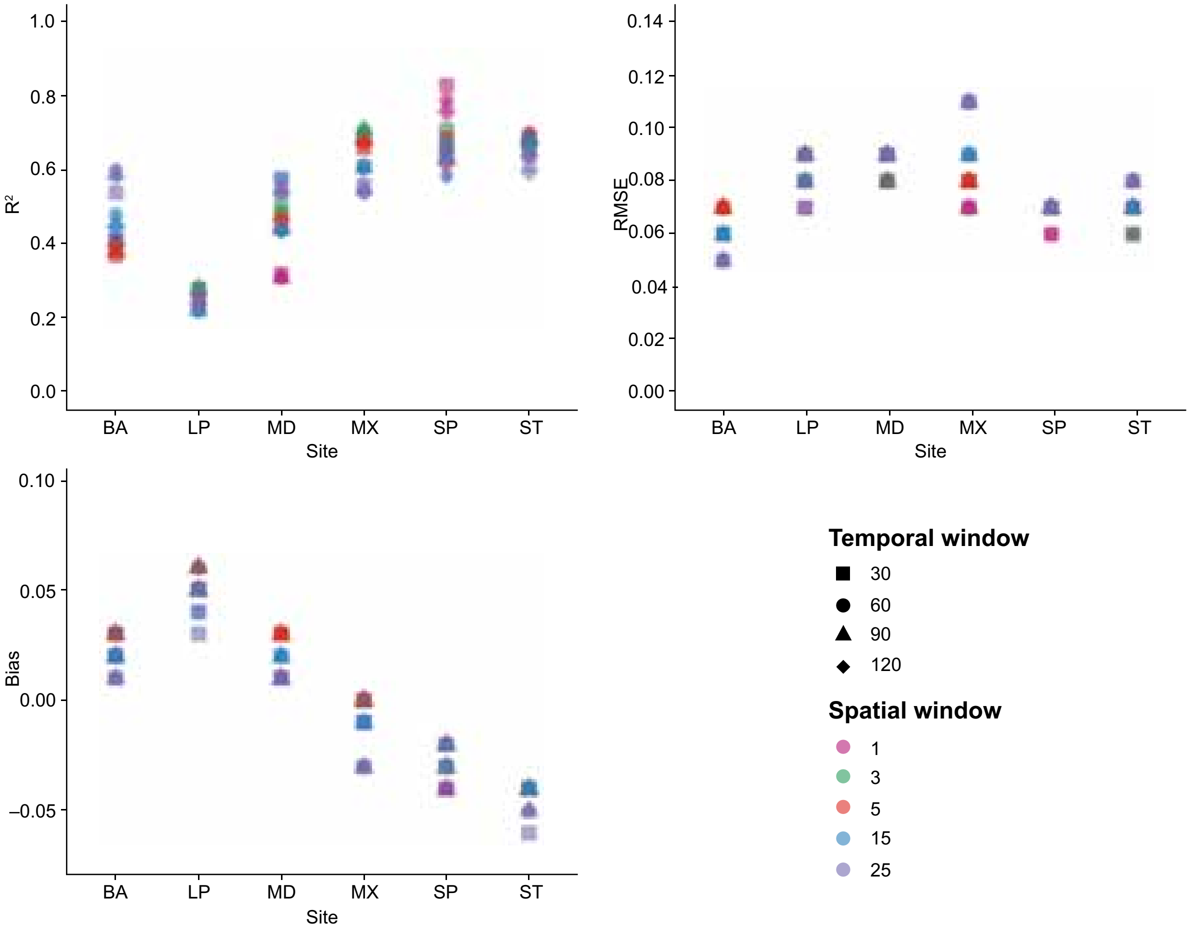

Fig. 3. MAIAC C6.1 Performance metrics. (a) R^2; b) RMSE; c) bias for the space-time windows evaluated at each site.

BA tended to overestimate AOD. Unlike R^2, these metrics exhibited lower variability across the window combinations within each site. These results allowed the identification of two groups: (i) LP and BA, with poorer performance (lower R^2, positive bias [overestimation], and lower AOD levels); and (ii) SP, ST, and MX, with better performance (higher R^2, negative bias [underestimation], and higher AOD levels). MD served as an exception, with similar metrics to the first group but higher AOD levels. However, the high percentage of missing data (section 3.1) limited the ability to obtain solid conclusions about the satellite performance. The analysis of spatial windows revealed that the highest resolution window (1 km-pixel) demonstrated the best performance (higher R^2 and lower RMSE) for LP, MX, ST, and SP. For these sites, model performance generally decreased as the spatial window size increased, with the lowest performance observed at the largest window size (25 km). In BA and MD, the 15 and 25 km windows exhibited a better R^2, although with a variable RMSE. Regarding the bias, in SP, the metric decreased as the spatial window size increased, showing the highest values at 1 km, despite also recording the best R^2 and RMSE results at this window. In LP, MD, and BA, the bias closest to zero was found in the 25 km windows, followed by the 1 km window, with an increase observed in the intermediate windows. This behavior is not uniform across all sites and could be associated with the land use patterns (a proxy for reflectance) (Zhdanova et al., 2020). Regarding the performance based on the time intervals used, the metrics exhibited minimal variability as the temporal window size increased at each site. Due to this low variability, a more detailed analysis of this factor was not performed.

The results obtained are consistent with those reported by other authors. Martins et al. (2017) highlighted that the temporal interval had a limited impact on the evaluated metrics. Zhang et al. (2019) found that, in China, a 25 km/±60 min interval yielded the best performance compared to a 3 km window, suggesting that higher spatial resolution does not always improve accuracy. In contrast, Falah et al. (2021) and Shaylor et al. (2022) concluded that spatial and temporal windows larger than 1 km and ±15 min, respectively, do not provide significant improvements, and that the metrics tend to stabilize beyond 15 km. Nonetheless, increasing the spatial window can raise uncertainties from surface reflectance, especially in heterogeneous urban areas, with local factors (topography, aerosol properties, meteorology) also influencing results (Mei et al., 2019; Chen et al., 2021). Martins et al. (2017) found that mixed land cover areas (LP) agree better than dense urban zones (BA, SP). However, our study shows LP's lower performance, indicating land cover alone does not explain discrepancies. These results highlight the importance of local context beyond aerosol load in algorithm performance.

3.3 MAIAC C6.1 performance at 1 km

Air quality assessment in urban areas requires high spatiotemporal resolution. In this context, MAIAC (1 km), is a useful tool for estimating PM with a diameter less than 2.5 micrometers ($PM_{2.5}$) (Pu and Yoo, 2021). Although validation methodologies with AERONET vary across studies and spatiotemporal windows, it is crucial to assess performance at the pixel level. As discussed in the previous section, performance can vary depending on the window used, especially at the spatial level. While pixel-level performance may not always be the best, it should be considered when using MAIAC for other purposes. Figure 4 presents the performance metrics for the analyzed cities using the AOD product with a 1 km and ±60 min window. The R^2 values ranged between 0.27 and 0.79, with the best results in SP, MX, and ST. In contrast, the remaining cities exhibited values lower than 0.50, indicating a poorer model fit in these locations. The RMSE varied from 0.06 to 0.08, showing relative differences between the sites. SP and ST had better regression fits (intercepts ≈ 0, slopes ≈ 0.7), while LP and MD showed poorer agreement (intercepts ≈ 0.07, slopes 0.60-0.67). These patterns indicate challenges in accurately retrieving surface reflectance and representing local aerosol properties. High intercepts suggest biases in surface reflectance retrieval, while low slopes reflect discrepancies between modeled and observed aerosol characteristics (Falah et al., 2021). In all cases, the regression line lay below the 1:1 line, with the data points showing some dispersion, predominantly clustering near the 1:1 line at lower AOD levels. In particular, for ST, SP, and MX—where the highest AOD values were found across all sites (averaging from 0.16 in ST to 0.29 in MX)—the satellite product tended to underestimate

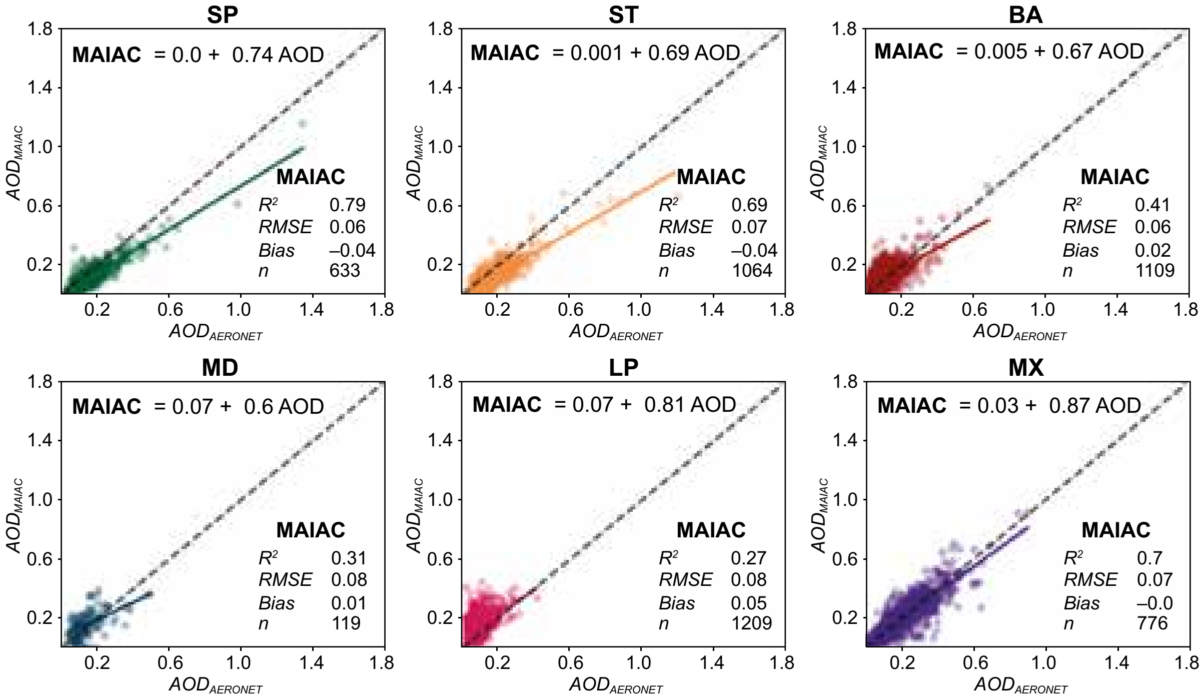

Fig. 4. Regression and associated metrics for MAIAC C6.1 with a 1 km/±60 min window for each site. The black dashed line represents the 1:1 line, and the regression line is shown in solid color.

AOD, with a bias ranging from –0.04 to –0.002. Conversely, in BA, LP, and MD, the measurements were overestimated, with bias values ranging from 0.01 to 0.05.

These results are consistent with findings from other urban areas characterized by bright surfaces. For instance, Mhawish et al. (2019) in South Asia and Ettehadi Osgouei et al. (2022) in Turkey, Greece, and Bulgaria reported negative bias with RMSE values comparable to those found here. Likewise, Tao et al. (2019) reported similar underestimations in China for comparable AOD levels. Falah et al. (2021) demonstrated that a negative bias for AOD values between 0.1 and 0.3 is common, regardless of location, while lower correlations may result from retrievals over brighter surfaces. Martins et al. (2017) reported slight underestimations in urban and mixed areas for low AOD (< 0.2). In contrast, Rogozovsky et al. (2023) found that MAIAC overestimates AOD under very clear atmospheric conditions in urban areas of the Eastern Mediterranean. Jethva et al. (2019) reported better correlations and lower RMSE in North American urban areas, with a negative bias similar to the one observed in this study. This is because complex urban areas present challenges for satellite aerosol retrievals, as even small errors in surface reflectance estimates can propagate and increase the overall bias (Martins et al., 2017; Tao et al., 2019). In cases of low AOD levels (< 0.2), the static aerosol models used by the MAIAC algorithm may not account for in situ conditions related to spatiotemporal variations in environmental attributes and aerosol properties (Lyapustin et al., 2018).

3.4 Improvements compared to MAIAC C6.0

A comparative analysis between MAIAC C6.0 and C6.1 was conducted to evaluate the impact of the recent algorithm enhancements on AOD retrieval performance in the study area. Figure 5 presents the linear regression results for a 1 km/±60 min window in both collections. In terms of R^2, the performance ranged from low to moderate (0.32-0.83) for both products, with slight differences observed across most sites. For C6.1, a slight improvement was observed in MX and ST, while in SP, the performance remained unchanged. In contrast, the C6.0 version exhibited a better R^2 at BA

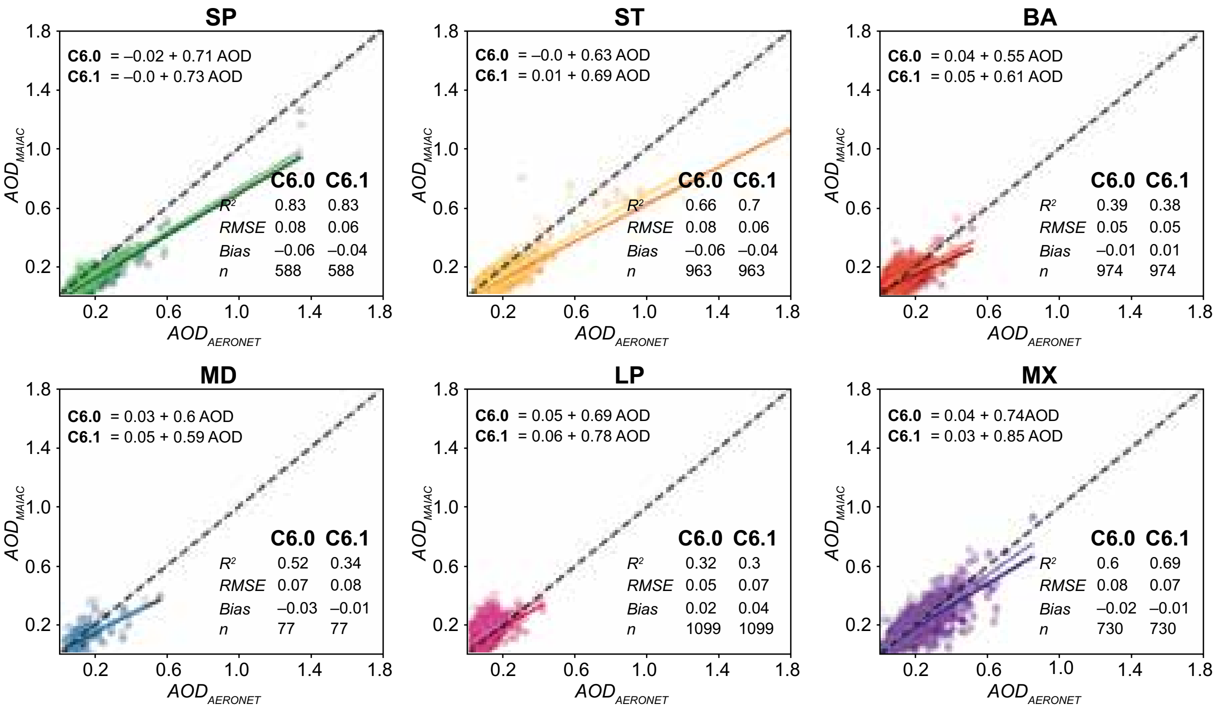

Fig. 5. Regression lines and associated metrics for MAIAC C6.0 and C6.1 at the study sites (1 km/±60 min window).

and LP. At MD, however, a significant decrease in the metric was observed (from 0.52 for C6.0 to 0.34 for C6.1). The RMSE (0.05-0.08) was consistent across sites and versions, with improvements in C6.1 for SP, ST, and MX, and in C6.0 for MD and LP. Regarding bias, AOD was underestimated in SP, ST, MX, and MD in both collections, with a reduction in the metric for C6.1. In contrast, reference values tended to be overestimated in LP, showing an increase in the metric for C6.1. In BA, C6.0 underestimated, while C6.1 overestimated AOD, although both exhibited the same absolute values. The regression line in C6.1 was closer to the 1:1 line at high AOD levels, while at lower levels, both versions showed similar results. Additionally, no significant differences were observed in data dispersion between the two collections. These results suggest that MAIAC C6.1 offers a partial improvement over its predecessor.

Recent studies have evaluated these improvements in different regions. In the western United States, Ye et al. (2022) analyzed extreme wildfire events and found that MAIAC C6.1 provides more accurate retrieval compared to C6.0, which significantly underestimates values in dense smoke conditions. This confirms the impact of the implemented modifications and is particularly relevant for the urban centers included in this study, where intense wildfire seasons dominate (de Miranda et al., 2016; Vara-Vela et al., 2018; Mardoñez et al., 2023). In China, the algorithm update showed mixed behavior. While the overall accuracy of MAIAC C6.1 slightly improved, regional differences were observed: performance increased in the northern, central-eastern, and western parts of the country, but decreased in the south (Huang et al., 2024). Therefore, deviations in AOD retrieval persist due to two main challenges: (i) the high spatial and temporal variability of aerosols, which limits the accuracy of static aerosol models; and (ii) the presence of bright surfaces, which complicate the estimation of surface reflectance and increase the uncertainty satellite retrievals (Martins et al., 2017; Qin et al., 2021). Nonetheless, recent improvements in the MAIAC have contributed to reducing bias and enhancing AOD accuracy.

Despite these advancements, studies comparing both versions remain limited in Latin America, where, to our knowledge, no specific studies have evaluated the improvements.

3.5 MODIS DT 3 km-MAIAC C6.1

This section evaluates the performance of MODIS DT and MAIAC C6.1 to assess their suitability for urban-scale analyses. Considering the heterogeneous land cover typically found around urban sites, the DT algorithm is especially appropriate for this study. Since MODIS DT is natively available at 3 km, MAIAC data were aggregated using a 3 km spatial window to ensure a consistent comparison. Figure 6 compares the MODIS DT and MAIAC products. Both products exhibit noticeable and variable differences relative to the 1:1 line, as well as in the dispersion of points around this line. In general, the regression lines of MODIS DT lie above the 1:1 line, whereas MAIAC tends to fall below it. In sites like MX and LP, MAIAC is closer to the 1:1 line, while in sites like MD and SP, MODIS DT exhibits better relative accuracy. Both products exhibited differences in their explanatory capacity, although the variability of R^2 was greater in MODIS DT (from 0.18 in BA to 0.85 in SP) compared to MAIAC (from 0.25 in LP to 0.81 in SP). SP was the site with the best fit for both products, whereas BA and LP showed the lowest values, possibly related to lower AOD levels. In LP, although R^2 improved by 9.96% in MAIAC, performance remained low ($R^2 < 0.5$) for both products. However, MODIS showed better results in MD (17.78%) and SP (5.32%). Regarding RMSE, MAIAC exhibited lower variability (ranging from 0.06 in BA to 0.09 in MD) compared to MODIS (from 0.07 in SP to 0.23 in BA). Relative to bias, MODIS tended to overestimate across all sites (ranging from 0.01 in SP to 0.16 in BA), while MAIAC alternated between underestimations (MX, SP, ST) and overestimations (MD, BA, LP). These results reinforce how local conditions strongly influence algorithm performance and highlight the value of incorporating uncertainty-based metrics into satellite evaluations.

Unlike MODIS DT, which uses predefined static surface reflectance ratios, MAIAC estimates them dynamically using time series analysis (Lyapustin et al., 2018; Chen et al., 2021). This adaptive methodology enhances the accuracy of surface reflectance characterization and likely contributes to MAIAC's superior performance in urban areas, where high reflectance and surface heterogeneity complicate AOD

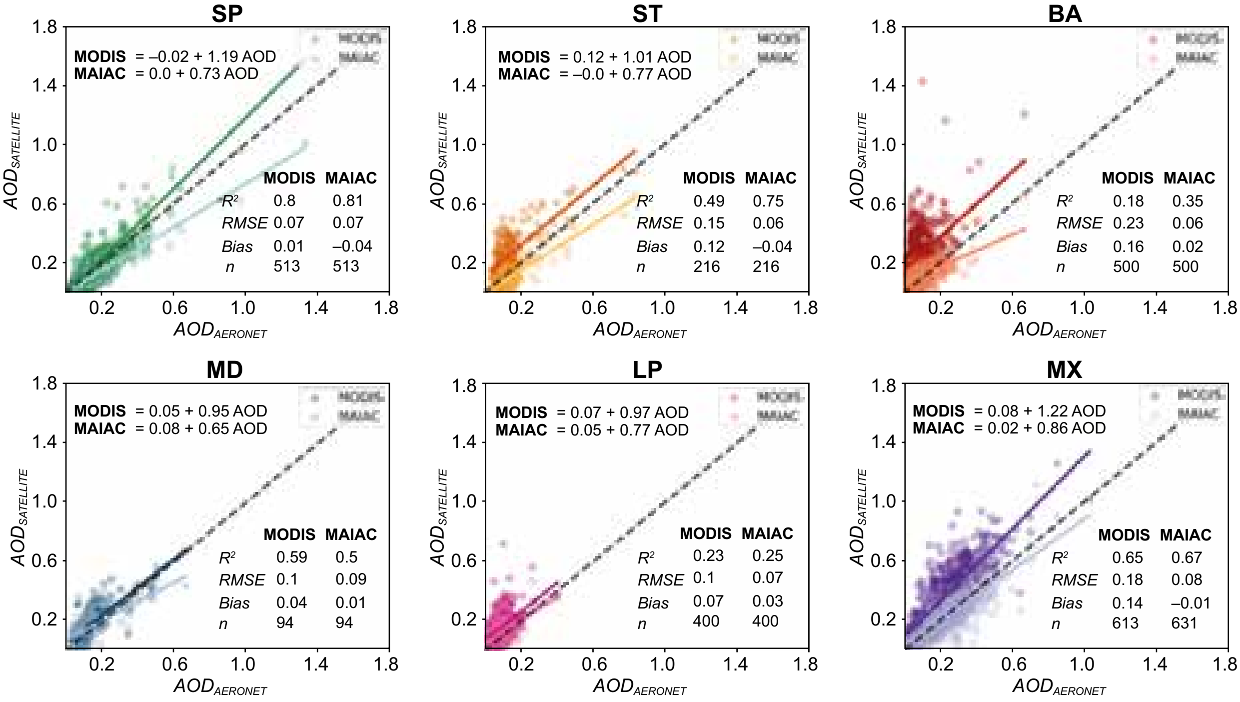

Fig. 6. Regression lines and associated metrics for MAIAC C6.0 and MODIS DT (3 km) at the study sites (1 km/±60 min window).

retrievals. Previous studies indicate that MAIAC performs better than MODIS DT (Liu et al., 2019; Chen et al., 2021). Although MODIS DT provides better recoveries in forested areas, it exhibits a positive bias compared to MAIAC, as observed in SP. This occurs because its algorithm assumes that aerosols increase the measured signal, which is not the case over bright surfaces, leading to increased noise (Munchak et al., 2013; Ye et al., 2022). In contrast, MAIAC improves AOD accuracy in urban areas and over bright surfaces (Lyapustin et al., 2018; Zhang et al., 2019). While some authors suggest that its performance over bright surfaces is lower than over darker surfaces, it still exceeds the performance of the MODIS DT algorithms (Mhawish et al., 2019; Qin et al., 2021). The findings underscore how urban aerosol variability challenges models relying on generalized assumptions, emphasizing the advantage of adaptive approaches like MAIAC (Zhdanova et al., 2020).

4. Conclusions

This study evaluated the performance of the MAIAC C6.1 product in several urban centers across Latin America. A lack of ground-based AOD data was observed, particularly in MD and SP, alongside low AOD values (< 0.2) in LP and BA. The performance of MAIAC C6.1 revealed two distinct groups: (*i*) LP and BA, exhibiting poorer performance (lower R^2, positive bias, and lower AOD levels); and (*ii*) SP, ST, and MX, demonstrating better performance (higher R^2, negative bias, and higher AOD levels). Significant differences in performance metrics were found depending on the spatial window size, while the temporal window size did not significantly affect the results. The behavior observed in MD was atypical, likely due to the substantial amount of missing data. Finer spatial windows (1 km) generally improved performance, supporting their use in urban studies. This highlights the importance of considering local context when selecting spatial resolution for satellite-based aerosol assessments.

Compared to MAIAC C6.0, no substantial improvements were observed in R^2 and RMSE; however, a noticeable reduction in bias was evident across most sites in C6.1. These modest improvements were more pronounced at sites with higher AOD levels, while in low-AOD environments, performance gains were marginal or even negative, highlighting ongoing challenges in retrieving weak aerosol signals over bright surfaces.

When compared to MODIS DT, MAIAC C6.1 demonstrated greater precision and exhibited a lower absolute bias, as MODIS overestimates AOD at all sites, while MAIAC alternates between underestimation and overestimation, but to a lesser degree. This improved performance is attributable to its adaptive capacity to estimate surface reflectance using time series analysis, making MAIAC more suitable for air quality studies urban environments.

Nonetheless, this study presents some limitations that must be considered. Firstly, the evaluation is based on a relatively small set of urban AERONET stations, with only one collocated site per city, which restricts spatial representativeness and may not adequately reflect the variability of aerosols within urban areas. Secondly, the analysis was limited to a subset of satellite AOD products, specifically MAIAC and MODIS DT, leaving out other retrieval algorithms such as Deep Blue and newer satellite products (VIIRS, PACE). Finally, to ensure a consistent multi-year assessment, a minimum temporal coverage criterion was applied, which resulted in the exclusion of several potential sites in Latin America and reduced the overall number of cities included. Together, these factors limit the robustness and representativeness of the study's findings.

However, these findings suggest that while recent advancements in high-resolution products such as MAIAC C6.1 have improved AOD retrieval performance, significant limitations remain. Our results highlight the need to adapt AOD retrieval algorithms to the local characteristics of the region in order to overcome these limitations. It is recommended to conduct continuous validation of satellite AOD products using local data, such as those provided by the AERONET network, especially in urban areas with limited coverage. Looking ahead, our next step will be to use satellite-derived AOD to estimate ground-level $PM_{2.5}$, with the aim of improving exposure assessments and supporting the development of region-specific air quality policies.

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