

Article

First Land Use and Air Quality Study in Greater Rosario, Argentina: A Ground-Satellite Assessment of PM_{2.5}

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Abstract

Fine particulate matter (PM_{2.5}) is studied for the first time at ground level in different sites of Greater Rosario (GR), an urban and industrial area of central-eastern Argentina. Twelve sites were selected according to land use, and 87 samples were analyzed during winter 2021 and summer 2022. The spatial and temporal distribution of PM_{2.5} was examined, comparing results among sites and with global data. Ground-based data were complemented with satellite-derived Aerosol Optical Depth (AOD) and nitrogen dioxide vertical column density (NO₂ VCD). During winter, the highest PM_{2.5} was obtained at an industrial site in northern GR, while in summer, maximum values were observed in the center of Rosario. Summer rain events could contribute to the wet deposition of suspended particles, resulting in lower PM_{2.5} concentrations. Satellite data indicate higher average AOD in summer (attributable to forest fires in NE Argentina) and higher NO₂ VCD in winter, coinciding with burning events in the Paraná Delta islands and reflected in some PM_{2.5} peaks. This analysis represents the first approach to assessing the air quality of Rosario and its surroundings, with on-site data collected in association with land use.

Keywords: PM_{2.5}; in situ measurements; Greater Rosario; air quality; AOD; NO₂



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1. Introduction

Atmospheric aerosols exert both direct and indirect effects on the planet's radiative balance, causing difficulties in global temperature regulation [1]. At the same time, they serve as an important indicator of air quality. Particulate matter with a diameter $\leq 2.5 \mu\text{m}$ (PM_{2.5}) plays a critical role due to its association with adverse health effects in humans, such as lung cancer, cardiovascular events and asthma, among others [2–4]. In its latest report, the World Health Organization (WHO) warned that in 2019, 4.2 million deaths were attributable to ambient air pollution [5].

The PM_{2.5} fraction originates from natural emission sources (e.g., sea salt, volcanic eruptions, forest fires; [6]) and anthropogenic ones (e.g., automobiles, industries, commer-

cial activities, ports; [7]). Together, they influence the air quality of cities, affecting the daily lives of those who inhabit them.

Despite how harmful $PM_{2.5}$ can be to health, in many parts of the world, there is still no ground-based monitoring network to monitor this pollutant and provide continuous data to warn the population about its risks in real time. While monitoring of this parameter is increasing in the United States, Europe, and East and South Asia [8], in South America, data are still spatially and temporally scarce.

In Argentina, not only is continuous $PM_{2.5}$ monitoring limited to a few locations, but even temporary campaigns have also not been carried out at different sites and periods in large urban–industrial conglomerates, such as Greater Rosario, prior to the present work. Additionally, there is little published research available on this pollutant in the country, mainly focusing on cities such as San Juan [9], Córdoba ([10–14]) and Buenos Aires ([15–17]), or for a specific site of astrophysical interest such as the Pierre Auger Observatory ([18]).

Despite Rosario being the third most populous city in the country [19] and hosting intense industrial and commercial activity, ground-based studies on $PM_{2.5}$ have been nonexistent; only satellite-based investigations during specific high pollution events have been conducted ([20–23]).

The use of satellite data is highly valuable because it provides information on the state of the atmosphere and allows for the study of areas that lack in situ monitoring. Hence, evaluating Aerosol Optical Depth (AOD) is important as a first approach to aerosol levels in the atmosphere for a given time and place. Another variable that could be used as a proxy for urban human activities is nitrogen dioxide (NO_2), as suggested by Amritha [24], Kovács [25] and Prunet [26]. In both cases, it must be considered that data are being obtained for the total atmospheric vertical column, so they are not direct measurement of the state of air quality at ground level.

This investigation aims to carry out the first study on $PM_{2.5}$ collected from the air at various GR locations, near ground level, to assess the spatiotemporal distribution of fine particles according to the land use of the different sampling sites and seasons. This information will be complemented with satellite data on the AOD obtained with the MAIAC/MODIS and the vertical column density of nitrogen dioxide (NO_2 VCD) from TROPOMI, in order to understand in more detail the air quality of the GR region.

2. Materials and Methods

2.1. Study Area

Greater Rosario (GR) is located in the central region of Argentina, in Santa Fe province. The GR comprises the cities of Rosario (the third most populated city in Argentina, combining industrial, commercial and port activities, among others, with 1,030,069 inhabitants [19]) and San Lorenzo (an urban and industrial city with 50,954 inhabitants [19]) and small localities like Ibarlucea and Pueblo Esther, among others. With a population exceeding one million inhabitants [19], the GR region hosts a significant concentration of industries and factories. Additionally, its ports on the Paraná River make it a strategic axis for trade and economic activity on a regional and international level due to its multiple road and rail connections and the bioceanic corridor. The main products exported and imported are iron ore, raw sugar, soybean meal, fertilizers, and vegetable oil [27].

According to data provided by the National Meteorological Service (SMN) of Argentina [28] (Figure 1), the climate is temperate, with an average annual rainfall of 1053.4 mm, where the warm season is more humid than the winter. The mean temperature is 17.8 °C, and the predominant winds come from the east, although the strongest gusts usually arrive from both the north and south, with October and November registering the highest average wind speeds.

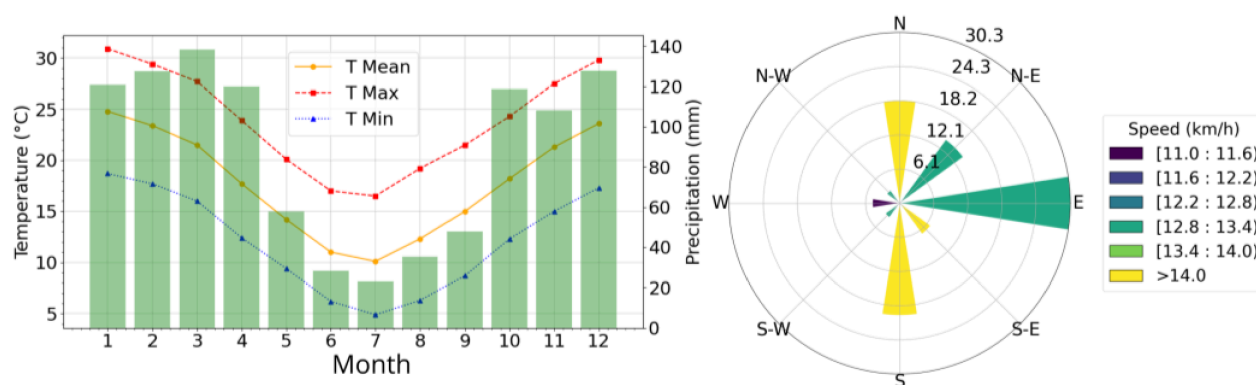


Figure 1. Rosario weather data at Rosario’s Airport Meteorological Station for the 1991–2020 (**left**) and 2011–2020 (**right**). (**Left**): Temperature (lines) and precipitation (green bars) monthly means. (**Right**): Wind speed and direction. Source: National Meteorological Service (SMN), Argentina.

The study area is bounded by the geographical coordinates 32.69724 S, 33.19461 S, 60.62001 W and 60.7747 W (Figure 2). The terrain is basically flat, corresponding to the so-called Argentine Pampas, with an average elevation of 27.6 m a.s.l and maximum and minimum elevation values that vary between 51.1 and 10 m a.s.l across the analyzed sites.

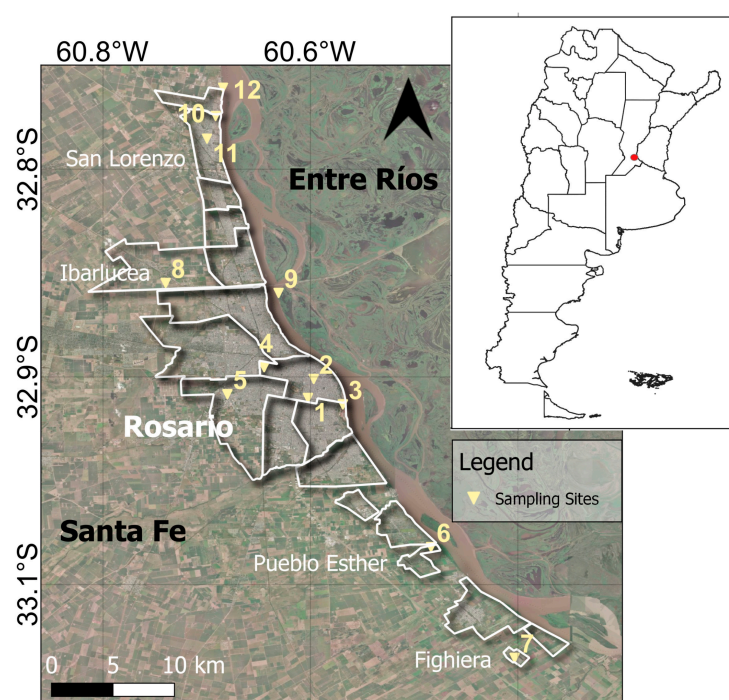


Figure 2. Study area with locations of twelve sampling sites (yellow marks). In the right: map of Argentina; the red point indicates the study area in the Santa Fe province. “Entre Ríos” is the province bordering Santa Fe to the east.

Table 1 presents the exact location of each sampling site (see Figure 2), a description of the site and the main activities conducted there, and the land use type.

Table 1. Description of sampling sites.

ID	Sampling Site	Geographic Location	Brief Description	Main Land Use
1	Rosario macrocenter 1	32°58'3" S 60°39'1" W 26 m a.s.l	It is an urban area of medium population, commercial and vehicular density. There is a high concentration of 1 storey houses and a few bus lines. The neighborhood is characterized by having many hospitals. It is a space close to the green lung of the city, the "Independencia Park"	Urban–macrocenter (hospitals/park)
2	Rosario microcenter	32°57'3" S, 60°38'43" W 45.6 m a.s.l	Urban site located in the commercial center of Rosario. It is an area with high population, commercial and vehicular density, due to the high concentration of businesses in the area. There are many high-rise buildings	Urban–microcenter
3	Rosario Port Center	32°58'23" S, 60°37'12" W 11 m a.s.l	Port site located in the city of Rosario, close to the commercial center of the city. Typical port activities are carried out: loading and unloading ships that market different types of goods. Zone of high vehicular density.	Port–urban
4	Rosario macrocenter 2	32°56'27" S, 60° 41'19" W 20 m a.s.l	Located near the geographical center of Rosario. Commercial area but with less population density and shops than the microcenter. The Rosario bus terminal is 2 km away from this site.	Urban–macrocenter (bus station)
5	Rosario Industrial site	32°57'51" S, 60°43'14" W 28 m a.s.l	It is in the collector of the Rosario Ring Road in the west of the city. It is an area with high industrial and automobile activity but with low density of family houses.	Industrial (urban)
6	Pueblo Esther	33°5'53" S, 60°32'35" W 30 m a.s.l	It is a residential area where citizens live permanently but it is also widely used as a space to rest during the weekend by the inhabitants of the large surrounding cities. To the south there is an industrial zone with different activities: agribusiness, chemicals, plastics manufacturing, cereal and fertilizer suppliers. Total inhabitants: 12,679	Residential (town)
7	Fighiera	33°11'42" S, 60°28'7" W 51.1 m a.s.l	A small town in a rural area. It has low commercial activity due to its small size. Total inhabitants: 5962	Rural–village
8	Ibarlucea	32°52'0" S, 60°46'22" W 30 m a.s.l	A town to the NW of Rosario that is characterized by its high amount of green spaces and less vehicle circulation compared to the city. An area chosen to spend the weekends, although it also hosts a permanent population. It is located 800 m from a provincial route. Total inhabitants: 9224	Residential (town)
9	Isla Verde (Green Island)	32°52'34" S, 60°40'34" W 10 m a.s.l	Natural site located in the Paraná wetland. It is a river island with no vehicular circulation since there are no roads, only a few people live in the surroundings or reach the area by small boats for recreation. It is a space of land with native vegetation, surrounded by sandy beaches and separated from the big city by the big channel of the Paraná River.	Natural
10	San Lorenzo Industrial site *	32°43'19" S 60°43'52" W 20 m a.s.l	Urban/industrial site located in the San Lorenzo city (in the San Lorenzo department). Total inhabitants: 50,954	Industrial (urban)
11	San Lorenzo Urban site **	32°44'30" S, 60°44'19" W 30 m a.s.l	Urban site located in the San Lorenzo city (in the San Lorenzo department). Total inhabitants: 50,954	Urban (in industrial area)
12	Puerto General San Martín **	32°41'50.1" S, 60°43'28.5" W 30 m a.s.l	Port/industrial site in the locality of Puerto General San Martín (in the San Lorenzo department). Total inhabitants: 17,977	Port–industrial

* Used only in the winter sampling campaign ** Replace the site 10 in the summer sampling campaign (the site 10 splits in site 11 and site 12, to take measurements in the North of GR). Total inhabitants at different localities are obtained from INDEC, National Census 2022.

2.2. PM_{2.5} Sampling

2.2.1. Sample Collection

PM_{2.5} was collected using Harvard impactors (Figure 3) connected to a low-flow vacuum pump (16.5 ± 2 L/min). The samplers were installed at a height between 1.5 and

2 m above ground level. Particles were collected on Teflon (PTFE) filters (Figure 3) with a diameter of 47 mm and a pore size of 1 μm [14]. Replacement of the filters was carried out every 72–144 h, according to weather conditions.

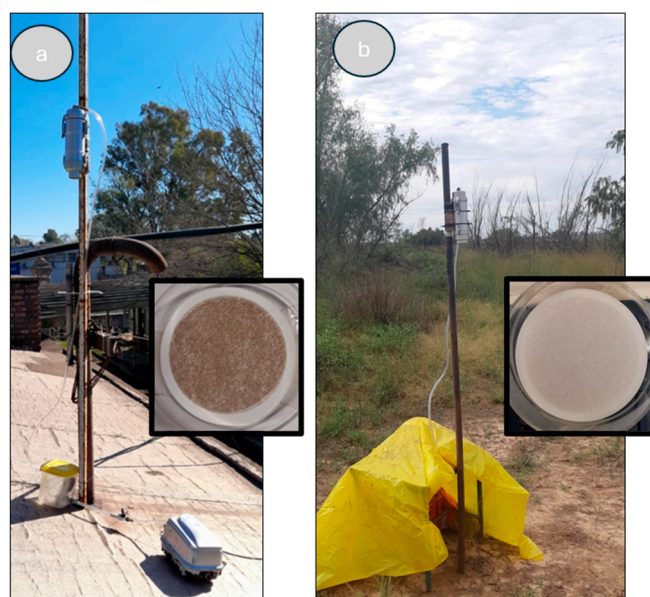


Figure 3. Harvard impactors installed at measurement sites and Teflon filters (embedded figures) after collecting $\text{PM}_{2.5}$ during a sampling period at each corresponding site. (a) Site 3 (port–urban), winter campaign, filter sampling period 26–29 July 2021. (b) Site 9 (natural), summer campaign, filter sampling period 2–8 March 2022.

The sampling campaigns were performed during periods (lasting more than one month) corresponding to the Southern Hemisphere winter and summer. The winter and summer campaigns, in turn, were composed of two stages each. Typically, six sites were sampled simultaneously during each stage of a given campaign. During winter 2021, the first stage extended from 26 July to 7 August and the second stage from 18 August to 30 August. Similarly, in summer 2022, the first stage was conducted from 13 February to 26 February, and the second stage from 2 March to 23 March. Between 7 and 8 samples were collected from each site, except for site 1 (reference site), where the equipment operated during all sampling stages, resulting in a total of 16 samples. Table 2 shows in detail the methodology adopted for sampling.

Table 2. Sampling schedule and sites during the winter (W) and summer (S) campaigns. Each “x” represents one $\text{PM}_{2.5}$ filter sample collected at the corresponding site (1–12) during each sampling stage (1 or 2).

Season	Stage	Period	Site ID											
			1	2	3	4	5	6	7	8	9	10	11	12
								Samplings						
W	1	26 Jul–7 Aug	xxxx	xxxx	xxxx			xxxx	xxxx			xxxx		
W	2	18 Aug–30 Aug	xxxx			xxxx	xxxx			xxxx	xxx			
S	1	13 Feb–26 Feb	xxxx	xxxx	xxxx			xxxx	xxxx				xx	xx
S	1	2 Mar–23 Mar	xxxx			xxxx	xxx			xxxx	xxx		x	x
W = winter; S = Summer														

Once sampling was completed, the filters were stored in an oven at 65 °C in their respective acrylic Petri dishes to remove any moisture that they may have absorbed from the environment, preventing it from affecting the subsequent weighing.

2.2.2. PM_{2.5} Concentration Calculation

The mass of PM_{2.5} was determined by the gravimetric difference between the final mass of the filter (with the collected particulate matter) and its initial mass (before exposure to atmospheric particles). A microbalance (0.01 mg, Shimadzu, Kyoto, Japan) was used for this purpose [11].

The final concentration (mass of the PM_{2.5} fraction per unit volume), as given by Equation (1), was calculated based on the volume of air sampled, which is equal to the flow rate (Q) multiplied by the sampling time (t). The results are expressed in $\mu\text{g m}^{-3} \pm$ the standard deviation (SD).

$$C = \frac{m}{V} = \frac{m}{Q \cdot t} \quad (1)$$

2.2.3. Statistical Evaluation

Given the heterogeneity of the collected samples, the Mann–Whitney U test ($p < 0.05$) and the Kruskal–Wallis non-parametric analysis of variance ($p > 0.05$) were employed to compare the obtained concentrations.

2.3. Satellite Data Description

To complement the ground-level PM_{2.5} measurements, we studied the Aerosol Optical Depth (AOD) using MAIAC and the atmospheric column densities of NO₂ (NO₂ VCD) using TROPOMI. As our ground data for PM_{2.5} concentrations were obtained by weighing the filters containing particles accumulated on them during at least 72 h (corresponding to the total volume sampled during this period), average values from the satellite data were also calculated for the exposure period of each PM_{2.5} sample (using the data available during those days).

2.3.1. Aerosol Optical Depth (AOD)

This study is complemented by Aerosol Optical Depth (AOD) observations from the MCD19A2 Version 6.1 product. This dataset provides satellite-derived AOD in the blue (470 nm) and green (550 nm) bands, retrieved from the Moderate Resolution Imaging Spectroradiometer (MODIS) aboard the Terra and Aqua satellites. It offers AOD values at a 1 km spatial resolution with daily temporal coverage, spanning from 24 February 2000 to the present globally. The dataset is accessible via NASA's data distribution platforms, and a detailed description of its algorithm, including its capabilities, constraints, and improvements, is documented in the literature [29–31].

In this study, the AOD at 470 nm was analyzed for the area shown in Figure 2. To obtain a more representative AOD value for each sampling site, a 4 km buffer was applied around each sampling point. High-quality data were ensured by filtering AOD values using the Quality Assurance (QA) dataset, specifically selecting QA Bits 8–11, which were set to “0000” for “Best Quality” data.

2.3.2. TROPOMI NO₂ Data

The atmospheric column densities of NO₂ (NO₂ VCD) were determined from the 405–465 nm wavelength bands recorded by the TROPOMI (TROPOspheric Monitoring Instrument) sensor on board the Sentinel-5P satellite, which features a spatial resolution of $5.5 \times 3.5 \text{ km}^2$. The NO₂ VCD, measured by TROPOMI, represents the number of moles of NO₂ per unit area (expressed in mol/m^2). These measurements were then converted to molecules/ cm^2 by multiplying the variable's values by the conversion factor of 6.02214×10^{19} [32].

The data used in this study were obtained from Sentinel-5P/TROPOMI Level-3 offline (OFFL) products (COPERNICUS/S5P/OFFL/L3_ NO₂), retrieved via the Google Earth

Engine (GEE) API [33]. In GEE, Sentinel-5P Level 2 (L2) datasets were converted to Level 3 (L3) using the bin_spatial procedure of the harpconvert tool [34]. The NO₂ columns were computed from pixels filtered with a quality assurance (QA) threshold of 75%, excluding low-quality pixels or those affected by cloud cover.

3. Results

3.1. Meteorological Data and Fire Situation

Meteorological data, supplied by the National Meteorological Service of Argentina, from a station located at the international airport “Islas Malvinas” in Rosario city (32.92° S, 60.78° W), were used to provide a general description of the conditions during the sampling periods. While these data accurately reflect regional weather patterns, they may not capture specific local micrometeorological variations or wind fields at the most remote sites. For the meteorological description, the entire duration of each sampling campaign was considered. Additionally, data from the ERA5 reanalysis [35] were used to analyze the planetary boundary layer (PBL).

During the winter period, low temperatures and reduced relative humidity were observed compared to summer. Conversely, atmospheric pressure was lower during the summer. No precipitation was recorded during the winter, but there was rainfall during the summer, which can cause a wet deposition of the particles during this season, thus reducing PM_{2.5} concentrations [36] (Table 3). The PBL height was higher in summer than in winter, as reported in the literature [37]. It is worth noting that the mean value during the winter campaign was 473.1 m and its standard deviation was 228.3 m, indicating the wide variation observed during this period, particularly from 26 July to 29 July, when the mean value was 990 m. This anomaly implies that the average winter PBL height was 15% lower than during the summer.

Table 3. Meteorological conditions during each sampling period. Southern Hemisphere (SH) Winter data correspond to the year 2021 and SH Summer data correspond to 2022. Sources: National Meteorological Service (SMN), Argentina, and ERA5 to Planetary Boundary Layer.

Sampling Period	Temperature (°C) Mean ± SD	Relative Humidity (%) Mean ± SD	Atmospheric Pressure (hPa) Mean ± SD	Planetary Boundary Layer Height (PBLH) (m) Mean ± SD	Accumulated Precipitation (mm)
26 July–7 August	10.2 ± 6.6	66.0 ± 21.8	1024.7 ± 5.4	439.4 ± 308.1	0.0
18 August–30 August	14.0 ± 6.2	57.5 ± 23.1	1014.2 ± 5.7	448.6 ± 39.8	0.0
TOTAL Winter campaign	12.1 ± 6.7	61.8 ± 22.8	1019.6 ± 7.7	473.1 ± 228.3	0.0
13 February–26 February	23.6 ± 5.8	62.8 ± 21.4	1012.0 ± 3.5	618 ± 105.5	15.4
2 March–23 March	20.8 ± 4.8	73.8 ± 20.4	1013.4 ± 5.3	499.8 ± 57.4	173.8
TOTAL Summer campaign	21.9 ± 5.4	69.5 ± 21.4	1012.8 ± 4.7	562.9 ± 104.2	189.2

During the first sampling period from 26 July to 7 August (2021), the prevailing wind directions were from the NE and SW, while during the second winter sampling period, winds from the S and SE prevailed. In the summer sampling period, wind directions varied mainly between the E, NE, S and SE (Figure 4).

In both seasons studied, the meteorological conditions were under the influence of the La Niña phase of the ENSO phenomenon in central Argentina [38], which resulted in a three-year cycle (2020–2022) that was much drier than the standard years in the area.

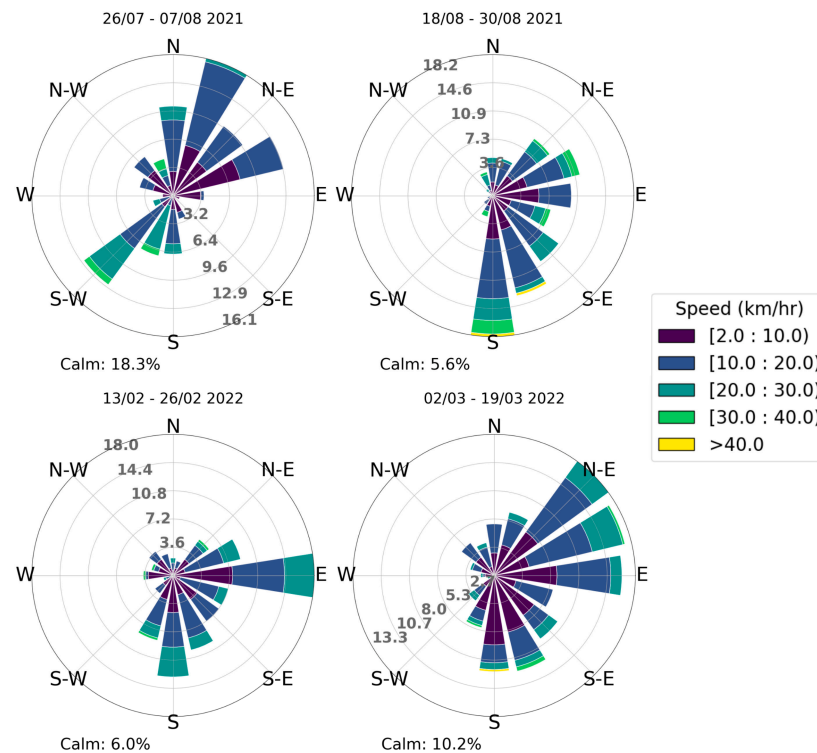


Figure 4. Wind Roses for Winter (**top panel**) and Summer (**bottom panel**) Sampling Stages. Source: National Meteorological Service (SMN), Argentina.

During the winter of 2021, the islands of the Paraná River Delta (located east of Rosario city and the extended GR coastal area) experienced two major fire events (Figures 5 and 6) associated with the prolonged three-year drought linked to the La Niña phase. The first occurred between 27 July and 3 August and the second between 26 August and 30 August.

As observed in Figure 4, the winds that reached the GR during the first stage of sampling basically avoided the fire zone, whose emissions therefore had virtually no effect on the GR area, except for 31 July and 1 August (see wind rose in Figure 5d), when locations in the southern part of the GR, such as Fighiera, were particularly affected by nearby fires and easterly winds. Air mass back-trajectory analyses show that the air masses that reached the study area passed through the fire-affected region during sampling periods 2 and 3 of the first winter stage.

During the second stage, there was a greater predominance of winds from the fire sector towards the GR (Figure 4), but the fires occurred during the last days of sampling, with 27 August being the only date presenting winds that reached the GR from the SE sector (see the wind rose and air mass back-trajectories in Figure 6). Thus, emissions from the fires developing on the islands of the Paraná River Delta, off the coast of the GR, had little effect on the overall sampling.

However, winds from the SE on 31 July, 1 August and 27 August were able to transport particles and NO₂ from the fires to the study area as detected in previous studies for other analyzed periods by using satellite data [22,23].

Additionally, a non-parametric Spearman correlation analysis was performed to evaluate the potential relationship between PM_{2.5} concentrations and local meteorological parameters (mean wind speed, temperature, relative humidity, and PBLH). No statistically significant correlations were observed ($p > 0.05$) during either the winter or summer campaigns.

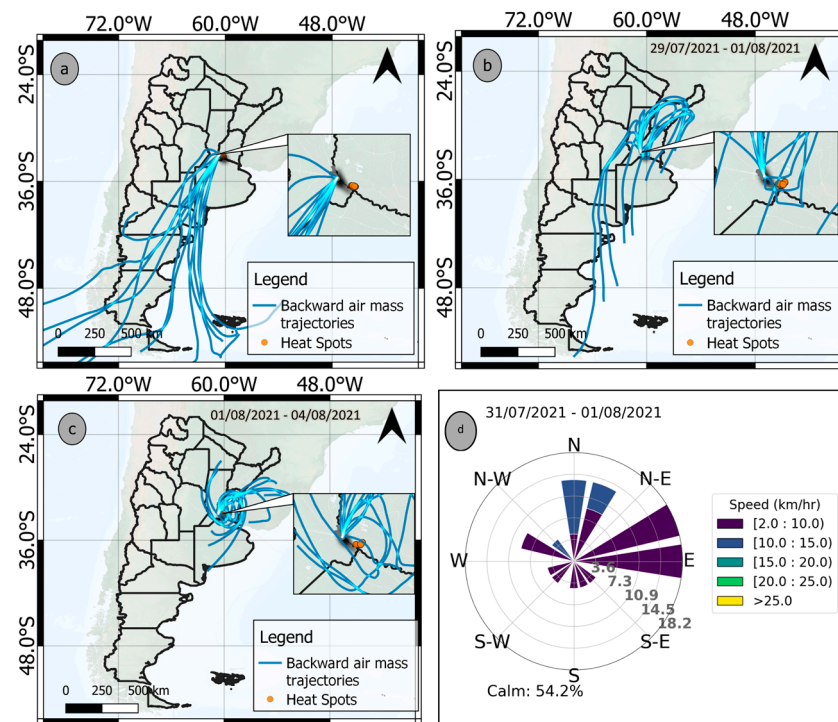


Figure 5. Back-trajectories of air masses (blue lines) calculated for the duration of each sampling period, with Site 1 as the arrival point at 500 m AGL; active fires (orange dots) near the study area; and wind rose diagrams for the critical days. (a) Sampling period: 26–29 July 2021. (b) Sampling period: 29 July–1 August 2021. (c) Sampling from 1 August to 4 August 2021. (d) Wind rose for 31 July and 1 August 2021.

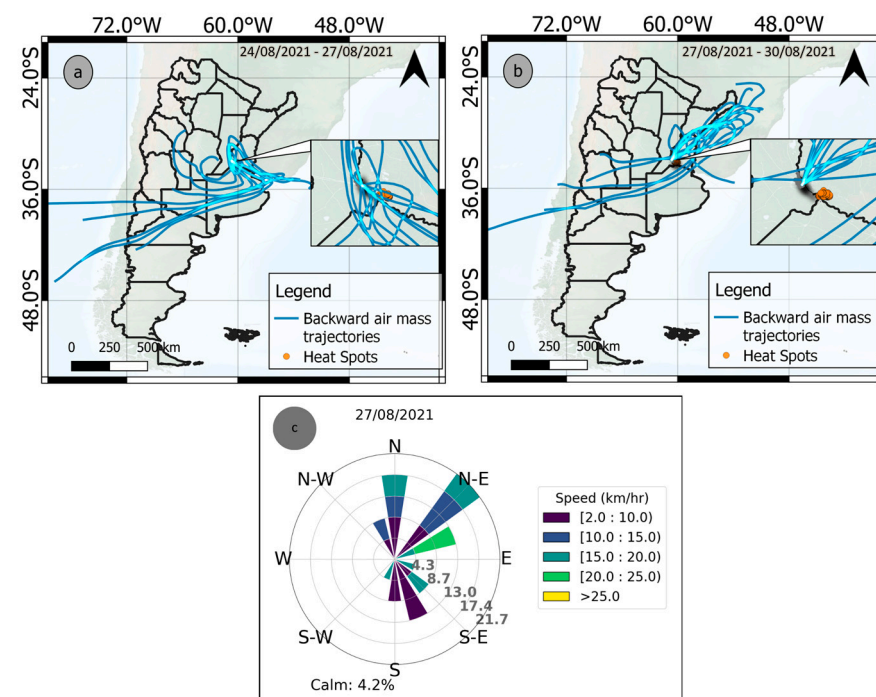


Figure 6. Back-trajectories of air masses (blue lines) calculated for the duration of each sampling period, with Site 1 as the arrival point at 500 m AGL; active fires (orange dots) near the study area; and wind rose diagrams for the critical days. (a) Sampling period: 24–27 August 2021. (b) Sampling period: 27–30 August 2021. (c) Wind rose for 27 August 2021.

During the three-year drought, the fires intensified during the winter, which is the driest season in the GR area. The sampling carried out on the days corresponding to Figures 5 and 6 coincided with some of these important episodes of burning and the subsequent arrival of air masses from them during the SH winter of 2021.

During the summer 2022 sampling campaign, no fires were recorded near the study area; however, the large number of hotspots recorded in the northern part of Santa Fe Province and in the northeastern part of the country (primarily in Corrientes Province) is worth noting. For this reason, we present the air mass back-trajectories (see Figure 7) for the first sampling periods of the first summer stage (13–16 February and 16–19 February), during which satellite imagery detected the arrival of air masses in the study area from these fires.

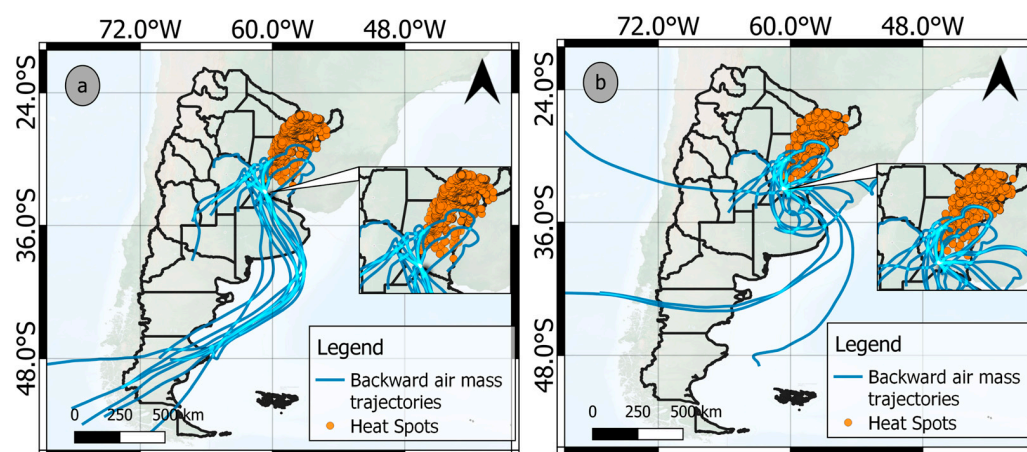


Figure 7. Back-trajectories of air masses (blue lines) calculated for the duration of each sampling period, with Site 1 as the arrival point at 700 m AGL and active fires (orange dots) near the study area. (a) Sampling period: 13–16 February 2022. (b) Sampling period: 16–19 February 2022.

3.2. $PM_{2.5}$ Mass Concentrations

3.2.1. In Situ Ground Measurements

Figure 8 shows the spatial distribution of $PM_{2.5}$ mass concentrations calculated for each sampling site. Two maps were created, one for the winter sampling campaign and another for the summer sampling campaign. These maps were generated using Inverse Distance Weighting interpolation (IDW) [14] in QGIS (version 3.28.3) [39]. To avoid erroneous extrapolations to unmonitored areas within the region, interpolation was limited to a 10 km buffer around each sampling point, in accordance with the EPA recommendation regarding the representative spatial scale for air sampling [40].

Higher $PM_{2.5}$ concentrations were observed during the winter campaign, with the industrial area of San Lorenzo exhibiting the highest values. During the summer campaign, the highest values were observed in the center of Rosario and in the urban area of San Lorenzo. The lowest concentrations were observed in the area around sites 6 and 7.

Figure 9 illustrates the temporal variation in $PM_{2.5}$. During the winter campaign, a similar behavior was observed across all sites towards the end of the season (except for site 1). At the end of the first summer sampling stage and the beginning of the second stage, rainfall events (approximately 100 mm) occurred, which could explain the low concentration values found during this period. Towards the end of this campaign, an increase in $PM_{2.5}$ concentrations was observed.

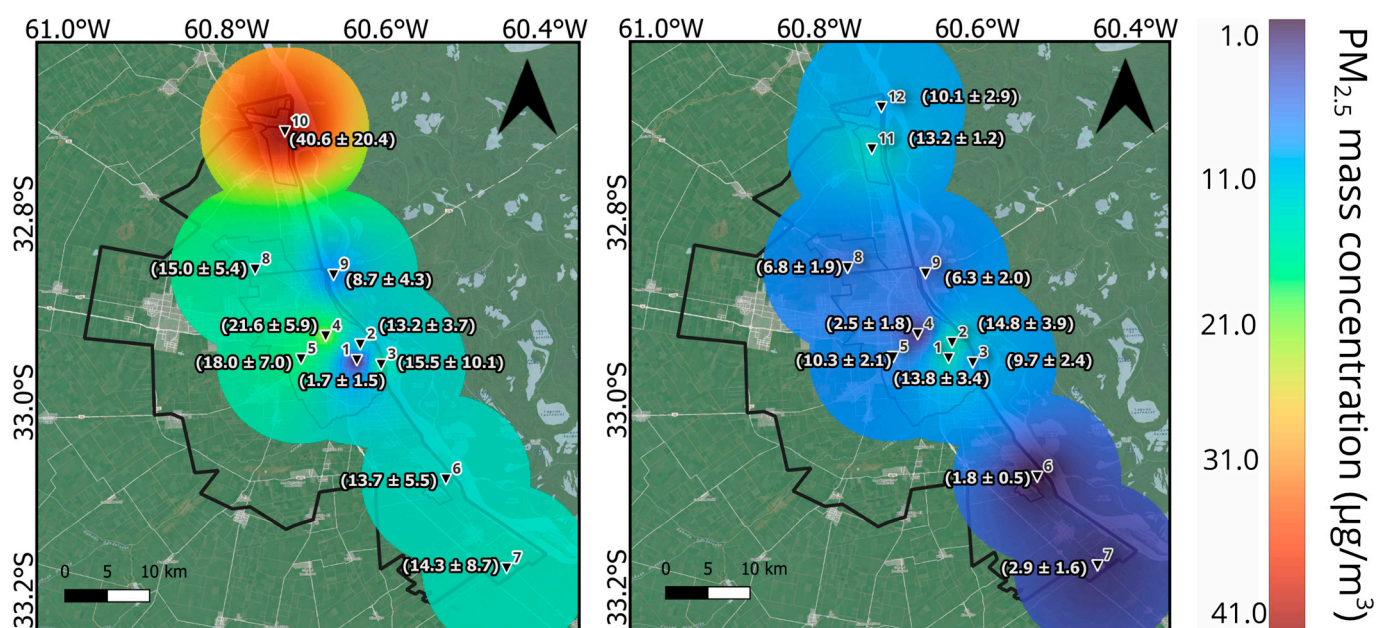


Figure 8. PM_{2.5} mass concentration ($\mu\text{g m}^{-3}$) in GR during the winter campaign (left) and summer campaign (right). The spatial representation was generated via Inverse Distance Weighting (IDW) interpolation restricted to a 10 km buffer around each sampling site. Numeric labels indicate the exact in situ mean values and standard deviations (SD) for each location.

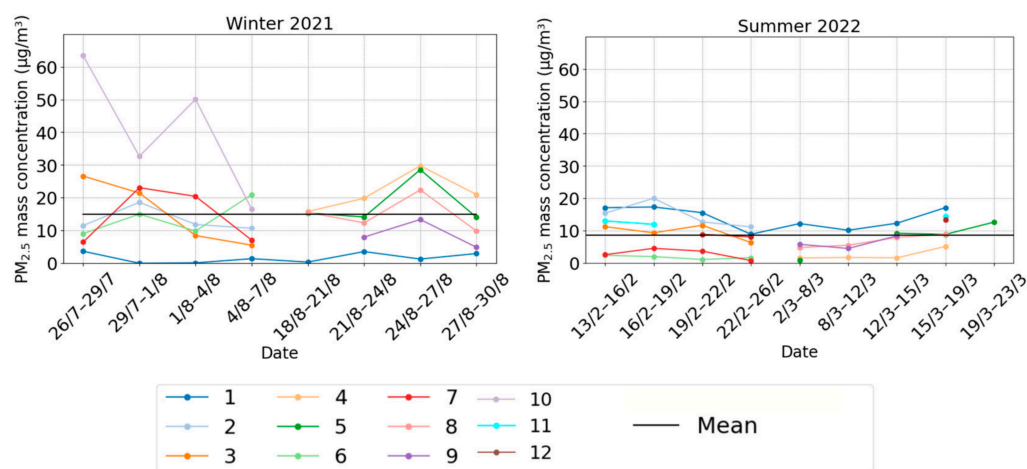


Figure 9. Temporal variation in the mass concentration PM_{2.5} at each site for the winter (left) and summer (right) sampling campaign. The colored lines represent the different sites and the solid black line represents the average (total mean, for all sites and sampling periods) for each (winter and summer) campaign.

The WHO guidelines establish a maximum daily PM_{2.5} threshold of $15 \mu\text{g m}^{-3}$ for good air quality [41]. Although the concentrations found in this study correspond to filters exposed for 72 to 144 h, this comparison is useful as a reference point. Since multi-day cumulative sampling inherently smooth out and dilutes daily pollution peaks, if a 72 or 144 h average exceeds the 24 h threshold, it provides evidence of a sustained degradation of air quality during that period.

During the winter campaign, 45.2% of the samples exceeded the threshold suggested by the WHO, whereas in the summer, this percentage decreased to 13.6%. Sites 4 (urban) and 10 (industrial) exceeded this limit in all winter samplings, a pattern that was not observed at any site during the summer season. At site 7, the exceedance of $15 \mu\text{g m}^{-3}$

occurred on two occasions, coinciding with the wildfire events recorded during the winter of 2021. Meanwhile, site 5 (industrial) exceeded the recommended value twice, while in the remaining two sampling periods, the PM_{2.5} concentration remained close to the threshold, at approximately 14 µg m⁻³. During the summer of 2022, the only cases presenting values higher than 15 µg m⁻³ were limited to specific measurements at sites 1 and 2 (urban).

Table 4 presents the mean values for each site (for both campaigns), along with the maximum and minimum values obtained in each season, and the similarities identified among the sites using the Kruskal–Wallis test.

Table 4. PM_{2.5} statistics and non-parametric Kruskal–Wallis analysis of variance ($p < 0.05$) results for each sampling site during the winter (**top**) and summer (**bottom**) seasons. n refers to the number of individual samplings (or filters that collected PM_{2.5}) at each site during the corresponding (winter or summer) campaign, being equal to the number of “x” for each season in Table 2.

PM _{2.5} Mass Concentration (µg m ⁻³) Winter Campaign							
Site ID	n	Mean ± SD	Min	Max	Group	Group	Group
1	8	1.7 ± 1.5	0.1	3.7	A		
2	4	13.2 ± 3.7	10.7	18.6		B	C
3	4	15.5 ± 10.1	5.5	26.6		B	C
4	4	21.6 ± 5.9	15.8	29.8		B	
5	4	18.0 ± 7.1	14.0	28.6		B	C
6	4	13.7 ± 5.5	9.0	21.0		B	C
7	4	14.3 ± 8.7	6.5	23.1		B	C
8	4	15.0 ± 5.4	9.8	22.4		B	C
9	3	8.7 ± 4.3	4.9	13.4	A	B	
10	4	40.7 ± 20.4	16.5	63.4			C
All	43	15.5 ± 12.7	0.1	63.4			

PM _{2.5} Mass Concentration (µg m ⁻³) Summer Campaign							
Site ID	n	Mean ± SD	Min	Max	Group	Group	Group
1	8	13.8 ± 3.4	8.9	17.3			D
2	4	14.8 ± 3.9	11.2	20.0			D
3	4	9.7 ± 2.4	6.3	11.7		B	C
4	4	2.5 ± 1.8	1.6	5.2	A	B	
5	3	10.3 ± 2.1	8.9	12.7	A	B	C
6	4	1.8 ± 0.5	1.1	2.4	A		
7	4	2.9 ± 1.6	0.8	4.6	A	B	
8	4	6.8 ± 1.9	4.8	8.9	A	B	C
9	3	6.3 ± 2.0	4.5	8.4	A	B	C
11	3	13.2 ± 1.2	12.0	14.5			C
12	3	10.1 ± 2.9	8.1	13.4		B	C
All	44	8.6 ± 5.3	0.8	20.0			

Means with a common letter are not significantly different ($p > 0.05$).

Significant differences were observed between the concentrations obtained in winter and summer at sites 1 ($p = 0.00031$), 4, 5, 6, 7 and 8 ($p = 0.028$).

In winter, site 1 (urban) presented the most significant differences compared to the other locations, while in the summer, sites 1 and 2 (urban) showed the most significant differences with respect to most of the land uses studied.

Except for sites 1 and 2, the mean PM_{2.5} concentration was higher in samples collected during the winter, as observed in other cities around the world [37,42,43]. The maximum point values were also visibly higher during this period.

When comparing seasonal dynamics, some distinctive patterns were observed regarding land use and regional transport events. At site 2, PM_{2.5} concentrations remained stable between winter and summer (winter: 13.2 ± 3.7 µg m⁻³ vs. summer: 14.8 ± 3.9 µg m⁻³).

This suggests that in the city center, local sources (such as vehicular traffic and commercial activity) predominated during the periods analyzed and that the contribution of biomass burning aerosols did not significantly alter the air in the area.

On the other hand, at site 7 (rural site), a strong seasonal contrast was observed. Measurements in the summer indicated a low concentration ($2.9 \pm 1.6 \mu\text{g m}^{-3}$), but during the winter, the mean $\text{PM}_{2.5}$ value was drastically higher ($14.3 \mu\text{g m}^{-3}$), accompanied by a significant increase in the standard deviation (± 8.7). This fluctuation, which indicates greater variability during the winter measurements, was caused by the arrival, in a typically unpolluted area, of air masses from the Paraná Delta fires during certain periods.

In the San Lorenzo area (sites 10, 11 and 12), high seasonal variability was also perceived. During the winter, site 10 recorded the highest mean and standard deviation of the entire campaign ($40.7 \pm 20.4 \mu\text{g m}^{-3}$), suggesting fluctuating pollutant sources. Sites 11 and 12, which replaced site 10 during the summer season, showed high averages (13.2 and $10.1 \mu\text{g m}^{-3}$, respectively), but with significantly smaller standard deviations (± 1.2 and ± 2.9) compared to the winter period.

The industrial site of San Lorenzo presented the highest $\text{PM}_{2.5}$ concentration, with a value three times higher than that of the San Lorenzo urban site, which ranked second. Following these, the highest values were observed at the industrial and port sites of Rosario. The natural site exhibited the lowest average $\text{PM}_{2.5}$ concentration.

In general, considering all sampling sites, the winter campaign showed a much wider dispersion (± 12.73) compared to the summer (± 5.26). This indicates that air quality in the GR during the winter 2021 sampling campaign was influenced by the spatial and temporal heterogeneity of the regional transport of biomass-burning aerosols.

3.2.2. $\text{PM}_{2.5}$ Mass Concentration in Greater Rosario and Other Cities in the World

The sampling sites were classified according to their land use (urban, industrial, residential, natural, rural and port), and the average $\text{PM}_{2.5}$ concentrations were compared with those reported for other cities around the world (Table 5).

The $\text{PM}_{2.5}$ concentration values found at the urban sites in this study are similar to those reported in other cities such as Córdoba, Buenos Aires (Argentina) and Curitiba (Brazil), while the $\text{PM}_{2.5}$ values are much lower than those reported for Beijing (China). The industrial sampling site located in Rosario showed similar values to those reported for Córdoba and San Pablo; however, the industrial sampling site located in San Lorenzo (site 10) showed very high values compared to these cities, probably due to highly localized emission sources.

Residential sites exhibited $\text{PM}_{2.5}$ concentrations within the range reported for other Argentine cities (Córdoba, Buenos Aires, see Table 5). The natural site yielded lower values than those studied in Córdoba. A similar pattern occurred with the rural site, whose concentration found in this work was considerably lower than those reported in Córdoba and Beijing.

It is worth mentioning that the city of Córdoba, despite being similar in latitude and activities to Rosario, differs in its orography, since it is surrounded by mountains that can trap pollutants within the city. This contrasts with the GR region, where the winds cross the flat terrain, causing greater air circulation. This could explain the lower values found in GR compared to Córdoba across all land uses, as presented in Table 5.

The port sampling sites showed similar values among themselves, but there was a marked difference compared to the $\text{PM}_{2.5}$ values reported for Thessaloniki Port; however, this difference might be due to the fact that the latter is a seaport, influenced by marine aerosols, and situated in a different region.

Table 5. Comparison of PM_{2.5} mass concentration according to land use in Greater Rosario (present study, marked with *) and other cities around the world.

Site Type	City	Date	Average PM _{2.5} (µg/m ³) ± SD	Reference
Urban site	* Rosario, Argentina	July–August 2021, February–March 2022	10.4 ± 77	This study
	* San Lorenzo (GR), Argentina	February–March 2022	13.2 ± 1.2	This study
	Córdoba, Argentina	May–June 2018	12.7 ± 8.6	[14]
	Buenos Aires, Argentina	August 2006–March 2007	14 ± 6	[15]
	Curitiba, Brazil	June 2007–August 2008	14.4 ± 9.5	[44]
	Beijing, China	2006–2008	87.7	[45]
Industrial Site	* Rosario, Argentina	August 2021, March 2022	13.0 ± 7.8	This study
	* San Lorenzo (GR), Argentina	July–August 2021	40.7 ± 20.4	This study
	Córdoba, Argentina	August 2018	18.9 ± 2.8	[14]
	San Pablo, Brazil	March–June 2017	10.9 ± 6.8	[46]
Residencial Site	* Pueblo Esther (GR), Argentina	July–August 2021, February–March 2022	7.8 ± 7.3	This study
	* Ibarlucea (GR), Argentina	August 2021, March 2022	10.9 ± 5.8	This study
	Córdoba, Argentina	July–August 2018	15.2 ± 4.5	[14]
	Buenos Aires, Argentina	December 2006–March 2007	11 ± 6	[15]
Natural Site	* Isla Verde (GR), Argentina	August 2021, March 2022	7.5 ± 3.3	This study
	Córdoba, Argentina	June–July 2018	19.4 ± 22.9	[14]
Rural Site	* Fighiera (GR), Argentina	July–August 2021, February–March 2022	8.6 ± 8.4	This study
	Córdoba, Argentina	July 2018	37.8 ± 30.2	[14]
	Shangdianzi (Beijing, China)	2006–2008	54.2	[45]
Port Site	* Rosario, Argentina (river)	July–August 2021, February–March 2022	12.6 ± 7.5	This study
	* Puerto General San Marchtin (GR), Argentina (river)	February–March 2022	10.1 ± 2.9	This study
	Thessaloniki, Greece (sea)	June 2011–May 2012	65.5 ± 35.3	[47]

3.3. Satellite Data Analysis

3.3.1. Aerosol Optical Depth

Figure 10 presents the AOD for the GR region, the violet and blue colors represent a low AOD, the green-yellow colors a medium AOD and the reddish-orange colors a high AOD. Uncolored areas imply an absence of data. The map corresponding to the summer campaign (Figure 10 right) shows higher AOD values, mainly in the urban area of the city of Rosario (sites 1, 2 and 4) and San Lorenzo (site 11). Even though a large amount of satellite AOD data is missing from the winter campaign, small portions of areas with very high AOD values can be observed in Figure 10 (left) in the zone surrounding sites 6 (residential) and 7 (rural), near the Delta fire hotspots that occurred during that campaign.

For the present study area, higher AOD values were expected during the winter campaign because in August, this parameter begins to rise, as reported by Della Ceca et al. [48] for the city of Córdoba, Argentina (~400 km from the GR), and Castro Videla et al. [49] for the central region of the country. However, our results indicated higher AOD values during the summer campaign. This may be attributed to the extensive forest fires that occurred in the Province of Corrientes, which reached significant magnitudes (measured in Fire Radiative Power [FRP] and number of burned pixels), transporting particulate matter outside the provincial boundaries and altering the conditions in the upper atmosphere in central Argentina during the summer of 2022 [50].

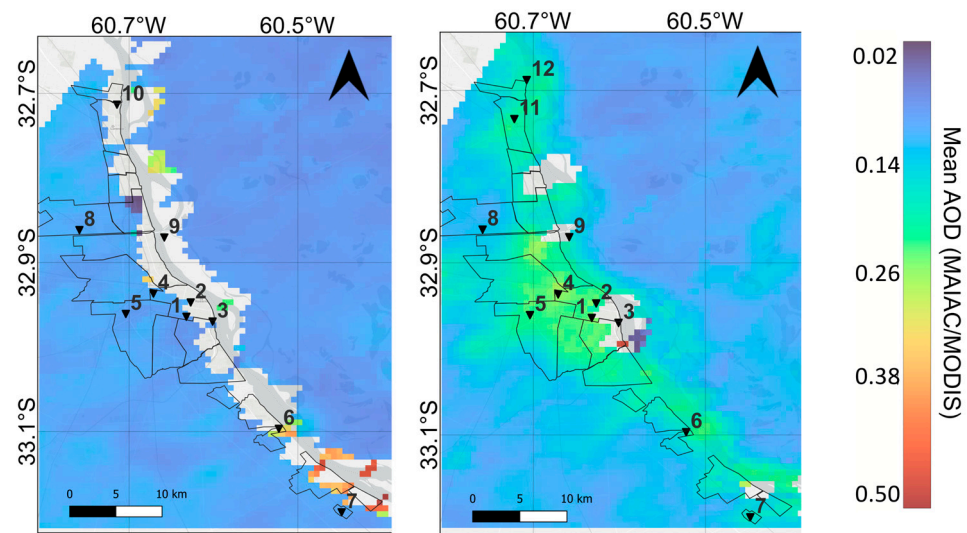


Figure 10. AOD map for the winter campaign (**left**)—26 July to 7 August and 18 August to 30 August, and summer campaign (**right**)—13 February to 26 February, and 2 March to 23 March. Data source: MAIAC/MODIS.

The average AOD value for the winter season (26 July to 7 August and 18 August to 30 August 2021) was 0.13 ± 0.04 (range: 0.06–0.23) and for the summer season (13 February to 26 February and 2 March to 13 March 2022), it was 0.20 ± 0.07 (0.07–0.35). Site 1 registered the highest value (0.35) between 16 February and 19 February, and site 3 the lowest one (0.06) between 26 July and 29 July.

During the winter campaign, a peak is observed between 18 August and 21 August, this being the maximum value reached across all sites. Thereafter, the behavior was quite similar throughout the sampling period, with the greatest differences observed at sites in the western locations of the GR (sites 5 and 8). In addition, in the first stage of sampling (26 July to 7 August), most of the values were below the average, while in the second stage (18 August to 30 August), the values were almost all above the mean value.

On the other hand, during the summer campaign, although the behavior was less consistent than during the winter, all sites exhibited an increase in AOD between 16 February and 19 February. Ibarlucea (site 8), Green Island (site 9), and the Rosario Industrial Site (site 5) consistently recorded values below the total mean, but this value was evidently increased by the higher values of the first stage of the campaign when the aforementioned sites were not sampled. A strong decrease in the general AOD situation for the GR region during the second summer stage can be deduced from the pronounced drop in AOD values for site 1, the reference site.

Valle Seijo et al. [51] studied the average AOD for the month of March for Rosario city and adjacent regions, identifying a minimum value on 20–23 March 2020. During this period, the atmosphere was clean due to several converging factors: rainfall in the preceding days, strict quarantine measures due to COVID-19, and the absence of nearby fires. The reference value found was 0.05, attributed to minimal anthropogenic influence and the convergent conditions. This indicates that our study period of March 2022 was 220% above this baseline AOD (mean value: 0.16).

Although AOD values take into account the total vertical atmospheric column, while the in situ measurements supply aerosol concentrations near ground level, some similarities can be found between Figures 7 and 9. Among these are:

- (1) A peak during the sampling period from 29 July to 1 August, coinciding with the extended fires shown in Figure 5. Top panel, for all the sites in Figure 11 and particularly for coastal sites specially affected by the fire plume such as the Rosario

microcenter (site 2), Pueblo Esther (site 6) and Fighiera (site 7), is shown in Figure 9. This could be related to the satellite resolution and to changing winds that have a specific influence at ground level, producing peaks in some sites when crossing through them. In this way, the fire effects are detected by satellite measurements in a more extended and diffuse way, for all sites, whereas they can be determined at the specific in situ measurement sites in a more localized manner. Both techniques complement each other, showing the usefulness of satellite data for a broader area when ground measurements in specific locations are not possible.

- (2) The San Lorenzo industrial site (ID 10) indeed presented higher AOD values than the rest of the sites sampled during the first winter stage, as shown in Figure 11, but the difference with the other sites was not as pronounced as it was for $PM_{2.5}$ concentrations in Figure 9. Additionally, the AOD at site 10 followed basically the same behavior as the other sites along this measurement stage, while the $PM_{2.5}$ concentrations showed a very distinct and outlier behavior, which suggests the influence of highly localized emission sources located in the surroundings of site 10 on the ground measurements. The high standard deviation found for site 10, as presented in Table 4, could also be an indication of the presence of intense, fluctuating sources, which partially could be attributed to pollution plumes from the Delta fires reaching San Lorenzo but also could be possibly due to local industrial emissions.
- (3) Both $PM_{2.5}$ and AOD reached higher values at the reference site (site 1) during the first summer stage than during the second one, with a drop initiating at the sampling period of 22–26 February, coinciding with rainfall on 24 February. In addition, $PM_{2.5}$ and AOD were both higher at site 1 than at the other sites, except for some similar values at the microcenter site (ID 2), along the whole summer campaign. During the winter campaign, $PM_{2.5}$ and AOD coincided in presenting, in general, lower values at site 1, being always below the values of other sites in the $PM_{2.5}$ case, and below most of the values of other sites (especially during the second stage) for AOD. This behavior of the reference site during the measurement periods corresponding to the opposite seasons analyzed, while distinctive, can be successfully cross-checked by using in situ and satellite data. The reference site has a special significance for air quality assessment because it is an area where several hospitals are concentrated.
- (4) At the residential town in the northwest of the GR (site 8), next to rural areas, AOD values were lower there than for the rest of the simultaneously tested sites along the summer measurement periods and were also lower than those of the other sites during some winter periods or intermediate between them for other winter periods. On the other hand, $PM_{2.5}$ values for this location were intermediate between the other sites' values in both seasons. This could indicate the presence of low-altitude (respirable) aerosols attributable to dust from the soil and rural roads that impacted the in situ concentration measurements, while, conversely, not producing a noticeable increase in the satellite AOD data values. It is worth noting that residential or rural locations located close to the Paraná River coast (sites 6 and 7) were influenced by aerosols linked to residential or rural land use (similar to site 8) but also by aerosols linked to river activities and the wetland natural ecosystem. Soil dust is expected to be more abundant in rural areas further from water surfaces; for instance, it was likely higher at site 8 than in sites 6 and 7.

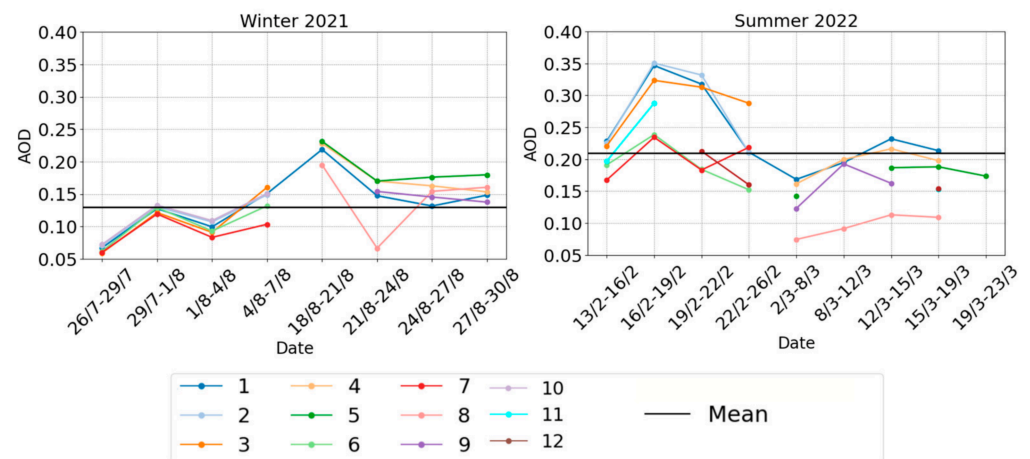


Figure 11. AOD total mean value in the winter campaign (left) and summer (right). The colored lines represent the different sites and the solid black line represents the average (total mean, for all sites and sampling periods) for each (winter and summer) campaign. Data source: MAIAC/MODIS.

3.3.2. Densities of the Atmospheric Column of NO_2

In the summer, increased solar radiation contributes to the breakdown of NO_2 molecules through photolysis, which leads to a reduction in their concentration in the troposphere. The maps in Figure 12 show a higher concentration of NO_2 VCD during the winter season, coinciding with the report by the authors of [52] on their study in different cities of South America.

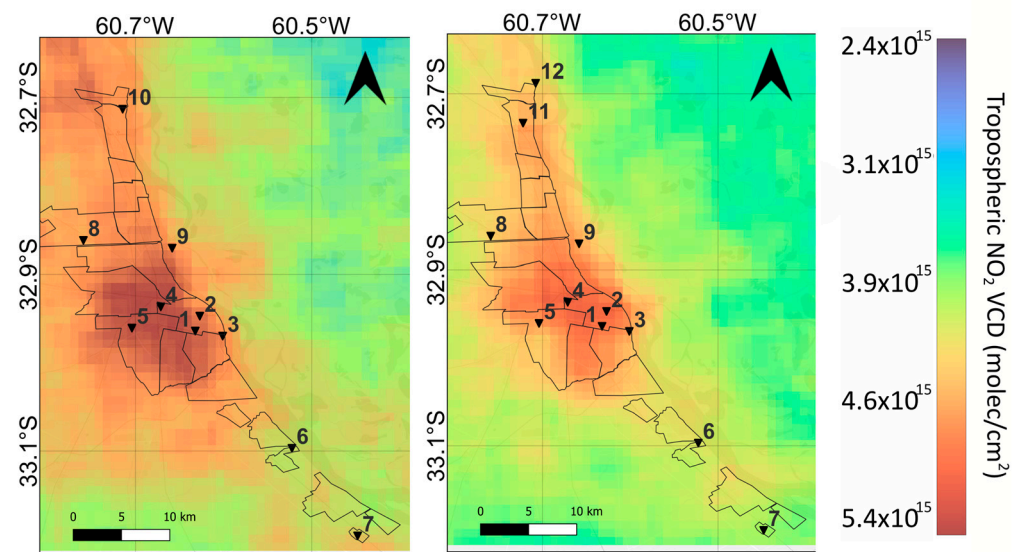


Figure 12. Map of the densities of the atmospheric column of NO_2 (molec/cm^2) in the winter campaign—26 July to 4 August and 18 August to 30 August (left)—and summer campaign—13 February to 26 February, and 2 March to 23 March (right). Data Source: TROPOMI.

For the month of March in Rosario city and adjacent regions, the NO_2 VCD for a period of minimal anthropogenic activity due to the strict COVID-19 lockdown (in the year 2020) and no fires in the zone was 3.00×10^{15} molecules/ cm^2 [51]. During our sampling campaign, in March 2022, the average obtained was 4.66×10^{15} molecules/ cm^2 , which is 55.3% above the mentioned baseline value.

For the winter season, the mean NO_2 VCD found was $5.08 \times 10^{15} \pm 9.54 \times 10^{14}$ molecules/ cm^2 (range: 3.40×10^{15} – 7.50×10^{15}) and for the summer season, $4.78 \times 10^{15} \pm 7.64 \times 10^{14}$ molecules/ cm^2 (3.70×10^{15} – 6.50×10^{15}). Site 7 registered the maximum value

(7.50×10^{15}) between 29 July and 1 August, coinciding with fires developing in the wetland opposite that locality; however, it did not reach the peak of 1.66×10^{16} molecules/cm² recorded there during the September 2022 fires [22]. The peak in NO₂ for the 29 July–1 August period due to fires in Figure 13 was reached at all sites but was higher at site 7, which is located closer to the fires and was directly affected by winds coming from the east during this winter sampling period (Figure 5). This is also in accordance with the atypically high PM_{2.5} values registered at site 7 during the in situ measurements from 29 July to 1 August (the period with the highest PM_{2.5} concentration obtained at this site) and from 1 August to 4 August (the filter change took place at 15:30 on August 1, with winds from the fires impacting both the second and the third winter sampling periods), as shown in Figure 9. Site 6 registered the minimum NO₂ VCD value (3.40×10^{15} molecules/cm²) between 4 August and 7 August. In the rural site (site 7), the NO₂ VCD also decayed to very low values during this period, once the arrival of air masses carrying pollutants from the fires had concluded.

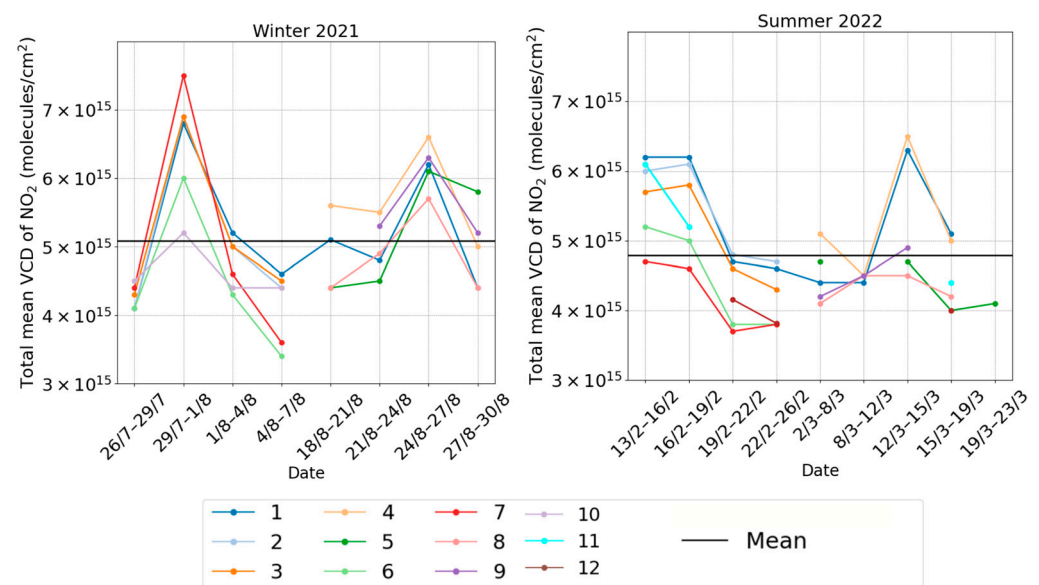


Figure 13. Total mean of NO₂ VCD (molecules/cm²) in the winter campaign—26 July to 4 August and 18 August to 30 August (**left**)—and summer campaign—13 February to 26 February, and 2 March to 23 March (**right**). The colored lines represent the different sites and the solid black line represents the average (total mean, for all sites and sampling periods) for each (winter and summer) campaign. Data source: TROPOMI.

During the winter season, two distinctive peaks were observed for the NO₂ VCD at all sites in Figure 13 (left), which match the peaks observed at many sites for PM_{2.5} in Figure 9: one from 29 July to 1 August and the other from 24 August to 27 August. During 31 July and 1 August, while an extended fire was developing in the wetland of the Paraná River Delta, opposite the town of Fighiera (site 7), winds traversing the burning area blew towards our study area, thereby contributing to the high NO₂ values, as previously explained. A similar situation occurred when winds on 27 August blew from the southeast, where a new forest fire was developing in the Paraná Delta, on the border between Santa Fe and Buenos Aires Provinces.

It is noteworthy that Fighiera (site 7) registered the lowest NO₂ VCD values during the summer campaign (period without fires) but showed the highest peak during the winter campaign (period with fires), thus indicating the substantial negative impact that large pollution events can have on rural sites with usually low pollution levels.

During the summer 2022, fires in Corrientes Province (that took place at approximately 650 km northeast of Rosario) combined with air masses traversing the burning zone, associated with winds from the N and NE directions on 16 February, could be responsible for the high values of NO₂ VCD during the sampling periods of 13–16 February and 16–19 February (Figure 13, right), as well as for the peak in AOD during the period of 16–19 February (Figure 11, right). In addition, the peaks observed in NO₂ VCD and AOD for most of the sites during the period of 12–15 March are attributed to meteorological conditions such as low-speed northerly winds (mainly during the first 6 h of 14 March, as detected by the National Meteorological Service of Argentina), which favored pollutant concentration in the troposphere, mainly at the macrocenter sites of Rosario City (sites 1 and 4). It can be noted that during the summer campaign, these discussed peaks in NO₂ VCD do not correlate with peaks in PM_{2.5}, unlike the winter campaign peaks. This may be related to the fact that the winter peaks were caused by nearby fires in the Paraná Delta, off the coast of the GR, directly impacting the PM_{2.5} concentrations detected at breathing height at the measurement sites. Conversely, the peaks during the summer campaign are attributed to special weather conditions favoring gas and particle concentrations, or to pollutants coming from more distant burning zones; thus, they traveled at higher altitudes, showing a peak in the AOD but not clear peaks in the in situ PM_{2.5} data.

4. Discussion

The PM_{2.5} concentrations showed seasonal differences, with higher values in winter attributed partially to the lack of rainfall and to the development of widespread nearby fires in the Paraná River Delta. During the winter of 2021, higher aerosol concentration levels may have been reached compared to other winters due to fires caused by a prolonged drought, even though it was a period of partial lockdown (not as strict as during certain months of 2020) because the COVID-19 pandemic was still ongoing. This lockdown may have had the opposite effect, decreasing certain types of aerosols, such as anthropogenic ones. Thus, during that winter, the peak increases in aerosols were directly associated with nearby fires, rather than with highly polluting human activities, with the exception of an industrial site (site 10) possibly affected by strong, fluctuating, and highly localized emissions. During the summer measurements, five out of eight samples were affected by rainfall, which could have contributed to the low presence of PM_{2.5} in the ambient air. It should be pointed out that the summer of 2022 did not present any fire events in the vicinity of Greater Rosario. In addition, the summer period includes the summer holiday season in Argentina; therefore, reduced vehicular movements and fewer anthropogenic activities were expected.

The average PM_{2.5} values found in urban, industrial, and residential areas were similar to those recorded in other cities around the world. On the other hand, natural and rural areas showed lower averages compared to other places globally. The PM_{2.5} values in our two Paraná River port sampling areas were similar to each other, but quite different when compared to a seaport.

The higher AOD found during the summer campaign compared to the winter season can be attributed to the fires developing in the nearby province of Corrientes (northeastern Argentina), whose particulate emissions were detected in the total atmospheric column measured by MAIAC but did not significantly affect the ground-level PM_{2.5} measurements. March 2022 presented an AOD value 220% higher than the one reported as a baseline for the same month in 2020 under a severe lockdown due to COVID-19.

The average NO₂ VCD was higher in the winter sampling campaign, which is expected due to the behavior of this gas during this time of the year. In addition, two peaks in its concentration were observed, coinciding with the direction of the wind coming from the

forest fires present in the islands and Delta of the Paraná on 31 July–1 August and 27 August. In accordance with this event, the sampling carried out between 29 July and 1 August and between 1 August and 4 August in site 7 (the closest to the fires) showed a considerable increase in $PM_{2.5}$ concentration, surpassing the concentrations at the other sites (except for the outlier industrial site 10). This is noteworthy, as site 7 is a rural site where low $PM_{2.5}$ concentrations were typically found outside of fire periods.

AOD and NO_2 VCD satellite data proved to be a valuable complement for understanding aerosol behavior during the sampling periods and their origin. While NO_2 is a well-known tracer for urban and industrial anthropogenic emissions, its simultaneous enhancement with AOD and ground-level $PM_{2.5}$ during specific burning episodes suggests it can also reflect regional biomass burning inputs. Complementing ground studies with satellite data is crucial to gain a more complete understanding of the atmospheric status during sampling, thus attaining deeper and clearer conclusions about the $PM_{2.5}$ concentrations obtained.

The dynamics of the planetary boundary layer height (PBLH) were also analyzed to evaluate its potential influence on vertical mixing and pollutant accumulation. Although the mean winter PBLH (473.1 m) was roughly 15% lower than the summer average (562.9 m), this vertical constraint did not act as a dominant driver for $PM_{2.5}$ variability. This decoupling is supported by the lack of statistical correlation ($p > 0.05$) and further evidenced during specific episodes. For instance, between 26 July and 29 July, the region experienced an anomalous winter expansion of the PBLH, reaching a mean value of 990 m. Despite this significantly larger volume available for vertical dispersion, $PM_{2.5}$ concentrations at most monitoring locations remained relatively low but highly variable, rather than showing a uniform drop. These observations suggest that in Greater Rosario, the sheer strength and proximity of emission sources exert a far greater control over surface air quality than the mechanical modulation of the boundary layer.

Air mass back-trajectories computed via HYSPLIT were selectively analyzed during critical episodes to identify regional transport pathways. During the Winter 2021 campaign, the highest $PM_{2.5}$ concentrations recorded at site 7 (the location closest to the Delta wetlands) strictly coincided with days when incoming air masses directly traversed active localized burning areas, confirming a direct surface-level impact. Conversely, at the beginning of the Summer 2022 campaign, back-trajectories revealed a long-range transport pattern originating from intense wildfires in northeastern Argentina. Interestingly, this regional influx caused a much more pronounced increase in satellite-derived AOD and NO_2 VCD than in ground-level $PM_{2.5}$. This spatial mismatch strongly supports our hypothesis that the long-range smoke plume traveled as an elevated atmospheric layer, altering the total column optical and chemical properties while leaving the immediate breathing zone relatively unaffected.

Regarding local surface meteorology, wind speed variations further confirm that mechanical stagnation was not the primary factor governing $PM_{2.5}$ cycles. Lower wind speeds typically favor the accumulation of local impurities due to reduced ventilation [53]. However, our winter campaigns frequently exhibited the opposite behavior, explaining the weak statistical correlations observed. For instance, during the regional $PM_{2.5}$ peak between 24 August and 27 August, concentrations rose simultaneously across almost all sites under a mean wind speed of 12 km/h (maximum of 31 km/h), which coincided with air mass back-trajectories directly intersecting active wildfire zones before arriving at the study area. Conversely, during the subsequent period (27 August to 30 August), a generalized drop in $PM_{2.5}$ occurred despite a decrease in the average wind speed to 10.1 km/h. A similar decoupling was observed at the end of the first winter set (4 August to 7 August), where concentrations declined as winds averaged 11.7 km/h, close to the

campaign mean of 10.6 km/h. These counterintuitive trends demonstrate that rather than wind-driven dilution or stagnation, air quality dynamics in GR are governed by advection and the temporal intensity of the upwind emission sources.

Finally, the role of short-term atmospheric stability and surface inversions must be evaluated to understand the cumulative history captured by the multi-day filter integration. Hourly ground-level data highlighted that the regional PM_{2.5} peak observed between 24 August and 27 August was driven by a multi-stage meteorological process rather than a single event. On 26 August, intense nocturnal radiative cooling caused temperatures to drop from a daytime maximum of 21.9 °C to a minimum of −0.5 °C at dawn, accompanied by prolonged periods of absolute wind calm. This sharp thermal amplitude favored the formation of a strong, ground-based radiation inversion that trapped local urban and industrial emissions near the surface during the morning. This localized accumulation phase was followed on 27 August by a sharp synoptic shift: winds rotated toward the south-southeast and east (140° to 70°), initiating a massive advection pathway that transported the smoke plumes from the Delta fires directly into the urban canopy. Therefore, the integrated mass on the filters reflects a combination of severe local stagnation and regional pollutant injection, a compounding mechanism that aligns with observations in other temperate systems where anticyclonic stability and surface inversions govern extreme aerosol concentrations [54].

The results show a generalized aerosol behavior (with simultaneous peaks at all or most of the sampled sites) modulated by fires (which are even more homogenized when the fires are not so close), and another behavior characteristic of each site, associated with land use. Regarding the latter, outside of the episodes of aerosol arrival from the fires, lower PM_{2.5} values were obtained in rural, residential and natural sites, while higher values were obtained in industrial, port and urban sites (except for the reference site in the macrocenter of Rosario during the winter of 2021).

While determining PM_{2.5} mass concentrations provides a critical baseline for the GR region, the lack of chemical characterization represents a limitation of this study. Conducting elemental or chemical analyses would offer valuable insights into specific source apportionment and precise emission profiles. This aspect will be considered in future work.

This work represents the first air quality study in Greater Rosario. It presents the first results of in situ measurements of aerosol concentrations at different sites with varied land uses. Future research including the remaining seasons of the year will provide an expanded picture of PM_{2.5} levels, their temporal evolution as well as emission sources in the GR. Additionally, to overcome the temporal resolution constraints of integrated filter sampling and improve alignment with daily satellite data, incorporating a network of low-cost continuous sensors would be a highly beneficial future perspective. Such an approach would significantly increase data volume and provide deeper insights into short-term pollutant dynamics across the region.

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Abbreviations

The following abbreviations are used in this manuscript:

GR	Greater Rosario
PM _{2.5}	Fine Particulate Matter
AOD	Aerosol Optical Depth
NO ₂ VCD	Nitrogen Dioxide Vertical Column Density
WHO	World Health Organization
NO ₂	Nitrogen Dioxide
SMN	National Meteorological Service of Argentina
PTFE	Teflon Filters
MODIS	Moderate Resolution Imaging Spectroradiometer
QA	Quality Assurance
TROPOMI	Tropospheric Monitoring Instrument
GEE	Google Earth Engine
SH	South Hemisphere
IDW	Inverse Distance Weighting

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