



Research Articles

METROCLIMA-MASP: pioneering urban greenhouse gas monitoring in South America's largest megacity

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ABSTRACT

Cities account for over half of global greenhouse gas (GHG) emissions, yet monitoring is very limited, especially in the Global South. A GHG monitoring network was established in 2019 in São Paulo, the largest metropolitan area in the Southern Hemisphere. Five sites were strategically selected, including four measuring surface mole fraction of carbon monoxide (CO), carbon dioxide (CO₂), and methane (CH₄): Pico do Jaraguá (PDJ; −23.46°, −46.77°), IAG (−23.56°, −46.73°), UNICID (−23.54°, −46.56°), and ICESP (−23.56°, −46.67°). The fifth site, CIENTEC (−23.65°, −46.62°), was dedicated to measuring CO₂ fluxes within a vegetated area. At IAG, δ¹³C-CO₂ was also measured. The results revealed the influence of local sources, vegetation, and surface characteristics on GHG patterns. The elevated, forested site of PDJ provided urban background GHG levels, while urban core sites were heavily affected by traffic and biomass burning. CO₂ levels increased across the city, with annual growth rates of 4.86 ± 2.84 ppm at UNICID (from 2021 to 2024), 4.92 ± 0.56 ppm at IAG (from 2021 to 2024), and 1.67 ± 0.38 ppm at PDJ (2019–2024). CH₄ levels were more stable, exhibiting minor seasonal variability and no clear trend at PDJ. At UNICID, strong CO₂-CO correlations ($r > 0.9$) during traffic peaks suggested emissions dominated by combustion, while weaker correlations during outside peak hours ($r < 0.7$) indicated the uptake of CO₂ by the vegetation. Diurnal CO₂ patterns across stations reflected the balance between human activity and biogenic processes, driven by photosynthesis and respiration, emphasizing the role of vegetation in modulating urban CO₂ levels. These results highlight the importance of urban GHG measurements for understanding emission dynamics, assessing the influence of urban structure and meteorology, and supporting mitigation strategies at the city scale. This work clearly highlights the need to establish similar networks across Latin America to fill this critical data gap, which is key for developing effective climate mitigation strategies.

Introduction

According to the World Meteorological Organisation (WMO) bulletin on greenhouse gas (GHG) mole fractions, the carbon dioxide (CO₂) in the atmosphere increased 2.57 ppm/yr in the last 10 years (2015–2024) primarily due to anthropogenic emissions[47]. The oceans and land ecosystems are responsible for absorbing half of the atmospheric CO₂,

however, each region in the world exhibits specific characteristics regarding the origin of this gas, from fuel burning to biomass combustion, resulting in a net positive mole fraction as the sinking processes are not removing it from the atmosphere at the same rate as the emissions. Globally, the primary CO₂ sources include fuel combustion for energy generation, such as coal burning, cement production, transport, and the use of domestic solid fuels for cooking and heating [11].

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CO₂ emission inventories are based on bottom-up estimates derived from emission factors and present great variation among different studies. Andrew [2] reviewed various global CO₂ emission inventories and found significant differences which can affect the CO₂ global budget. To improve the city's CO₂ emissions inventory, measurements have been performed at various cities, mainly from those with significant economic activity. The INFLUX (Indianapolis Flux Experiment) network, comprising twelve communication towers, measures CO₂, methane (CH₄), and carbon monoxide (CO) mole fractions[41]. It has successfully detected urban signals and observed increased mole fractions downwind of the city. The quantification of fossil fuel CO₂ emissions with high spatial and temporal resolution is very important in carbon cycle and climate change research, as described by Gurney et al. [13], who presented the “Vulcan” inventory (<https://vulcan.rc.nau.edu>).

The combination of large, concentrated carbon fluxes and rapid change makes cities critical components of the carbon cycle, offering the potential for them to act as “first responders” in climate action[16]. There is increasing interest in constraining and validating greenhouse gas (GHG) emission inventories at both urban and intra-urban scales. Christen [5] provided a comprehensive review of methods used to identify, quantify, and attribute emissions and sequestration of CO₂, CH₄, and nitrous oxide (N₂O) in cities, using in situ atmospheric measurements. In-situ urban GHG measurements can be implemented at multiple spatial scales: (i) at the micro-scale by capturing emissions from individual sources with mobile platforms and measuring vertical profiles within the urban canopy layer; (ii) at the local scale through direct eddy-covariance flux measurements taken from towers; and (iii) at the mesoscale, by analyzing mixing ratios and isotopologues of GHGs within the urban and rural boundary layers, in combination with box and inverse modeling approaches.

Several studies have highlighted discrepancies between local and global inventories. For instance, Huneus et al. [15] compared local and global inventories in South America, revealing significant differences. Similarly, Wu et al. [48] quantified CO₂ emissions for 20 cities worldwide based on OCO-2 satellite data, and showed that denser cities are more efficient in reducing emissions, particularly in transportation, by promoting shared infrastructure and shorter commutes.

Urban areas are central to the global efforts to mitigate climate change, as they concentrate economic activity, energy use, and GHG emissions. Cities in the Global South, including those in Latin America, remain underrepresented in atmospheric GHG monitoring networks. This gap limits the ability to evaluate emission inventories, support climate policy, and understand urban carbon dynamics under region-specific conditions. Improved quantification and understanding of urban processes will provide policy-relevant insights, enhance our understanding of urban dynamics and future scenarios, and lead to more accurate estimates of anthropogenic fluxes. This will advance our knowledge of the carbon cycle and climate feedback across multiple scales.

Verhulst et al. [42] reported CO₂ and CH₄ measurements in 2015 as part of the Los Angeles Megacity Carbon Project. They used two marine and offshore sites near San Clemente Island to establish background concentrations. The study estimated these mole fractions and addressed the calibration process, which remains a key factor in ensuring data quality. In the Paris Megacity, Xueref-Remy et al. [49] described the diurnal, synoptic, and seasonal variability of CO₂. They found that diurnal CO₂ cycles at regional stations were primarily driven by the biogenic CO₂ cycle, the atmospheric boundary layer height (ABLH) cycle, and urban CO₂ emissions. During the Paris Megacity experiment, two elevated sites, including one at the Eiffel Tower, exhibited a phase shift of a few hours in the CO₂ diurnal cycle relative to lower-altitude sites. This shift was linked to the diurnal cycle of the boundary layer.

São Paulo, the largest metropolitan area in South America, represents a critical case for addressing the knowledge gap in GHG emission inventory. Despite its size and complexity, long-term, in-situ

measurements of GHG mole fraction are not available. To address this, the METROCLIMA network was established in 2019 (<https://www.metroclima.iag.usp.br>), providing continuous, multi-year observations of CO₂, CH₄, and CO at key sites across the city. These include central (ICESP, UNICID), urban (ICESP), suburban (IAG), and forest-urban interface locations (Pico do Jaraguá – PDJ). This network delivers the first high-resolution, multiple sites dataset of atmospheric GHGs for São Paulo, enabling the analysis of spatial and temporal variability across different urban contexts. The availability of this dataset opens new opportunities to investigate the interplay between emissions, urban morphology, and meteorological drivers, and to support the development of climate mitigation strategies at the municipal level.

The ratio of CO-CO₂ in the atmosphere serves as an indicator of combustion efficiency, since both gases typically originate from the same combustion processes and exhibit characteristic emission ratios [45]. Such CO-CO₂ relationship is also valuable for constraining other emission source types, such as biomass burning, since its ratios are one order of magnitude smaller than those from fossil fuel power plants [44]. Recently, in Shanghai, China, Wei et al. [46] investigated the relationships between GHGs and atmospheric pollutants, identifying a significant correlation between CO₂ and CO mole fraction associated with vehicular emissions.

The city of São Paulo, with its 11.5 million inhabitants [19], is a significant source of CO₂ emissions (Table 1), primarily due to its extensive vehicular fleet of 9.7 million vehicles, including 6.4 million passenger cars (Ministério [28]). Experimental campaigns conducted in the city traffic tunnels have obtained values similar to the official reports, which provide estimates of total CO₂ emissions from gasohol and ethanol combustion [32]. The city is not only affected by fossil fuel emissions but also by biomass burning [33,38]. According to Souto-Oliveira et al. [39], the Pantanal fires in Central Brazil in 2020 led to an increase of over 100% in CO₂ levels, as indicated by $\delta^{13}\text{C-CO}_2$ measurements.

Brazil has implemented initiatives to develop emission inventories for both greenhouse gases and regulated pollutants. The SEEG[37], managed by Observatório do Clima (<https://plataforma.seeg.eco.br/>), provides emissions data at the national, state, and selected metropolitan levels. According to these official inventories, Brazil emitted 2.3 GtCO₂e in 2023, following the GWP-100 AR5 estimation protocol. Land-use change was the largest contributor, accounting for 46.2% of total emissions, followed by the agriculture sector at 27.5%. Brazil's net emissions amounted to 1.7 GtCO₂e when considering carbon removals by the vegetation. The state of São Paulo contributed 8.9% of the country's net emissions, with the energy sector being the dominant

Table 1

Methane (CH₄) and carbon dioxide (CO₂) emissions in metric tons for São Paulo City and the entire State of São Paulo (SP) across five key emission sectors: Agriculture and Livestock, Energy, Land-Use Change and Forestry, Industrial Processes, and Waste. Emissions data for 2023 from <https://seeg.eco.br/>. The numbers in parentheses indicate the percentage contribution of each sector to the total emissions of the respective GHG.

	CH ₄ (t)		CO ₂ (t)	
	São Paulo City	SP	São Paulo City	SP
Agriculture and Livestock	50 (0%)	682,992 (53.7%)	38 (0%)	3,005,160 (2.9%)
Energy	1,612 (1.2%)	19,072 (1.5%)	10,396,754 (99.7%)	87,310,141 (84.5%)
Land-Use Change and Forestry	10 (0%)	3,754 (0.3%)	21,402 (0.2%)	9,585,370 (9.3%)
Industrial Processes	0	261 (0%)	0	3,431,820 (3.3%)
Waste	131,538 (98.7%)	566,251 (44.5%)	6,037 (0.1%)	35,422 (0%)
Total	133,211	1,272,329	10,424,231	103,367,913

source (60.8%). In the city of São Paulo, the energy sector was responsible for 74.7% of emissions, with transportation accounting for the majority (88.0%) of this sector's share (9,108,718 t of CO₂). At the state level, transportation remains a major contributor, responsible for 48,999,486 t of CO₂ (56% of total energy emissions).

Despite urbanization, the biosphere continues to play a crucial role in CO₂ absorption, underscoring the importance of green spaces and the restoration of degraded areas within cities. The role of vegetation in the CO₂ balance is under study across diverse regions. For instance, Miller et al. [27] found that, for Los Angeles, the urban biosphere functions as a carbon source during winter and a carbon sink in summer, with an estimated seasonal variation of 4.3 ppm. This represents 33% of the annual average fossil fuel contribution of 13 ppm.

Kumar et al. [21] presented, in a review of worldwide studies, the positive role of vegetated areas in urban regions, including reductions in temperature and noise, the removal of pollutants, and the absorption of CO₂. The last role, CO₂ absorption, depends mainly on the type and distribution of vegetation in addition to meteorological conditions that influence the interactions between the biosphere and the atmosphere.

Methane mole fraction has increased globally, with the WMO [47] noting the most significant three-year increase from 2020 to 2022. This rise was primarily driven by anthropogenic emissions, mainly from livestock and fossil fuel production [36]. São Paulo city, being highly urbanized, contributes very little to CH₄ emissions from livestock and farming. For instance, from the total 133,211 t of CH₄ emitted in the São Paulo Municipality area, about 98% is due to the waste sector (Table 1). A source often considered negligible in many studies, but potentially significant, is the use of natural gas for cooking and in the transportation sector. In Brazil, most households use natural gas or Liquefied Petroleum Gas (PLG) for cooking, as these options are more cost-effective than electric ovens [8].

Therefore, measuring GHGs in the largest city in South America addresses an important information gap and highlights how surface characteristics, particularly vegetation cover, significantly influence their mole fractions. This study characterizes the diurnal and seasonal variability of CO₂, CH₄, and CO mole fractions in the city of São Paulo using data from the METROCLIMA network between 2019 and 2024 at five different sites. The results presented here mark the first study in South America to focus on a high-vehicular-emission-impacted megacity.

Materials and methods

Measurement network

The METROCLIMA network consists of five stations, four of which are equipped with Cavity Ring-Down Spectroscopy (CRDS) instruments to measure CO (at one site only), CO₂, and CH₄ mole fractions. Two of these stations were also equipped with CRDS for isotopic measurements during alternating periods. The fifth site measures CO₂ flux and vertical light backscatter profiles for boundary layer height assessments. Below is a detailed description of each station, including its surrounding area, instrumentation, and measurement period.

IAG Station

Located in a suburban area in the central-western part of the MASP, this station is positioned at an elevation of 731 m above sea level (asl). The air inlet is mounted on the rooftop of the Institute of Astronomy, Geophysics, and Atmospheric Sciences (IAG) building, 15 m above ground level (agl), within the University of São Paulo campus. The surrounding area features a mix of urban infrastructure, green spaces, and moderate density residential neighborhoods. The campus is surrounded by extensive vegetation, with large tree canopies and open grassy areas. Despite its proximity to major roadways and urbanized regions, the station is relatively isolated from direct emissions from heavy traffic and industrial sources. The IAG Station started its

operations in 2019 but was redesigned in 2020 to meet international standards. Here, it is presented continuous measurements of CO₂ and CH₄ from August 2020 through November 2024 with the Picarro CRDS G2301 series. During most of this period, isotopic measurements were also recorded using the Picarro CRDS G2201-i.

UNICID Station

Located in an urban area in the eastern part of the MASP, this station is situated at an elevation of 741 m asl. The air inlet is mounted on the rooftop of the City University of São Paulo (UNICID) building, 38 m agl. The site is surrounded by dense urban infrastructure, including medium-rise residential and commercial buildings, major roadways, and industrial zones. The area experiences heavy traffic, particularly from buses and freight transport, contributing to high local emissions. The UNICID Station commenced operations in early 2020, with some modifications made to the experimental setup during the first few months. Here, we present continuous measurements of CO, CO₂, and CH₄ from August 2020 through December 2024 using the Picarro CRDS G2401.

Pico do Jaraguá (PDJ) Station

Located in the highest location in the megacity of São Paulo, this station is located within the Jaraguá forest reserve, a protected area in the extreme western part of the MASP. It is at an elevation of 1,079 m asl, with the air inlet positioned 3 m agl at the air quality monitoring station operated by the State of São Paulo Environmental Company (CETESB). The surrounding landscape consists of dense Atlantic Forest vegetation. The site experiences lower temperatures and higher humidity compared to the urban dome, along with stronger winds due to its altitude and topographical exposure. During the night and early morning hours, the site is above the Atmospheric Boundary Layer, which is about 500–600 m high throughout the year [43,31]. These characteristics make it an ideal location for monitoring urban background atmospheric conditions with relatively low influence of urban emissions. The PDJ Station began operations in 2019 with the Picarro CRDS G2301 series and, starting in the second half of 2024, it has been operating with the Picarro CRDS G2201-i for isotopic measurements.

ICESP Station

Located in the densely populated urban core of the megacity of São Paulo, this station is situated on the rooftop of the Institute of Cancer of São Paulo (ICESP) at an elevation of 825 m asl. The air inlet is positioned 113 m agl. The surrounding landscape is dominated by high-rise commercial and residential buildings, with major avenues and highways contributing to heavy vehicular emissions. Limited green spaces and occasional tree-lined streets are interspersed among the concrete structures. The ICESP Station began operations in late 2020, measuring CO₂ and CH₄ fluxes using a Picarro CRDS G2311-f coupled with a sonic anemometer.

CIENTEC Station

Located in a suburban setting of the megacity of São Paulo, this station is situated within the Science and Technology Park of the University of São Paulo (CIENTEC) at an elevation of 810 m asl. A CHM15k ceilometer operates on the rooftop of the Museum of Meteorology, approximately 10 m agl, providing continuous light backscatter profiles. An IRGASON open-path gas analyzer (Campbell Scientific Inc., Logan, UT, USA) mounted on a tower at a height of 30 m agl, measures CO₂ and H₂O fluxes. This system integrates the open-path analyzer and sonic anemometer. The surrounding landscape consists of open green spaces, low rise institutional buildings, tree lined streets, and nearby water bodies, also surrounded by trees. The ceilometer started its operation on February 10, 2021, and the IRGASON system was installed later on October 20, 2021.

Fig. 1 shows the locations of the monitoring sites along with a surface characteristics map for the Metropolitan Area of São Paulo.

Local Climate Zone (LCZ) classification, determined using the LCZ

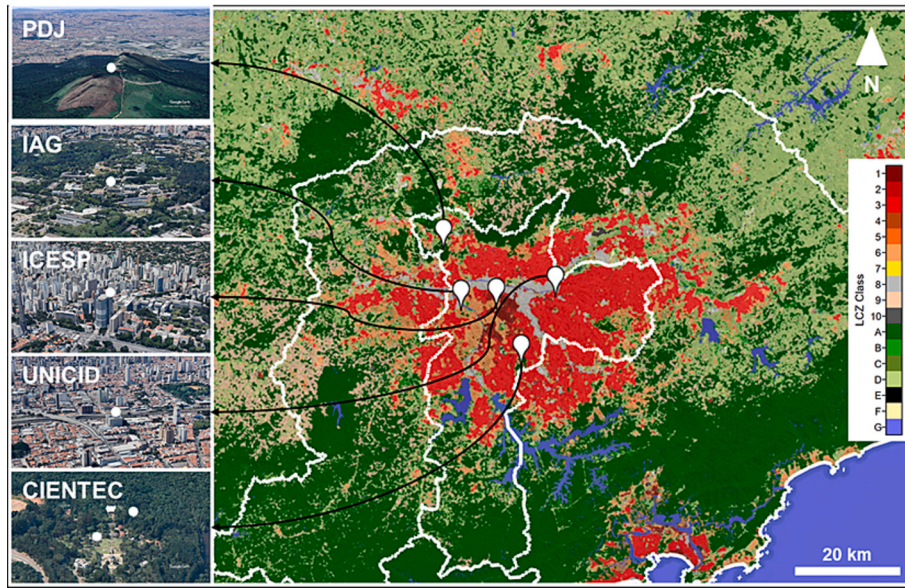


Fig. 1. METROCLIMA GHG Monitoring Network. The background map displays LCZ classifications (see reference table). The left panel shows photos of the immediate surroundings of each station. The map presents the outlines of Brazil and the state of São Paulo, highlighting the Metropolitan Area of São Paulo (MASP) and the city of São Paulo.

Generator from the WUDAPT Level 0 training data for São Paulo[6,20] was used to characterize the measurement sites. Table 2 presents the characteristics of each station, along with its corresponding LCZ classification.

In this study, we present data from three monitoring sites (IAG, UNICID, and PDJ), with a more comprehensive dataset covering the 2019–2024 period. Five years of data provide a representative overview of both seasonal and daily variations. Data from other sites are currently being processed and will be presented in a separate study.

Data Processing and quality Control

Stations with internet access automatically transfer data to the system at the IAG building every hour, while stations without internet access have their data collected manually at least once a week, depending on accessibility. We use the factor-corrected dry mole fractions (CO_2 dry and CH_4 dry) from the DataLog User file (not the synchronized one). These files contain a “species” column indicating the spectral range used for the measurements[12]. We filter the data by the species corresponding to the CO_2 measurements, referring to the resulting data as raw data.

Based on the raw data, three different flags were applied: (i) automatic flags (FA), (ii) manual flags (FM), and (iii) calibration flags (CAL). CAL flags are automatically assigned to identify standard gas tank sampling based on the position of the manifold described in the “MPVPosition” columns. Additionally, two timesteps before and twenty

timesteps after the tank sampling are flagged to account for potential interferences during the air sampling transition. Data flagged as CAL is removed from the time series and used to calculate calibration corrections, as described in the next section.

FA are applied using rules that identify timesteps when the cavity temperature is below 44.98°C or when any species mole fraction is zero. FM, on the other hand, is manually assigned by an expert to indicate any type of interference, including data contamination from station or instrument maintenance, as well as data that falls outside the expected range. In some cases, tank sampling was not identified by the “MPVPosition” variable. In these instances, we applied FM flags along with an internal descriptor to determine the corresponding periods.

After applying the aforementioned flags, the dataset is referred to as Level 0 data, and 1-minute time aggregations are then computed. The threshold for a valid minute varies by equipment. Hourly, daily, and monthly means are computed using data from the nearest time aggregation. Hourly and daily means are calculated when 75% of the data are available (at least 45 min for hourly and 18 h for daily), while monthly means are computed when approximately 50% of the data are available (at least 14 days).

Oftentimes, after Level 0 data and time aggregations are computed, certain interferences in the data become apparent. When this occurs, additional manual flags are applied, and the data is reprocessed. The described method was adapted from Hazan et al. [14].

Table 2

Experimental sites description, with the location and characteristics of the surface according to the LCZ classification.

Station	Measurements	Location (latitude and longitude in $^\circ$)	Elevation (m asl)	Sample height (m agl)	Surface classification
IAG (University campus)	CO_2 , CH_4 , $\delta^{13}\text{C}\text{-CO}_2$	–23.559478 –46.733533	731	15	LCZ 6 Open low-rise LCZ A Dense trees
UNICID (Downtown area)	CO , CO_2 , CH_4	–23.535864 –46.559550	741	38	LCZ 2 Compact mid-rise LCZ 1 Compact high-rise
PDJ (Forest reserve)	CO_2 , CH_4 , $\delta^{13}\text{C}\text{-CO}_2$	–23.456314 –46.766094	1079	3	LCZ A Dense trees LCZ 9 Sparsely built
ICESP (Hospital Rooftop)	CO_2 , CH_4	–23.556043 –46.668418	825	113	LCZ 5 open mid rise LCZ 1 Compact high rise
CIENTEC (Conservation area)	CO_2 flux, vertical backscatter light profiles	–23.651461–46.622572	810	30, 10	LCZ A Dense trees LCZ B Scattered trees

Calibration procedure

Each station is equipped with one natural air standard gas tank and one target gas tank. The standard tank was prepared by the National Oceanic and Atmospheric Administration Earth System Research Laboratory (NOAA/ESRL) and calibrated relative to the World Meteorological Organization (WMO) scales (WMO-CO₂_X2007, WMO-CH₄_X2004A). These standards have mole fractions close to ambient levels and were used for the calibration procedure. The current calibration strategy follows a single-point calibration, as described by Verhulst et al. [42]. This calibration method assumes a linear response in the analyzer. The target tank was used for linearity verification. Due to the limited number of gas standard samples available at the PDJ station, we opted not to apply a calibration correction to the data, thereby maintaining the completeness of the time series. However, this site is particularly important as it is an urban background station. This makes it valuable for interpreting both the transport of air masses toward urban areas and the outflow of pollutants from cities.

Meteorological characteristics

São Paulo's climate is classified as Cwa under the Köppen system, characterized by a temperate climate with moderate temperatures, dry winters with significantly less rainfall than summer, and hot summers. From December to March, the city experiences hot and rainy summers driven by convective storms and the influence of the South Atlantic Convergence Zone (SACZ). In contrast, from June to August, winters are mild and dry, largely influenced by the South Atlantic Subtropical High (SASH). São Paulo's proximity to the Atlantic Ocean allows sea breezes to influence local weather, particularly in coastal areas and during summer afternoons. Additionally, urbanization significantly modifies temperature and wind circulation patterns, intensifies heat, and alters local wind flows, which can contribute to elevated concentrations of air pollutants.

Another key characteristic is the occurrence of convective storms, particularly in spring and summer, triggered by intense surface heating and humidity. These storms often bring heavy rainfall, lightning, and

occasionally hail. Fig. 2 shows monthly mean values of temperature and precipitation from 2019 to 2024, indicating peak values for both variables during the summer months.

Results and discussion

Annual mean and trends

Table 3 presents the annual mean mole fractions and standard deviations for CO₂ and CH₄ measured at the three stations (UNICID, IAG, and PDJ) over the available data period. PDJ recorded the lowest CO₂ mole fraction among the stations; from 2019 to 2024, the annual average CO₂ mole fraction exhibited a gradual increase, rising from 416.86 ± 2.09 ppm to 426.81 ± 2.03 ppm, and maximum values followed a similar trend, going from 420.26 ppm in 2019 to 429.73 ppm in 2024.

At UNICID, CO₂ levels showed a marked upward trend, rising from 429.12 ± 4.44 ppm in 2021 to 443.69 ± 6.00 ppm in 2024, with an average annual increase of 4.86 ± 2.84 ppm yr⁻¹. The IAG station displayed a comparable pattern, with mole fraction rising from 430.49 ± 4.91 ppm in 2021 to 445.25 ± 7.40 ppm in 2024. The minimum recorded value at IAG was 421.93 ppm (2021), while the maximum reached 457.77 ppm (2024).

When compared with the global synthesis provided by the Multi-city Urban Atmospheric Greenhouse Gas Measurement Data Synthesis[29], the METROCLIMA results show urban CO₂ and CH₄ levels consistent with those reported for more than 20 cities worldwide. Mitchell et al. found average urban CO₂ mole fractions of 430 to 460 ppm, while METROCLIMA observations range from 417 to 445 ppm.

In contrast, the METROCLIMA UNICID station reveals higher annual CO₂ growth rates (4.86 ± 2.84 ppm yr⁻¹), indicating faster increases in urban greenhouse gas concentrations probably due to the increase in the urbanization associated with the high demand for transport and fuel consumption without preserving vegetation areas. These findings highlight São Paulo's importance in addressing the observational gap for megacities in the Southern Hemisphere. Not only the urbanization, but in recent years, biomass burning has also affected the CO₂

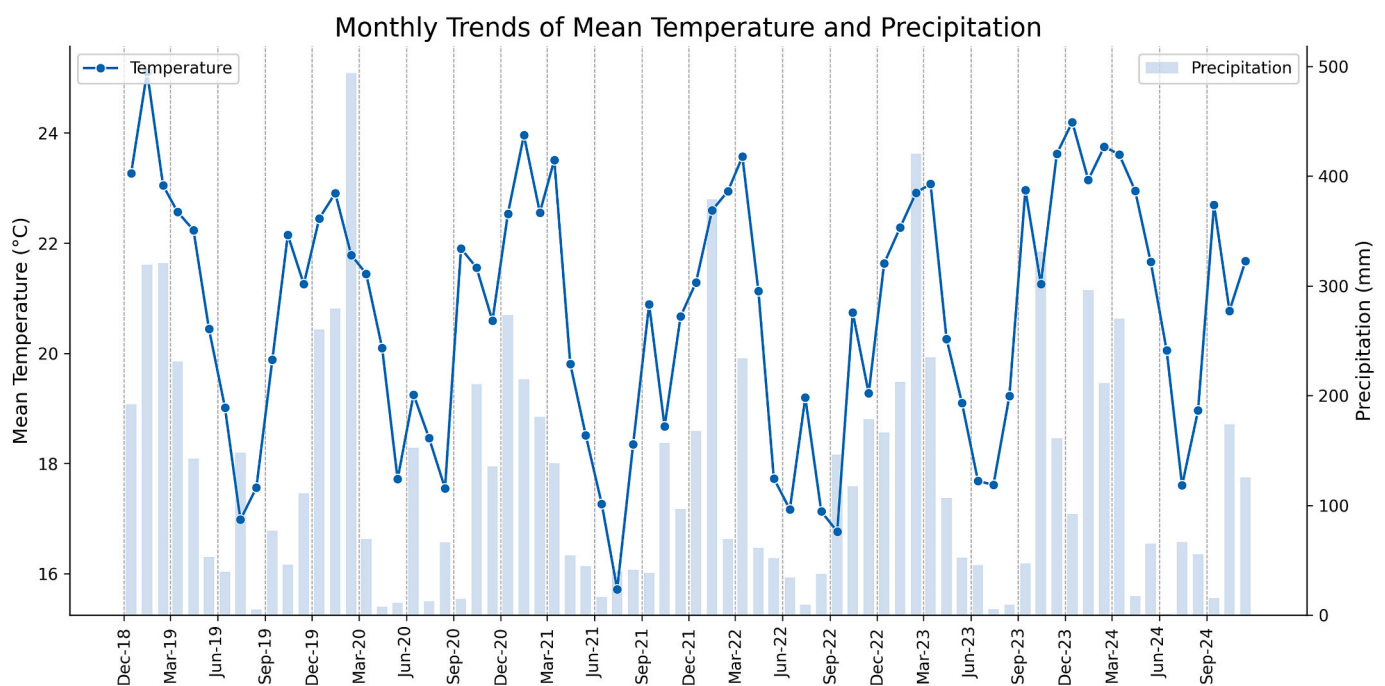


Fig. 2. Monthly mean values of temperature and accumulated precipitation from 2019 to 2024 at the Mirante de Santana meteorological station, São Paulo. Lines show the mean temperature for each month on the right y-axis. Data).

Source: INMET (<https://portal.inmet.gov.br/>)

Table 3Annual average mole fractions and standard deviation for CO₂ and CH₄ measured at the three stations (UNICID, IAG, and PDJ).

		CO ₂ (ppm)				CH ₄ (ppm)			
		Avg	Std	Max	Min	Avg	Std	Max	Min
IAG	2021	430.49	4.91	437.41	421.93	2.094	0.066	2.203	1.982
	2022	434.77	4.72	442.22	428.81	2.119	0.048	2.211	2.066
	2024	445.25	7.40	457.77	433.55	2.195	0.078	2.322	2.094
UNICID	2021	429.12	4.44	434.68	420.03	2.132	0.087	2.303	1.981
	2022	432.02	3.67	439.24	427.25	2.138	0.070	2.311	2.074
	2023	435.57	4.68	443.40	428.91	2.202	0.112	2.484	2.109
	2024	443.69	6.00	451.90	436.80	2.255	0.137	2.457	2.096
PDJ	2019	416.86	2.09	420.26	414.22	2.038	0.044	2.108	1.978
	2020	417.83	2.68	421.71	413.58	2.036	0.028	2.100	1.995
	2021	421.80	2.61	426.95	417.87	2.039	0.037	2.079	1.966
	2022	423.43	1.92	426.13	420.91	2.063	0.039	2.105	1.993
	2023	425.50	2.18	428.43	422.01	2.078	0.025	2.134	2.035
	2024	426.81	2.03	429.73	424.17	2.001	0.042	2.060	1.948

concentrations.

According to the WMO Greenhouse Gas Bulletin[47], the 3.5 ppm increase in global average CO₂ from 2023 to 2024 was driven in part by the high number of fires worldwide during that period. Luqman et al. [24] analyzed CO₂ emissions for 91 cities using a globally time-resolved proxy data set including fossil fuel emissions and urban areas. Their results show that expanding urban extent is the dominant contributor to emissions growth (3.5% yr⁻¹ on average), especially in rapidly developing regions. Similarly, Estruch et al. [9] demonstrated how heterogeneous urban landscapes modulate CO₂ accumulation. They observed CO₂ mixing ratios reaching 470–500 ppm under specific conditions and emphasized the role of local ventilation and the “urban CO₂ dome” effect in shaping concentration patterns. Together, these studies emphasize both the global consistency of rising CO₂ levels and the strong local variability imposed by urban structure, regional emission dynamics, and observational capacity.

When comparing the three stations, UNICID consistently recorded higher CO₂ minima and maxima, reflecting the urban influence. In contrast, PDJ showed lower values for both gases, CO₂ and CH₄, as expected for an urban background site. IAG, located in a mixed vegetated and academic building setting, displayed intermediate behavior, reflecting both urban and regional influences.

Unlike CO₂, CH₄ did not exhibit a clear increasing trend in annual averages across the monitoring period. At PDJ, CH₄ mole fraction fluctuated between 2.038 ± 0.044 ppm in 2019 and 2.001 ± 0.042 ppm (2024), with substantial interannual variability in the minimum (1.948 ppm in 2024) and maximum values (2.134 ppm in 2023). These fluctuations at PDJ suggest complex interactions among biogenic sources, atmospheric transport, and meteorological conditions, making it difficult to determine a long-term trend.

At UNICID, average CH₄ levels increased more systematically, rising from 2.132 ± 0.087 ppm in 2021 to 2.255 ± 0.137 ppm in 2024. This upward trend is consistent with emissions from urban environments, where methane emissions can originate from waste management systems, fuel combustion, and potential gas distribution leaks. Similarly, at IAG, CH₄ mole fraction followed a gradual increase from 2.094 ± 0.066 ppm in 2021 to 2.195 ± 0.078 ppm in 2024, although with a lower magnitude than at UNICID, consistent with the sites' locations. Minimum methane values remained relatively stable across stations, ranging between 1.966 ppm (2021) at PDJ and 2.096 ppm (2024) at UNICID.

Differences in CH₄ between the three stations were less pronounced than those observed for CO₂, but local conditions, including land-use type, urban density, and proximity to emission sources, still influenced the emission patterns. For instance, UNICID consistently recorded higher CH₄ averages, reflecting its urban signature. In contrast, PDJ, characterized by forested surroundings and the station height, exhibited the lowest methane levels. These variations show the importance of accounting for geographic and environmental context when interpreting

GHG data and designing mitigation strategies.

The observed increase in GHG mole fraction in the stations aligns with the global trends[47] and local air quality reports. The rise in pollutant levels post 2020 in São Paulo has been attributed not only to rebounding emissions after COVID-19 restrictions but also to enhanced biomass burning from both local fires and long-range transport of biomass plumes from the Amazon and Cerrado regions, as discussed by Souto-Oliveira et al. [39].

Seasonal characteristics

The lowest minimum values in the diurnal cycle for CO₂ were observed during the summer months (DJF) at all stations (Fig. 3 a-c). This behavior is associated with a higher planetary boundary layer and increased wind velocity during this season, resulting in stronger ventilation and enhanced pollution dispersion. Moreira et al. [31], by combining LIDAR data with meteorological and pollutant variables, demonstrated the significant role of summertime convective mixing in reducing near-surface mole fractions. The minimum values recorded in summer are comparable to those observed in fall (MAM), reflecting similar synoptic and thermodynamic conditions during transitional seasons.

In contrast, the highest minimum values in the diurnal cycle occurred during winter (JJA) and were similar to spring (SON) values at most sites (seasonal average concentrations and standard deviation for CO₂ and CH₄ measured at the three stations are presented in Table S1). However, at PDJ, a more noticeable difference between spring and winter was evident (Fig. 3c). This seasonal pattern can be attributed in part to increased biomass burning events in Brazil. Rosário et al. [35] presented a climatology of biomass burning events in Brazil from 2003 to 2019, highlighting September and October as the peak months for fire activity. Additionally, Vieira et al. [43] analyzed the aerosol chemical and physical properties during these biomass burning events, providing their contribution to enhanced pollutant loads and reduced atmospheric visibility.

Different approaches have been applied to characterize the contribution of biomass burning to the pollutant's concentration in São Paulo during the springtime. Chemical analysis by Pereira et al. [33] provided direct evidence, using Positive Matrix Factorization (PMF) on PM_{2.5} data to identify the high contribution of biomass burning associated to the northwest winds, where there are forest fires and sugar cane bagasse power plants.

Remote sensing studies from Tariq et al. [40], using AERONET data from São Paulo and other global sites, quantified a seasonal peak in aerosol loading during the spring. They reported high Aerosol Optical Depth (AOD = 0.39) and Ångström Exponent (AE = 1.48) for September, a signature indicative of a high concentration of fine-mode particles from Biomass Burning.

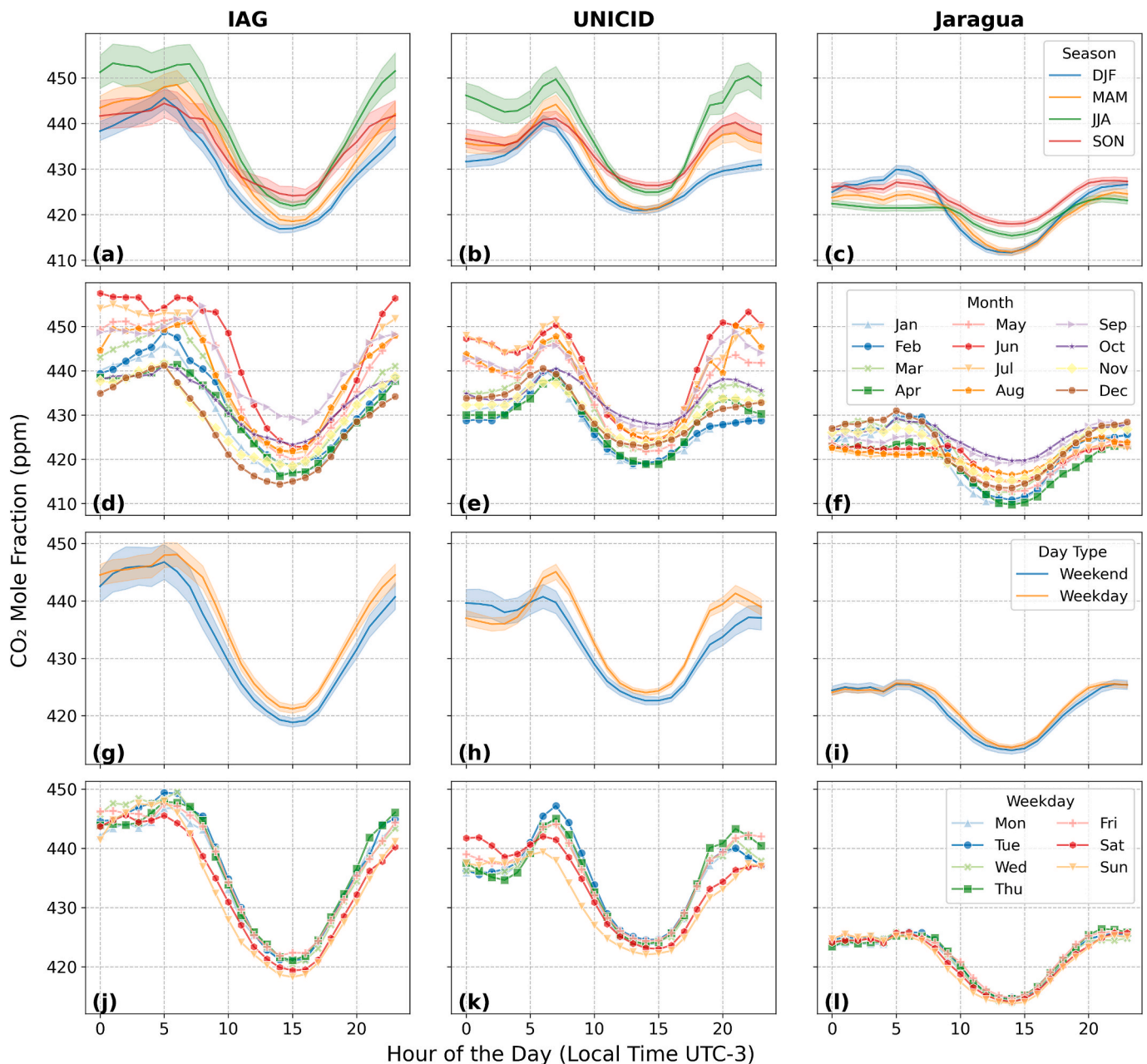


Fig. 3. Hourly mean CO_2 mole fraction at three monitoring stations (IAG, UNICID, and PDJ) in local time (UTC-3). Columns correspond to stations and rows display the diurnal cycle grouped by: (a-c) season, (d-f) month, (g-i) weekday vs weekend, and (j-l) day of the week. In plots (a-c) and (g-i), the shaded area represents the 95% confidence interval.

Monteiro dos Santos et al. [30] established a direct association between drought-heatwaves and the exacerbation of fire activity. They analyzed the Pantanal 2020 fire season, which was one of the most severe on record, demonstrating the effect of the climate drought extremes to increase fire intensity in Central Brazil.

PDJ station exhibits a distinct seasonal pattern from the other sites, with winter showing the lowest maximum values, while the summer maximum mole fractions, during nighttime, approach those observed in fall. This behavior at PDJ may reflect its unique topographic and land cover characteristics, with dense forest cover and elevated terrain modulating boundary layer dynamics and pollutant dispersion differently from urban sites.

Analysis of seasonal CH_4 mole fraction variations revealed the highest levels during winter, particularly at the UNICID station during morning and evening traffic peaks (Fig. 4 a-c), where mole fractions

exceeded those observed at IAG. At this site, peak mole fractions occurred during summer nights and winter days. This location exhibits unique characteristics due to its greater distance from emission sources and reduced influence from peak vehicular traffic. There is not a great difference between weekends and weekdays at the three stations (Fig. 4).

Fig. 5 shows that during the winter season, the average daytime CO_2 mole fraction from 10 AM to 9 PM (UTC-3) follows a similar pattern to the nighttime mole fraction from 10 PM to 9 AM (UTC-3), indicating limited diurnal variability. This reflects the characteristic wintertime stability of the boundary layer. In contrast, during summer, the two periods exhibit different behaviors, with increasingly higher average mole fractions during the night. This difference is likely associated with changes in the nocturnal boundary layer at the PDJ.

At PDJ, the differences among the seasons illustrate the critical role

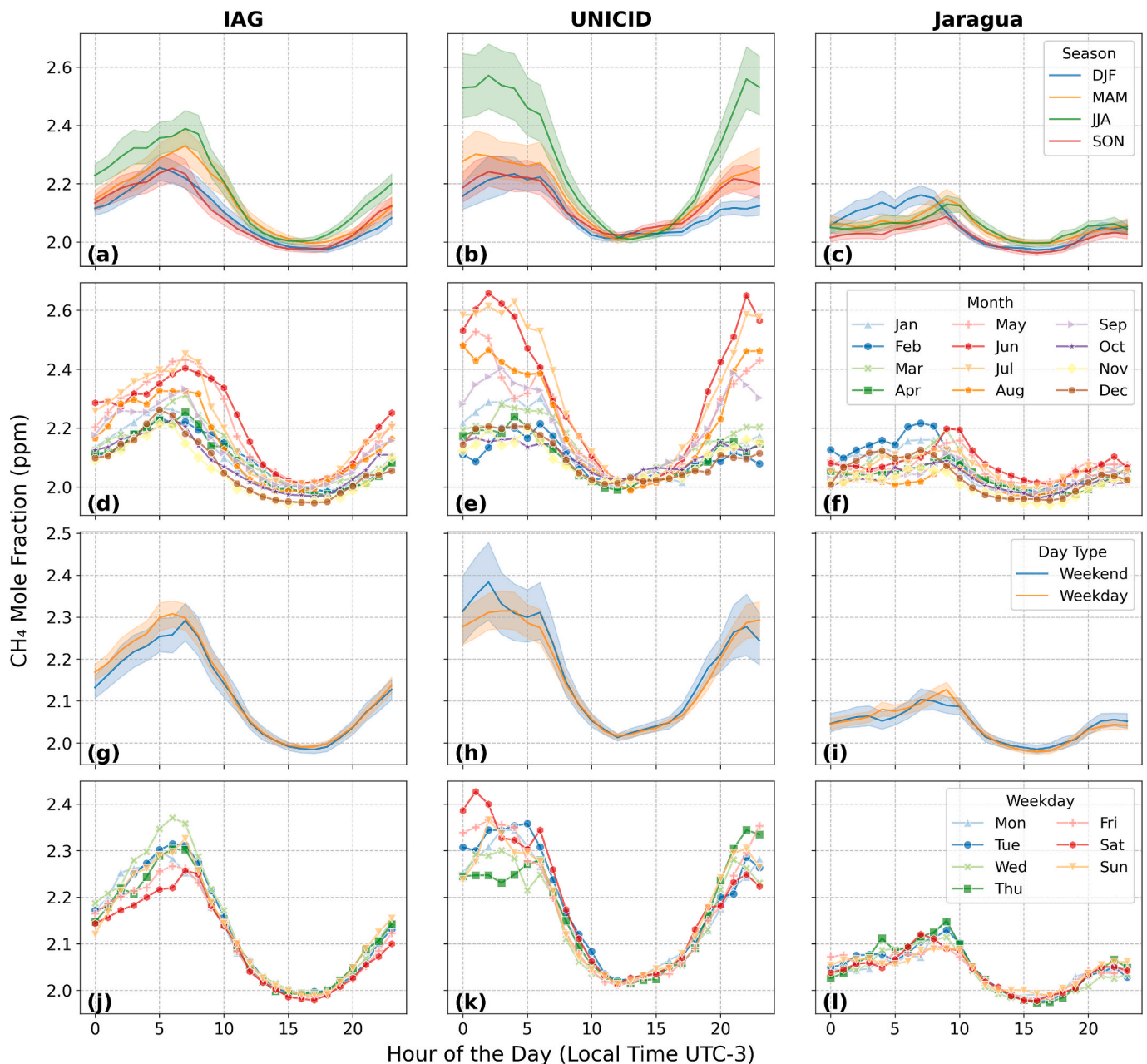


Fig. 4. Hourly mean CH_4 mole fraction at three monitoring stations (IAG, UNICID, and PDJ) in local time (UTC-3). Columns correspond to stations and rows display the diurnal cycle grouped by: (a-c) season, (d-f) month, (g-i) weekday vs weekend, and (j-l) day of the week. In plots (a-c) and (g-i), the shaded area represents the 95% confidence interval.

of the boundary layer dynamics in modulating the CO_2 mole fraction. During summer, the stronger convective activity and higher boundary-layer heights during the day facilitate the ventilation, whereas nighttime stability leads to an increased amount of CO_2 . However, in winter, the stability throughout the diurnal cycle results in similar mole fraction levels during both daytime and nighttime periods. These findings emphasize the interactions among meteorological conditions, atmospheric boundary layer processes, and regional emission patterns that shape the seasonal and diurnal mole fraction profiles.

Diurnal cycle for CO_2 and CH_4

The diurnal cycle of CO_2 is a widely used method for studying the variability of gas mole fractions and for understanding the main variables affecting these mole fractions, related to sources, sinks, and

atmospheric dynamics, such as the planetary boundary layer [26]. Therefore, the diurnal cycle of CO_2 is influenced by local, regional, and seasonal characteristics, making it an important record of gas dynamics in a given area [49,18].

Maximum hourly CO_2 mole fractions were observed during the night and early morning hours at all stations (Fig. 6b). At the UNICID station, a characteristic peak was observed during the morning rush hour (6–7 AM UTC-3) (Fig. 6b), associated with the intense vehicular traffic on nearby avenues, characteristic of this station. A similar peak was also observed at the IAG station, but it occurred one hour earlier (5–7 AM UTC-3) (Fig. 6b), suggesting a possible association with early morning traffic as well.

At the PDJ station, the smallest amplitude (11 ppm) and the lowest maximum value of the diurnal cycle (425.60 ± 9.07 ppm) were observed, in comparison to the other stations (Fig. 6b). The PDJ station,

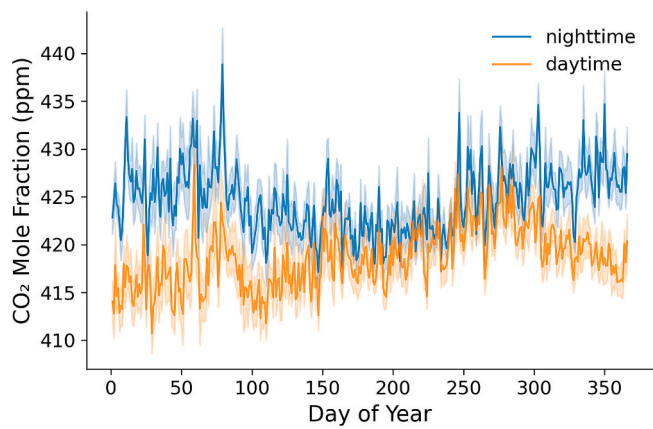


Fig. 5. Mean CO₂ mole fraction for each day of the year at PDJ station. Measurements are separated into daytime (10 AM–9 PM) and nighttime (10 PM–9 AM) periods in local time (UTC-3).

an urban background site, is located in a state park within a densely vegetated area, which explains its low CO₂ amplitude.

Vieira dos Santos et al. [43] analyzed ceilometer data and showed that, during the night, the PBL is usually below the PDJ site height, reducing its exposure to urban emissions during peak traffic hours at the beginning and end of the day. This condition, combined with vegetation, plays a key role in the site's lower mole fraction amplitude.

The largest amplitude (27 ppm) and maximum value of the diurnal cycle ($447.61 \pm 28.92 \text{ ppm}$) were observed at the IAG station (Fig. 6). This station is in a suburban area within the University of São Paulo (USP), comprising a semi vegetated area with intense vehicular traffic about 2 km away, making it intermediate in characteristics to the other two stations. In contrast, the UNICID station, despite being in a high-traffic area, has a lower diurnal cycle maximum ($443.54 \pm 20.06 \text{ ppm}$) and an amplitude 25% smaller (20 ppm), but a higher diurnal cycle minimum (423.63 ppm).

During the early morning and night, we observe higher mole fractions at the IAG station compared to UNICID (Fig. 6), which possibly indicates a contribution from vegetation respiration in the green areas that are practically absent at UNICID. High-traffic urban areas are often net sources of carbon, as demonstrated by Bezyk et al. [3] in their study of Wrocław, Poland. Using chamber measurements, they analyzed surface-atmosphere CO₂ exchanges and net fluxes across different land cover types, including grasslands, city parks, and agricultural fields. Liñán-Abanto et al. [23] reported CO₂ measurements in Mexico City from November 2014 to July 2016 and the diurnal cycle presented a similar pattern as observed at UNICID, with two peaks (in the morning

and evening) and minimum values in the late afternoon. Their station is located at the UNAM Atmospheric Observatory, characterized by a constant traffic of gasoline vehicles and local buses. However, the evening peak is less pronounced compared to UNICID, resembling the pattern observed at UNICID during the summer months (DJF) as shown at Fig. 3b, with a higher amplitude though.

Therefore, the maximum mole fractions during the nighttime may indicate the combined contributions of vegetation respiration and anthropogenic sources, mainly the vehicular emissions. Meanwhile, the minimum mole fractions, with values like those observed at the PDJ station in the early afternoon (1–3 PM) (Fig. 6), are possibly related to more intense photosynthetic activity than at the UNICID station, due to the land cover with greater vegetation.

Alberti et al. [1] combined WRF-GHG model results, vegetation representation using VPRM, and surface data for São Paulo to analyze CO₂ variations. Their study showed that the vehicular emissions model VEIN [17], along with VPRM [25], effectively represented the diurnal CO₂ variation for a period in 2019, highlighting the influence of land cover in its profile.

The CH₄ mole fraction exhibited different patterns at IAG, Pico do Jaraguá, and UNICID. At UNICID, the mole fractions were higher during the night, reaching their lowest levels at 12 PM. In contrast, at the other stations, the lowest mole fractions occurred later, around 3 PM local time. The UNICID station is in an area with higher natural gas usage for cooking. Notably, São Paulo's natural gas supply network primarily serves the central region, leaving other areas less covered. Previous studies have documented the impact of natural gas usage on CH₄ mole fractions in urban environments. For instance, Fischer et al. [10], have discussed that natural gas sources can contribute between 20% and 100% of regional CH₄ emissions in urban areas. In São Paulo another important source of CH₄ is the use of natural gas by the vehicular fleet of taxis. Currently, there are 34,000 taxis in the city of São Paulo, with approximately 33% running on vehicular natural gas, which generally operate more frequently in the central region of the city [7].

The highest mole fractions were observed on weekdays at IAG and UNICID, primarily due to local sources, mainly vehicular emissions. At PDJ, the difference was minimal, reinforcing its characterization as a site less impacted by urban emissions.

The increase observed at UNICID is likely associated with fugitive emissions from multiple sources, including leaks in the natural gas distribution system. These direct sources are difficult to identify and remain an important gap for future investigation. Although the official GHG emissions inventory for São Paulo does not explicitly account for natural gas related emissions, our results suggest that this source may be contributing to the observed signal.

Furthermore, to avoid unsupported speculation, we incorporated isotopic evidence from Miller-Tans analysis, as presented in Fig. 7. The

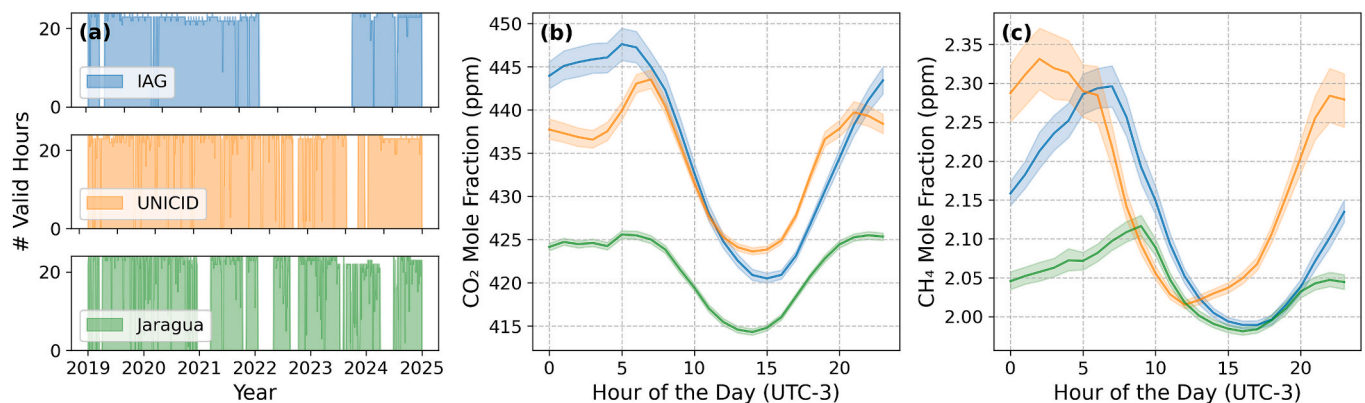


Fig. 6. (a) Data availability for each station, represented as the number of valid hours per day, ranging from 0 (absence of data) to 24 (complete day). (b) Diurnal cycle of CO₂ and (c) CH₄ mole fractions in local time (UTC-3), both computed over the entire available data record for each station. The shaded area represents the 95% confidence interval.

slope distribution obtained for IAG (a suburban/urban transition zone) shows a median $\delta^{13}\text{C-CH}_4$ signature of -41.38‰ , which lies within the established isotopic range of natural gas and gas distribution leaks in urban environments worldwide. For example, this value is comparable to measurements from the natural gas distribution network in the Heidelberg region, Germany ($-40.5 \pm 6.2\text{‰}$; [22], to discrete street-level leak samples in Boston, USA ($-42.8 \pm 1.3\text{‰}$; [34], and to recent observations of ground-level air at field stations in China ($-41.99 \pm 7.10\text{‰}$; [4]).

The CO_2/CO ratio as a Fingerprint of fossil fuel emissions

Fig. 8 presents the average hourly CO mole fractions on weekdays (top panel) and the seasonal diurnal averages (bottom panel). On weekdays, the influence of traffic is evident, with pronounced peaks during the morning and evening rush hours. The highest CO mole fractions occur on weekdays and during the winter season. Winter is marked by dry conditions and frequent atmospheric stability, including thermal inversions, which hinder pollutant dispersion.

As shown in Fig. 8c, the diurnal CO pattern on weekends differs substantially from that observed on weekdays. On weekends, the morning peak and the secondary minimum tend to converge to similar mole fraction levels, likely due to altered traffic dynamics and reduced commuter activity.

At UNICID, an urban station experiencing heavy traffic in its surroundings, the shape of the diurnal cycle of CO (Fig. 9) is very similar to that of CO_2 (Fig. 3), with a first peak at 7 AM and a second peak at 9 PM local time. However, the relative amplitude of the CO cycle is much greater (71%) compared to CO_2 (5%).

Both gases show a minimum in the early afternoon and a second minimum before sunrise. This second trough is more pronounced for CO than for CO_2 , likely due to a combination of reduced nighttime emissions and enhanced vertical dispersion as the stable nocturnal boundary layer begins to break down before sunrise.

The correlation between CO and CO_2 is typically strong, as shown in Fig. 9, especially when combustion processes such as vehicular emissions significantly contribute to the observed CO_2 levels [44,46].

The hourly correlation between CO and CO_2 (Fig. 10) was strongest during winter ($r = 0.93$), indicating a significant influence of combustion related emissions on CO_2 levels. This is also reflected in the diurnal

seasonal CO cycle, as the winter curve is different from those of the other seasons and closer to the CO_2 curve, reinforcing the dominance of common sources. In contrast, summer showed the weakest correlation ($r = 0.70$), suggesting the effect of temperature on the photosynthesis process. Spring and autumn showed intermediate and comparable values, with correlation coefficients of 0.86 and 0.85, respectively, as illustrated in Fig. 10.

The $\text{CO}_2\text{-CO}$ slope calculated according to Wang et al. [44] was 51.9 ppmv/ppmv for the non-summer seasons. This value is similar to the CO_2/CO ratio measured in tunnels in São Paulo (56 ppmv/ppmv, [32], reinforcing the association of CO_2 emissions with fossil fuel combustion. In Mexico City, the ratio reported by Liñán-Abanto et al. [23] varied from 58.8 to 90.9 ppmv/ppmv depending on the season (from cold dry to rainy season). At UNICID, the highest value was observed at night, between 3 and 6 am local time, during summer, of about 80 ppm/ppm (Fig. 10a). The diurnal cycle of the slope shows the lowest values after sunset, when there is a decrease in CO_2 mole fraction relative to CO, similarly to what occurs during morning rush hour from 6 to 9 AM.

Conclusions

METROCLIMA represents the first atmospheric monitoring network in South America focused on continuous, high precision measurements of CO_2 and CH_4 using Cavity Ring-Down Spectroscopy (CRDS). Installed in the megacity of São Paulo, Brazil, the network comprises five measurement sites, including an urban background station that has been operational since 2019. This study presented results from three stations: IAG site, located on the University of São Paulo campus, characterized by a mix of vegetation and built environment; UNICID site, a densely urbanized area with high vehicular traffic; PDJ site, an urban background station situated at Pico do Jaraguá, the highest elevation in São Paulo city.

Comparative analysis of the three monitoring stations reveals that local land use, topography, and emission source types are critical drivers of GHG mole fractions and variability in the São Paulo megacity. This is exemplified by the distinct CO_2 profiles observed at each site.

The lowest CO_2 mole fractions and diurnal amplitude were recorded at PDJ, with a maximum daily mole fraction of 425.60 ± 9.07 ppm and a diurnal range of 11 ppm, reflecting minimal anthropogenic influence and enhanced atmospheric mixing. In contrast, IAG exhibited the largest daily amplitude (27 ppm), consistent with strong biogenic activity and varying urban emissions. The UNICID site showed consistently high CO_2 mole fractions with comparatively lower amplitude, indicative of dominant anthropogenic sources and limited influence from natural sinks.

The study recorded annual CO_2 growth rates that significantly exceed the global average, underscoring the intensified forcing from the still increasing urbanization process and biomass burning activities, particularly in recent years. The mole fractions increased at all sites, in agreement with global trends reported by the WMO, albeit at higher rates: 3.69 ppm yr^{-1} at IAG (2021–2024), 3.64 ppm yr^{-1} at UNICID (2021–2024), and 1.73 ppm yr^{-1} at PDJ (2019–2023). These elevated growth rates emphasize the need for localized GHG monitoring in urban megacities. CO_2 displayed a marked diurnal cycle, especially at urban stations, with morning and evening peaks aligned with traffic emissions. The similarity between the $\text{CO}_2\text{-CO}$ correlation slope (51.9 ppm/ppm, for the winter season) and the emission ratio measured directly inside the São Paulo road tunnel confirmed that combustion-related processes, mainly from vehicles, are the main contributors to CO_2 enhancements. However, the correlation varied throughout the day and season due to photosynthetic uptake at midday and plant respiration at night, particularly at vegetated sites like IAG and PDJ.

CH_4 mole fractions showed spatial and temporal variability, reflecting the influence of multiple emission sources. Although vehicular emissions contributed to the observed patterns, the comparison with the official São Paulo emissions inventory indicates that waste-management

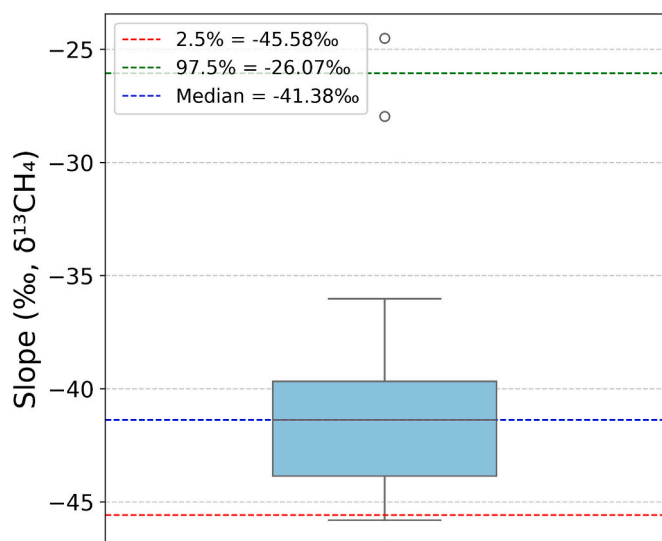


Fig. 7. Boxplot of isotopic signatures ($\delta^{13}\text{C-CH}_4$) based on slopes from the Miller-Tans approach at the IAG station. Dashed blue, green, and red lines represent the median, 97.5th percentile, and 2.5th percentile, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

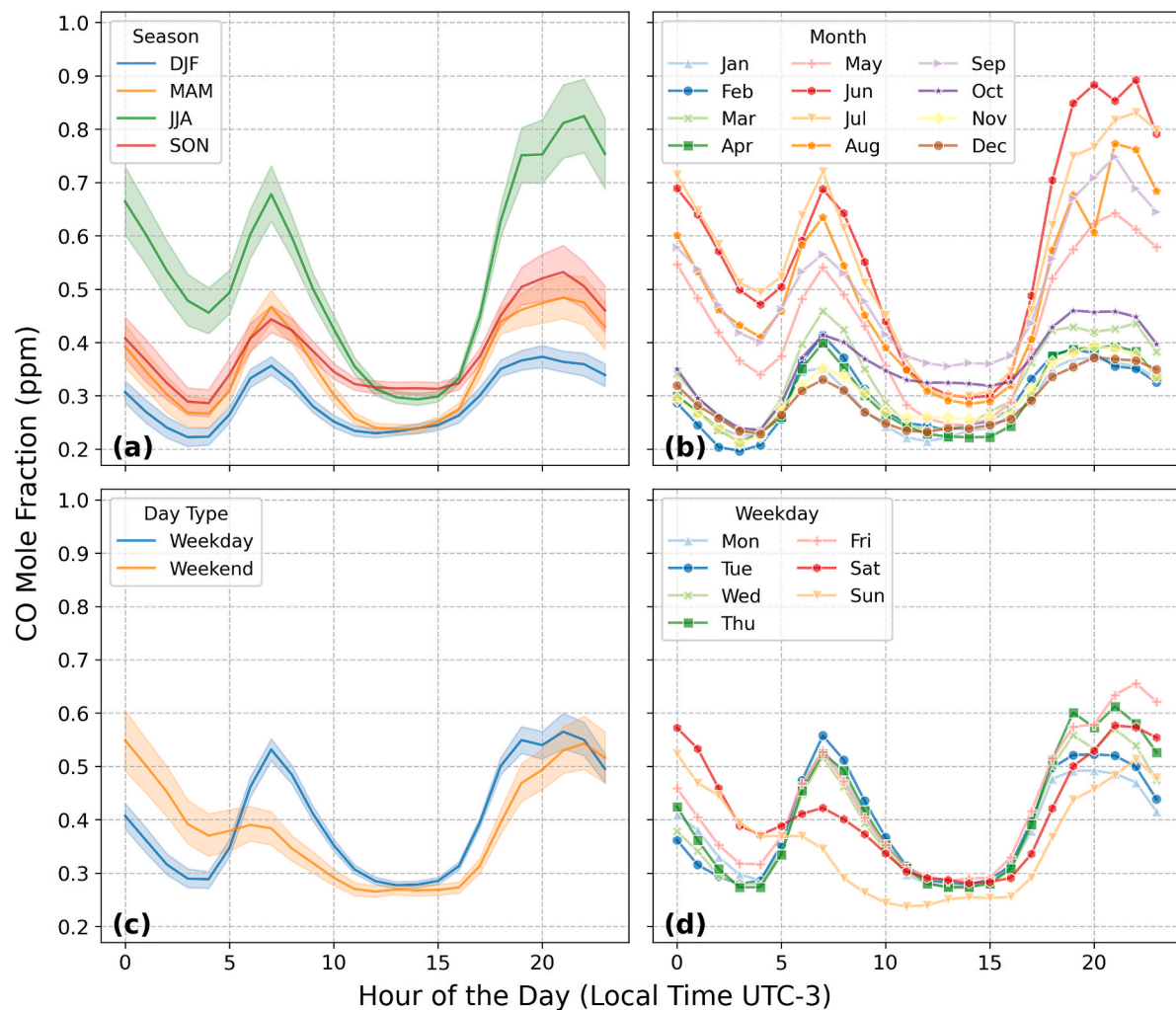


Fig. 8. Hourly mean CO mole fractions at UNICID. Panels show the diurnal cycle grouped by (a) season, (b) month, (c) weekday vs weekend, and (d) day of the week. In panels (a) and (c), the shaded area represents the 95% confidence interval.

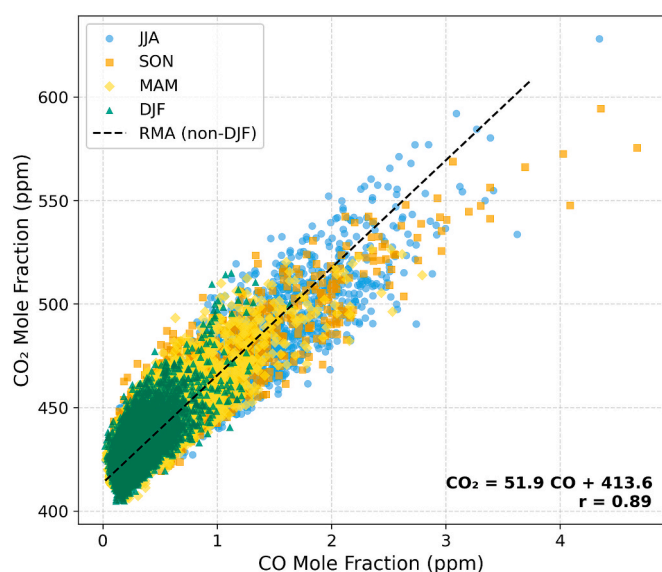


Fig. 9. Relationship between CO₂ and CO mole fractions observed at the UNICID site. Dot colors indicate the respective seasons.

infrastructure remains the dominant source in the region. However, our

observations also reveal transient CH₄ enhancements at urban sites that are not fully explained by the inventory. The $\delta^{13}\text{C}$ -CH₄ signatures point strongly to natural gas as a major contributor, likely associated with domestic use (e.g., cooking) and vehicular use, particularly by taxis. These sources appear to be insufficiently represented in the official inventory, revealing a critical knowledge gap. The findings imply that urban CH₄ mitigation requires not only managing waste but also addressing leaks in the natural gas distribution network and other non-inventoried point sources.

Comparative analysis across the three stations revealed the influence of land cover and topography on GHG mole fractions and variability. These findings underscore the importance of considering site-specific characteristics, such as proximity to emission sources and local meteorology, when interpreting CO₂ and CH₄ measurements.

While this study enhances the understanding of GHG dynamics in São Paulo, it also suggests that targeted mitigation policies could be informed by spatial and temporal patterns of emissions. In the case of CH₄, effective reductions will require going beyond the waste sector to address additional sources, such as natural gas infrastructure leaks and emissions associated with its use in the transport sector.

The METROCLIMA network demonstrates how surface heterogeneity modulates GHG trends, complementing emission sources and observations. To improve spatial resolution in emission inventories and inform effective mitigation strategies, future monitoring efforts should expand the network by integrating additional stations to capture urban-rural

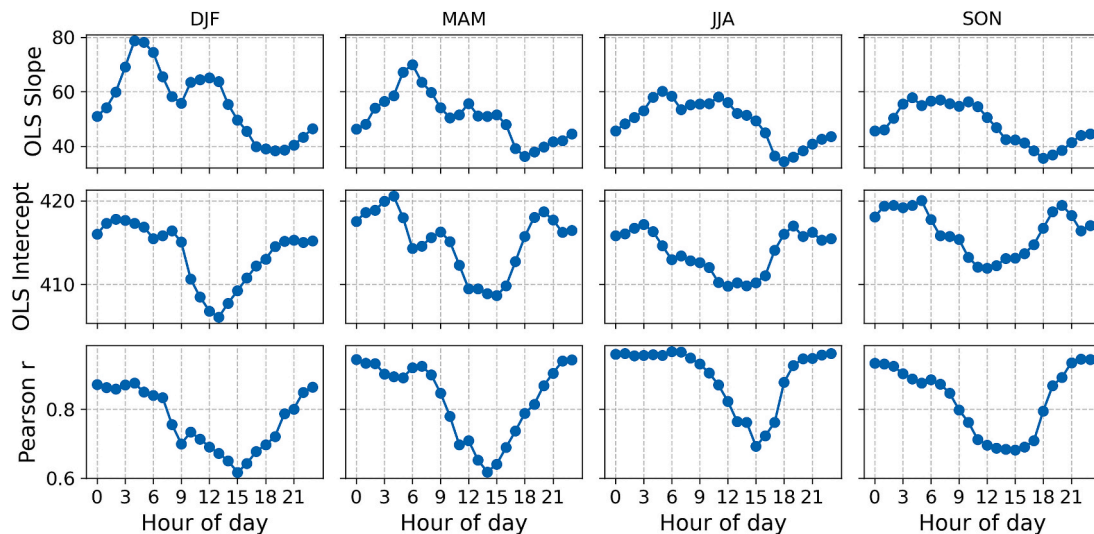


Fig. 10. Hourly CO₂-CO relationship metrics at UNICID station in local time (UTC-3). Columns correspond to the seasons: summer (DJF), autumn (MAM), winter (JJA), and spring (SON). And rows display the diurnal cycle grouped by: (a–d) Ordinary Least Squares (OLS) slope (dCO_2/dCO), (e–h) OLS intercept, and (i–l) Pearson correlation coefficient (r).

gradients, analyzing wind and meteorological data from key sites (e.g., PDJ, IAG, UNICID), and enhancing temporal resolution and automated data quality controls. Our findings also highlight the value of establishing analogous networks throughout Latin America to close this significant data gap, which could inform climate mitigation strategies.

Future research should expand monitoring in diverse urban land uses to better represent the spatial variability of both CO₂ and CH₄ emissions and their interaction with atmospheric mixing processes. Increasing vertical observations within the urban boundary layer, together with integration of atmospheric measurements and urban ecosystem studies, will improve understanding of how vegetation, land cover, and urban morphology influence greenhouse gas fluxes. Combining long term observations with atmospheric transport and inverse modeling will allow more accurate emission quantification and evaluation of mitigation strategies, particularly those related to traffic emissions, green infrastructure, and urban planning. At the same time, improved source attribution is needed, especially for CH₄, where fugitive emissions from natural gas distribution networks, transport use, and waste management appear to be underestimated in official inventories. Mobile monitoring, isotopic analysis, and high resolution satellite data can help identify urban hotspots and other sources. Research should also address policy and governance mechanisms supporting greenhouse gas mitigation, enabling cities to implement reduction strategies in accordance with urban decarbonization goals.

CRediT authorship contribution statement

Maria de Fatima Andrade: Writing – original draft, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Marcia Talita Amorim Marques:** Writing – original draft, Validation, Software, Methodology, Data curation. **Jose Agostinho Gonçalves de Medeiros:** Methodology, Data curation. **Carlos Eduardo Souto-Oliveira:** Methodology, Investigation. **Marco A. Franco:** Investigation, Methodology, Writing – original draft. **Prashant Kumar:** Writing – review & editing. **Lucas Gatti Domingues:** Methodology, Investigation. **Noele Franchi Leonardo:** Methodology, Investigation. **Marcia Akemi Yamasoe:** Writing – original draft, Investigation. **Leslie Lissethe Morales-Espinoza:** Writing – review & editing, Methodology. **Eduardo Landulfo:** Supervision, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.cacint.2026.100326>.

Data availability

Data will be made available on request.

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