

Article

Spatiotemporal Variation of Air Quality (PM and NO₂) in Southern Paris during COVID-19 Lockdown Periods

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Abstract: In urban areas, road transportation is the main source of pollutants, and weather impacts spatiotemporal variation of air quality. In this paper, we demonstrate the spatiotemporal variabilities of particulate matter (PM₁₀ and PM_{2.5}) and NO₂ in the south of Paris, with an emphasis on the comparison of air pollutant levels between COVID-19 lockdown and non-lockdown days according to meteorological conditions. The influence of COVID-19 lockdowns could be region-specific. Thus, it is worthwhile to conduct investigations across different regions and via different methodologies. This manuscript contains data that could be relied upon to evaluate available options for mitigation of urban air pollution. Using Airparif data and mobile survey data collected by Aeroqual 500 sensors, this study confirms that road traffic seems to be the determining factor of air quality in the southern part of Paris. The daily average concentrations of NO₂, PM_{2.5} and PM₁₀ calculated in 2020 show a strong spatiotemporal variability explained by the type of weather on the one hand and by the proximity of emission sources on the other hand. Mobile surveys show that during lockdowns in 2020, when the weather was stable, in 13th arrondissement of Paris, NO₂ values exceeded 250 µg/m³ with PM₁₀ values over 70 µg/m³, mainly in three locations: the area between Rue Tolbiac and Rue Nationale, along Rue de Chevaleret, and on Boulevard Périphérique.



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Keywords: Paris; atmospheric pollution; weather; lockdowns; mobile survey

1. Introduction

Air pollution is considered a silent killer, with undeniable adverse impacts on human health [1]. Ninety percent of the world's population resides in places where air quality levels exceed World Health Organization (WHO) recommended thresholds. In 2020, the WHO global air quality guidelines (AQG) 24-h mean values for fine particulate matter (PM_{2.5}) and coarse particulate matter (PM₁₀) were 20 and 50 µg/m³. The thresholds were changed for future PM monitoring in 2021 to 15 µg/m³ for PM_{2.5} and 45 µg/m³ for PM₁₀. The updated recommended guideline level for nitrogen dioxide (NO₂) concentrations is 25 µg/m³ averaged over 24 h [1]. Air pollution has been identified as the leading environmental cause of premature illness and death worldwide [2], with an estimated 4.2 million deaths in 2016 [3–5]. The sharp increase in road traffic in densely populated urban areas, as well as increasing industrialisation and high energy consumption, is one of the main causes. In Île-de-France, road transportation is the main source of pollutants, comprising 56% and 35% NO₂ and PM_{2.5} emissions, respectively [6]. The air quality monitoring association for this region (Airparif) estimates that three million Ile-de-France residents living near main roads are likely to be exposed to air pollution levels exceeding WHO global air quality guidelines [7]. However, air quality does not only depend on air pollutants from more or less known sources; it is also impacted by weather and climate conditions. Therefore, the most unfavourable meteorological factors for dispersion are low wind and vertical stability of the atmosphere [8–10]. Certain specific meteorological situations, such as anticyclonic weather, with thermal inversions at night and at daybreak, contribute, in part, to the build-up of pollution peaks [11].

Since the outbreak of the coronavirus (COVID-19) in Wuhan, China, many health, economic, and social problems have emerged [12–15]. On 30 January 2020, the WHO declared COVID-19 a global health emergency and Global pandemic March 11. Measures taken to limit the spread of the virus have led to significant changes in the various ways in which people and goods are transported, with unavoidable consequences for air pollution [16,17]. During the three lockdown periods in France, widespread adoption of teleworking and temporary closures of businesses and some shops limited the usual movement of the population. These successive lockdowns may have led to a change in the spatiotemporal variability of air quality. This paper examines how these sudden changes in traffic patterns may have affected the concentrations of fine particles (PM₁₀ and PM_{2.5}) and NO₂ in the south of Paris, according to major weather types (stable and unsettled weather).

First, we studied the temporal variation of these pollutants in the southern part of the Paris conurbation at three traffic stations of the Airparif network between 2013 and 2020. Secondly, we focused on the 13th arrondissement of Paris to carry out fine-scale mobile measurements during and outside lockdown periods. Finally, due to the high degree of traffic influence, we included traffic data in our analysis to identify which pollutant concentrations were influenced by the lockdown.

2. Study Area

In the north of France, the Île-de-France region is a source of economic dynamism on a national, European, and global scale (Figure 1). Half the jobs of the French economy are concentrated in this region [18]. According to the latest report by the French National Institute of Statistics and Economic Studies [19], Île-de-France has 12,213,447 inhabitants. Its population increased by 253,640 inhabitants between 2013 and 2018, an annual increase of 0.5%.

Various industrial and tertiary activities are concentrated in the region, with dense road traffic. Mobile sources significantly contribute to the deterioration of air quality in Paris, despite the Territorial Climate Energy Plan (PCET), which has contributed, in part, to a decrease in the concentrations of air pollutants. Nevertheless, PM₁₀, PM_{2.5} and NO₂, emitted by mobile and stationary sources, remain among the problematic pollutants in Île-de-France [20].

In this study, we carried out mobile measurements in the 13th arrondissement as part of an ongoing thesis. According to the latest INSEE census (2016), the average population density in the 13th arrondissement is 25,392 inhabitants/km² for an area of 7.2 km². The older neighbourhoods built in the 1970s, such as Olympiade, Place Nationale, and Place Pinel, are denser. These neighbourhoods are characterised by a tightly woven and homogeneous north-south/east-west road network. It is constituted of ring roads (Boulevard de Port-Royal, Boulevard Arago, Boulevard Saint-Marcel, Boulevard des Fermiers Généraux, Rue de Tolbiac), main radial roads (Avenue des Gobelins, Avenue d'Italie, Quai de la Seine, Boulevard de l'Hôpital), and secondary roads (Rue Jeanne d'Arc, Rue de Patay, Avenue de Choisy, Rue de Bobillot, Rue de Glacière, Rue Nationale, Rue de l'Amiral Mouchez, Rue de la Santé). Place d'Italie is the major nodal point of this district [21]. The number of vehicles recorded every five minutes reaches its maximum along the Boulevard Périphérique, where more than 500 vehicles were counted (Figure 2B).

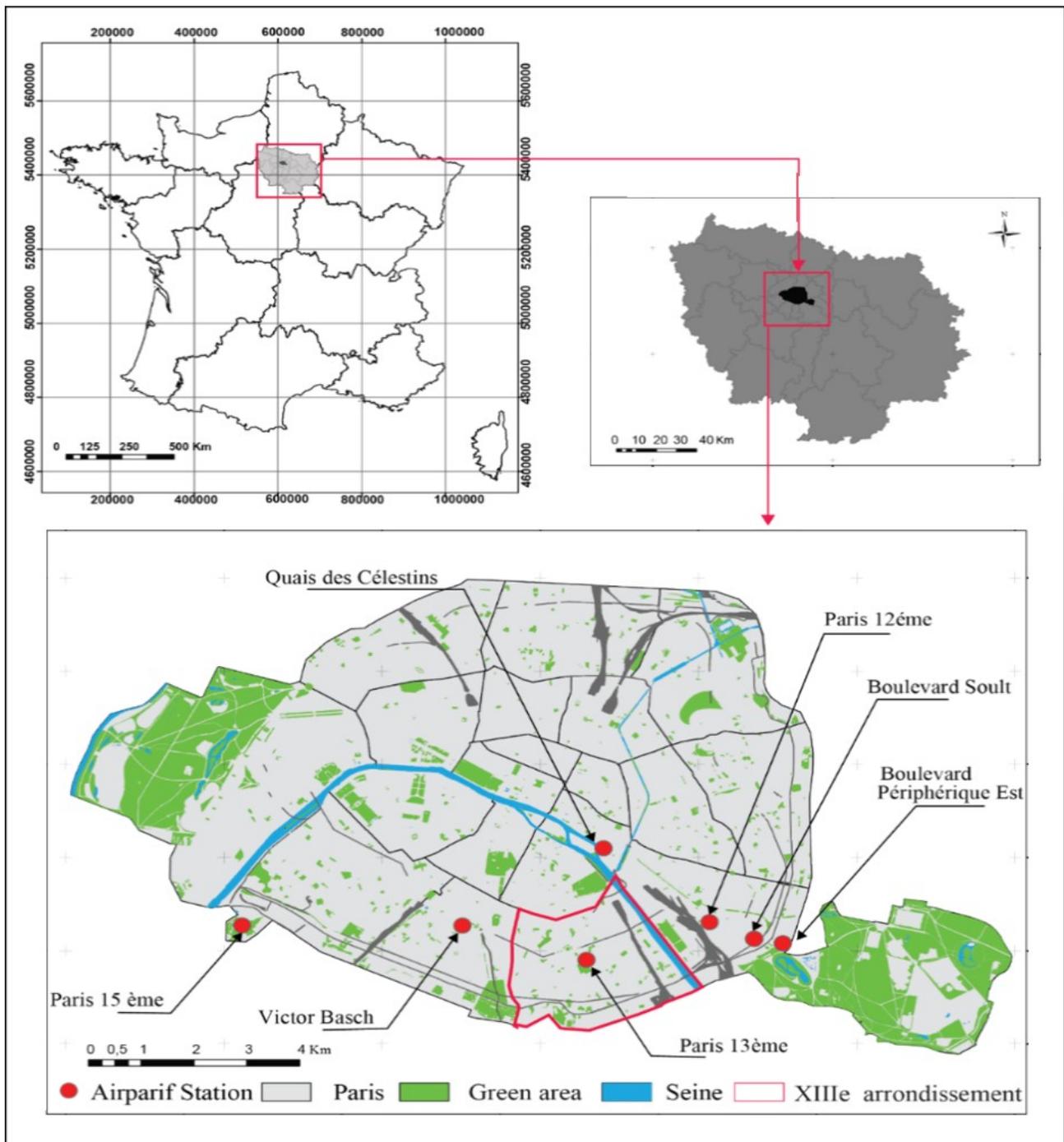


Figure 1. Location of the study area and Airparif air quality monitoring stations (source: www.data.gouv.fr).

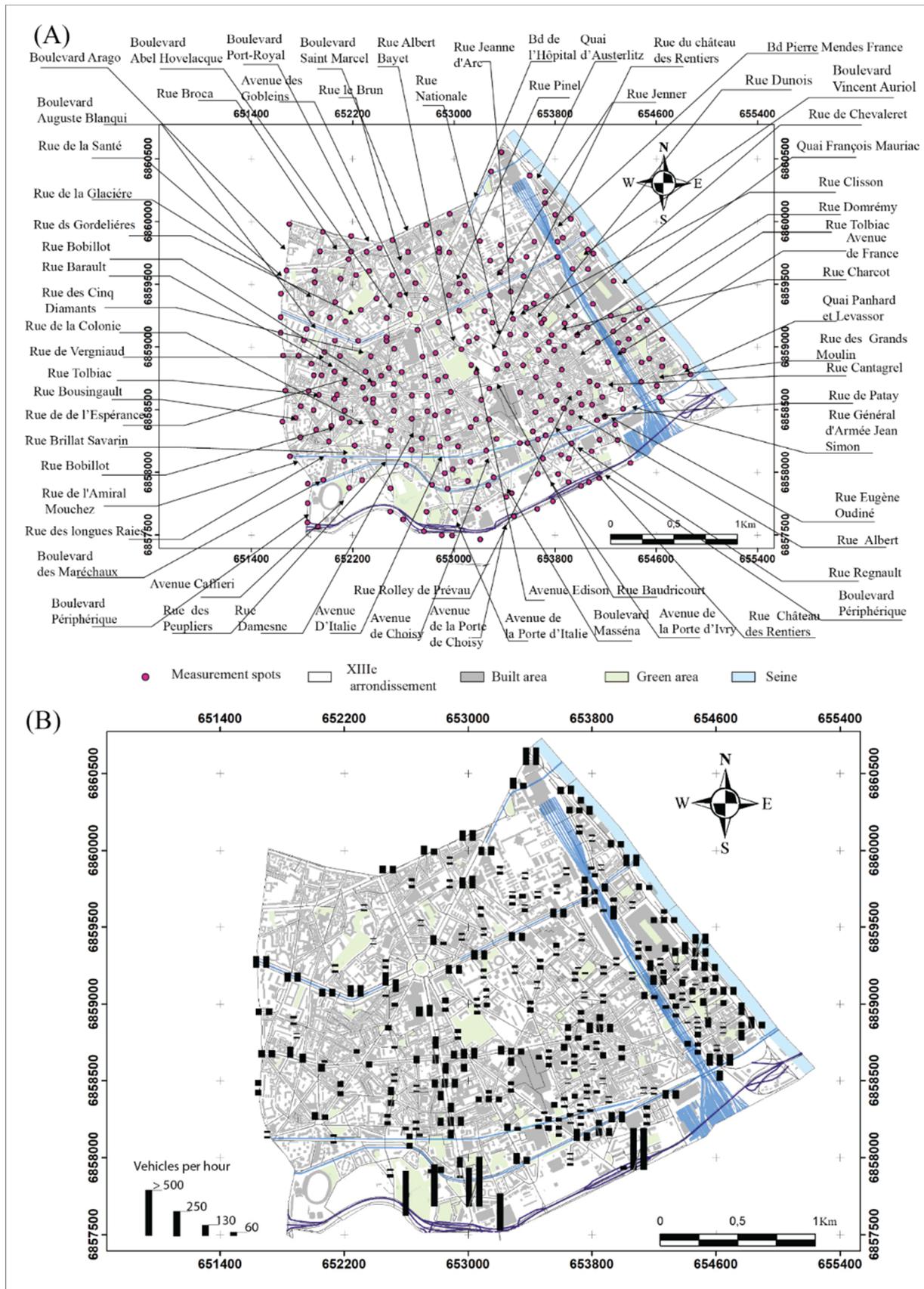


Figure 2. Location of measurement spots (A) and number of vehicles per 5 min (B) (personal survey).

Paris has a transitional oceanic climate, the annual average wind speed does not exceed 3 m/s, and anticyclonic situations are possible throughout the year. The central part of Paris has higher temperatures and slower wind speeds than the rural periphery [22].

3. Methods and Materials

The electrical signals provided by the automatic analysers of Airparif stations are converted into digital data by an acquisition frame every 15 min. From these data, averages for each hour and for each day are calculated [7]. We used hourly data from three traffic stations, one located at Place Victor Basch (Paris 14th), another on Boulevard Périphérique Est (Paris 12th), and the third on Boulevard Périphérique d’Auteuil (Paris 16th). Temporal variations of PM₁₀ and NO₂ analysis are based on Airparif network data.

To compensate for the limited nature of the fixed stations, we carried out semi-itinerant measurements near the main traffic arteries of the 13th arrondissement of Paris (Figure 2A). The problematic pollutants that we measured, such as NO₂, PM_{2.5}, and PM₁₀, are not provided by Airparif in the 13th arrondissement. In addition, we measured wind speed, counted the number of vehicles (Figure 2B), and considered the steepness and orientation of the arteries with respect to the prevailing wind.

Fifteen measurement campaigns were carried out from 3 November 2020 to 26 November 2020 during the lockdown. Apart from this period, measurements were performed from Monday to Friday during the months of July, September, and until 29 October 2020, as well as in January, February, and April 2021. We collected measurements of SO₂, PM_{2.5}, PM₁₀, and NO₂ with portable air quality monitors. Results for the latter two are presented in this work.

Two hundred and seventy-two (272) spots distributed throughout the study area were covered using “Aeroqual Series 500” portable air quality monitors with a 5 min stop per location. This equipment has shown its efficiency and performance in urban areas [23]. The sensors were calibrated on the basis of the Airparif stations. The sensors were programmed to record with a time step of 10 s. We retained the median value per stop. Two recording sessions were programmed: a first one in the morning from 7:30 to 9:30 and a second one in the early evening from 17:00 to 19:30. In this work, we mapped the values above the 75th percentile. Since the data collected in the morning are comparable to those collected at the end of the day, as confirmed by the Airparif data detailed below, we do not distinguish between the two measurement sessions in this study.

The meteorological data used are from the Paris Montsouris station, managed by Météo France, located in the 14th arrondissement of Paris, less than 4 km away from all the air quality monitoring stations used in this work. These data were supplemented by atmospheric pressure maps downloaded from the German meteorological website (Wetterzentrale.de) in order to study the types of weather responsible for high concentrations of pollutants. We distinguished between two major types of weather: (1) stable weather, when the atmospheric pressure exceeds 1015 hPa, the ambient wind speed is lower than 5 m/s, and the cloud cover is lower than 2 octas; (2) unsettled weather, when the pressure is lower than 1010 hPa, the ambient wind speed is higher than 8m/s, and the cloud cover exceeds 6 octas. In sum, during the second COVID lockdown, we carried out 8 measurement campaigns in stable weather and 7 in unsettled weather, compared with 11 and 12 in stable and unsettled weather, respectively, during non-lockdown periods.

4. Results

4.1. Temporal Variations in PM₁₀ and NO₂ Concentrations

In this section we use data from the Airparif network; we include only PM₁₀ as example of particulate matter because its variation is very similar to that of PM_{2.5}. On an annual scale, from 2013 to 2020, the average concentrations of PM₁₀ and NO₂ decreased for the three traffic stations (Figure 3A,B). The Mann–Kendall trend test confirmed a significant decrease in PM₁₀ and NO₂ concentrations at all three stations confirms with a confidence interval (5%).

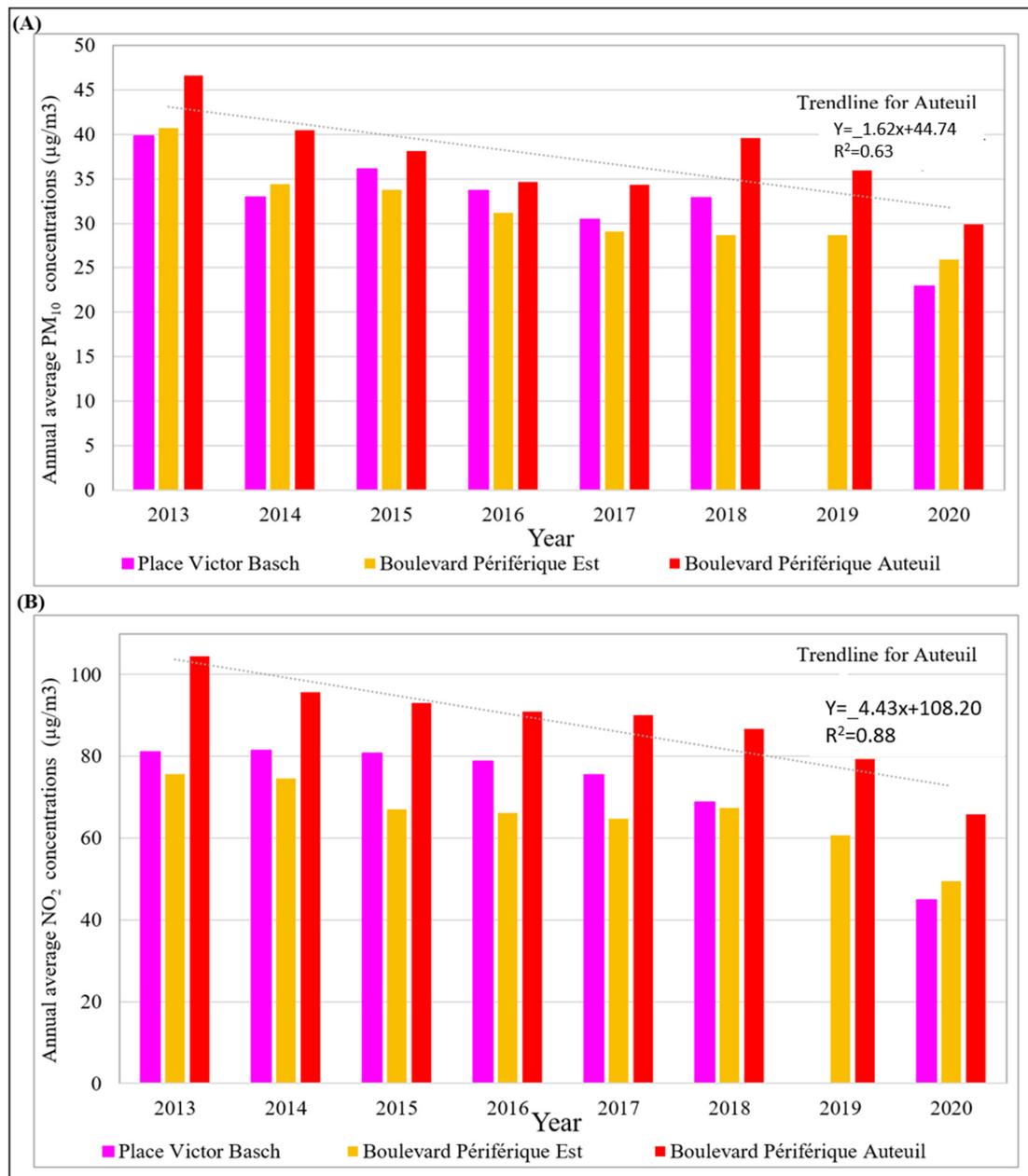


Figure 3. Annual variations in average PM₁₀ (A) and NO₂ (B) concentrations in the southern part of the Paris conurbation from 2013 to 2020 (Airparif data).

Figure 3 shows that air quality improved in 2020. This change can be explained by the influences of lockdown measures in the urban environment on one hand and by the downward trend in air pollutant concentrations observed since 2013 on the other hand.

On Boulevard Périphérique d’Auteuil, due to denser road traffic, the concentrations of the two above-mentioned pollutants were higher than those on Boulevard Périphérique Est and Place Victor Basch. Between 2013 and 2020, PM₁₀ levels fell from 47 to 30 µg/m³ on Boulevard Périphérique d’Auteuil, whereas they fluctuated between 39 and 22 µg/m³ on Place Victor Basch. As for NO₂, the annual average fell from 110 to 65 µg/m³ at the first station and from 75 to 45 µg/m³ at the second one. The latter recorded slightly lower values than the Boulevard Est station, which experienced the same trend.

During 2020, on a monthly scale, pollution varied during the year, according to three main periods. The highest level of PM₁₀ was recorded between January and April, ranging from 42 to 50 µg/m³ on Boulevard Périphérique d’Auteuil, from 33 to 40 µg/m³

on Boulevard Périphérique Est, and from 37 $\mu\text{g}/\text{m}^3$ to 45 $\mu\text{g}/\text{m}^3$ on Place Victor Basch (Figure 4A).

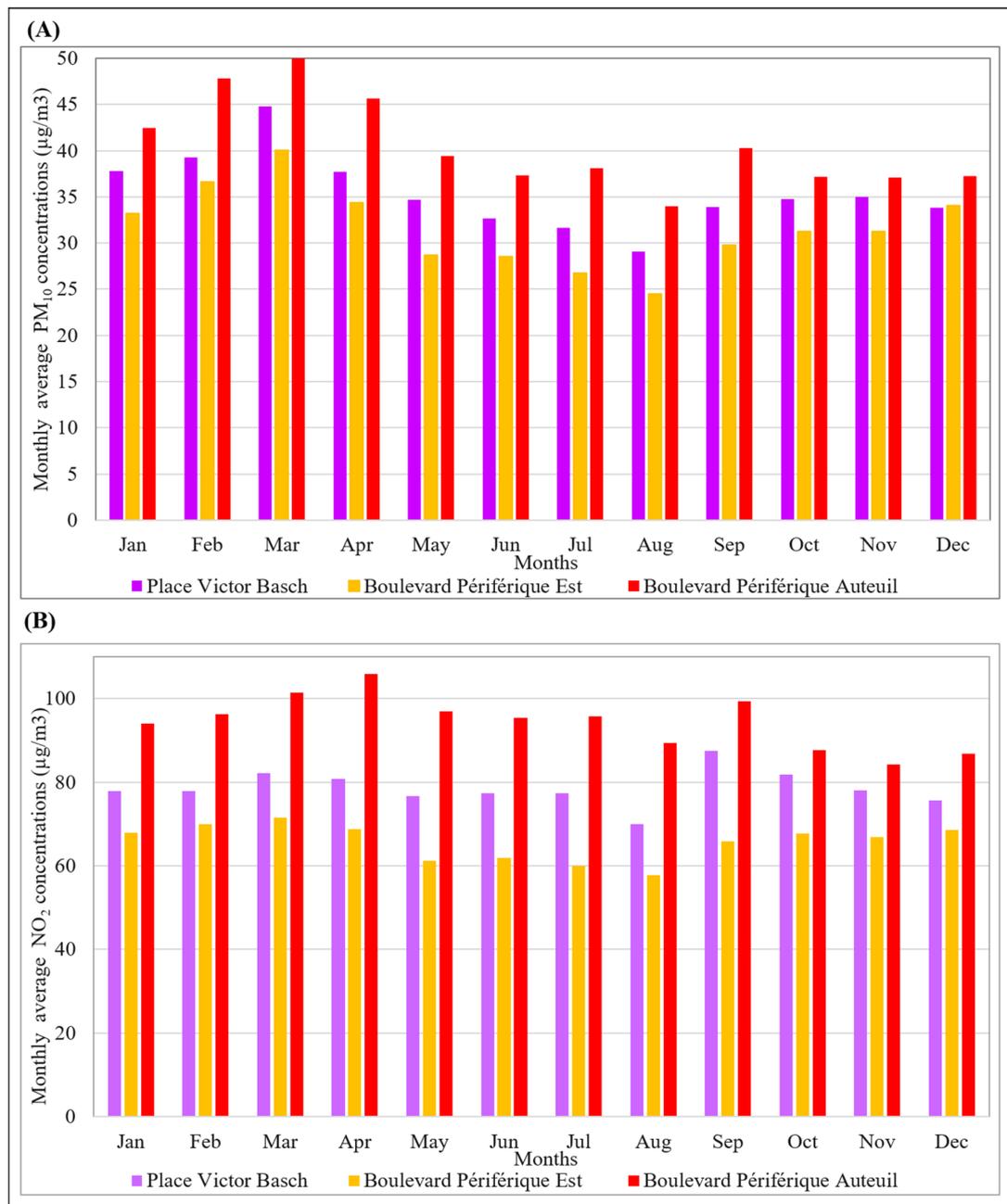


Figure 4. Monthly variation of daily PM₁₀ (A) and NO₂ (B) concentrations in the southern part of the Paris conurbation in 2020 (Airparif data).

The same spatial and temporal pattern is observed for NO₂ (Figure 4A). The winter peak corresponds, on the one hand, to very cold weather requiring an overconsumption of residential heating, and, on the other hand, to winter anticyclonic situations favouring air stability and the installation of thermal inversions [11]. Sea-level pressure (SLP) rates up to 1020 hPa are twice as frequent in winter compared to spring and summer (Figure 5A). In April, the level of PM₁₀ is partly explained by pollen activity [24,25]. In fact, PM includes acids, organic chemicals, metals, soil particles, dust, and some biological elements, such as pollen and fungal spores. A light to moderate wind prevails during the four seasons, with

a higher frequency of winds coming from the south to the west, especially in winter, under the influence of westerlies. The wind speed shows very little seasonal variability (Figure 5B). The lowest level of these two pollutants is recorded in summer (34 and 80 $\mu\text{g}/\text{m}^3$ PM_{10} and NO_2 , respectively, on Boulevard Périphérique Auteuil, 24 and 75 $\mu\text{g}/\text{m}^3$ on Boulevard Périphérique Est, and 29 and 55 $\mu\text{g}/\text{m}^3$ on Place Victor Basch); this is explained by holiday departures and the fluidity of road traffic. After a decrease in the levels of these pollutants during the summer period, they start to increase in September.

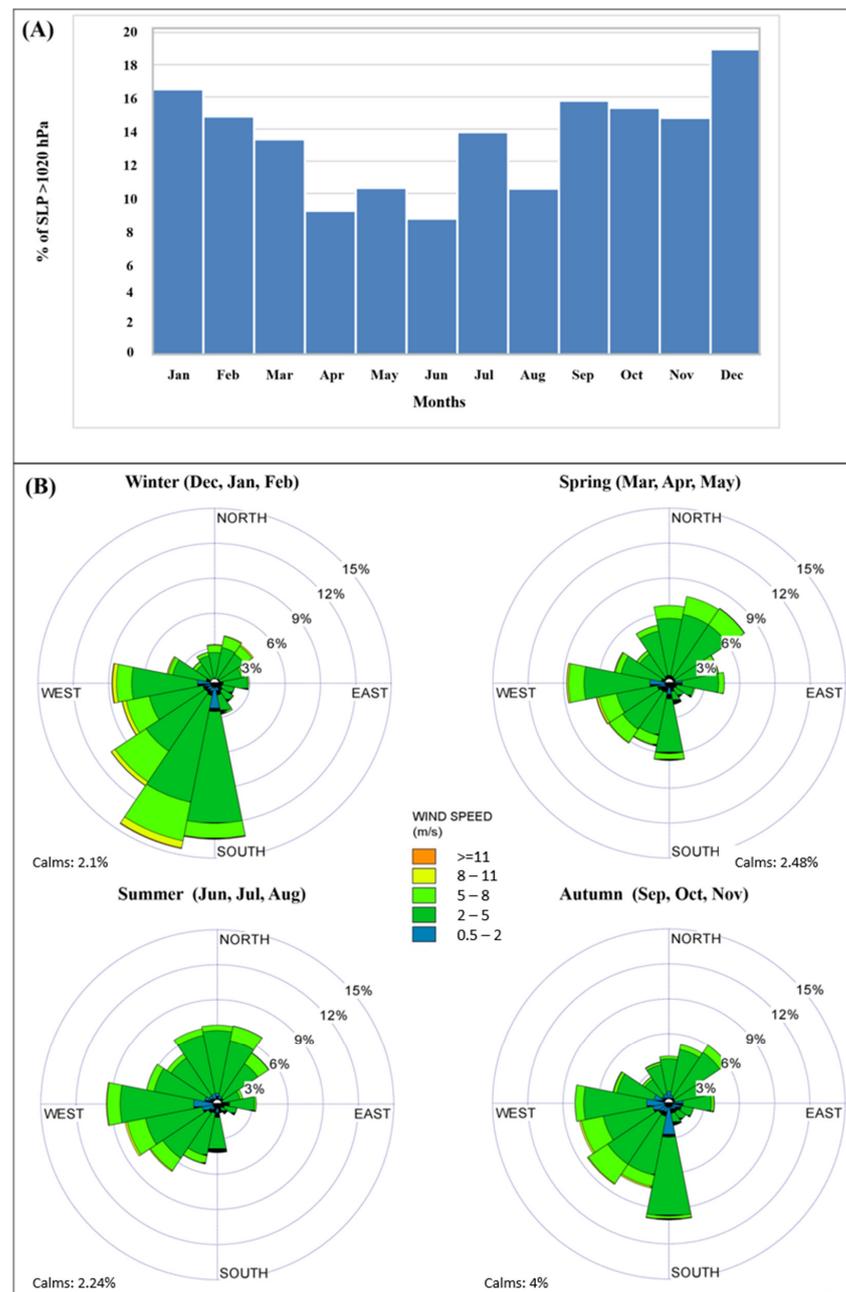


Figure 5. Sea-level pressure (SLP) rates up to 1020 hPa (A) and wind roses (B) (data recorded at the Paris Montsouris weather station).

On a monthly scale, in 2020, at the station with the highest PM_{10} and NO_2 concentrations (Boulevard Auteuil), the highest concentrations were observed in March and April despite the first lockdown effect. It is likely that meteorological conditions and seasonal variation can justify this temporal distribution.

On a weekly scale, the average concentrations observed on weekdays were higher than on Saturdays and Sundays for the three traffic stations. PM_{10} pollutant levels dropped from $34 \mu\text{g}/\text{m}^3$ during weekdays to $24 \mu\text{g}/\text{m}^3$ on weekends at the Boulevard Périphérique d’Auteuil station; at the Boulevard Périphérique Est station, a decrease from $28 \mu\text{g}/\text{m}^3$ to $23 \mu\text{g}/\text{m}^3$ was recorded. The Victor Basch station recorded a decrease of $5 \mu\text{g}/\text{m}^3$ (from $25 \mu\text{g}/\text{m}^3$ to $20 \mu\text{g}/\text{m}^3$) (Figure 6A). NO_2 pollutant levels fluctuated from $72 \mu\text{g}/\text{m}^3$ to $52 \mu\text{g}/\text{m}^3$ at the Boulevard Périphérique d’Auteuil station. The other two stations also recorded a drop of about $17 \mu\text{g}/\text{m}^3$ (from 51 to $34 \mu\text{g}/\text{m}^3$ at Victor Basch and from $57 \mu\text{g}/\text{m}^3$ to $39 \mu\text{g}/\text{m}^3$ at Boulevard Périphérique Est). For both pollutants, the peak level of the week, recorded on Friday, corresponds to an intensification of traffic due to weekend departures. At the Boulevard Périphérique d’Auteuil station, we recorded decreases of 15% in mean NO_2 , but we observed increases of 5% in mean PM_{10} concentrations over 2020 full lockdown periods compared to the remaining non-lockdown days of 2020. This slight increase was only observed during working days. This fact can be explained by home heating.

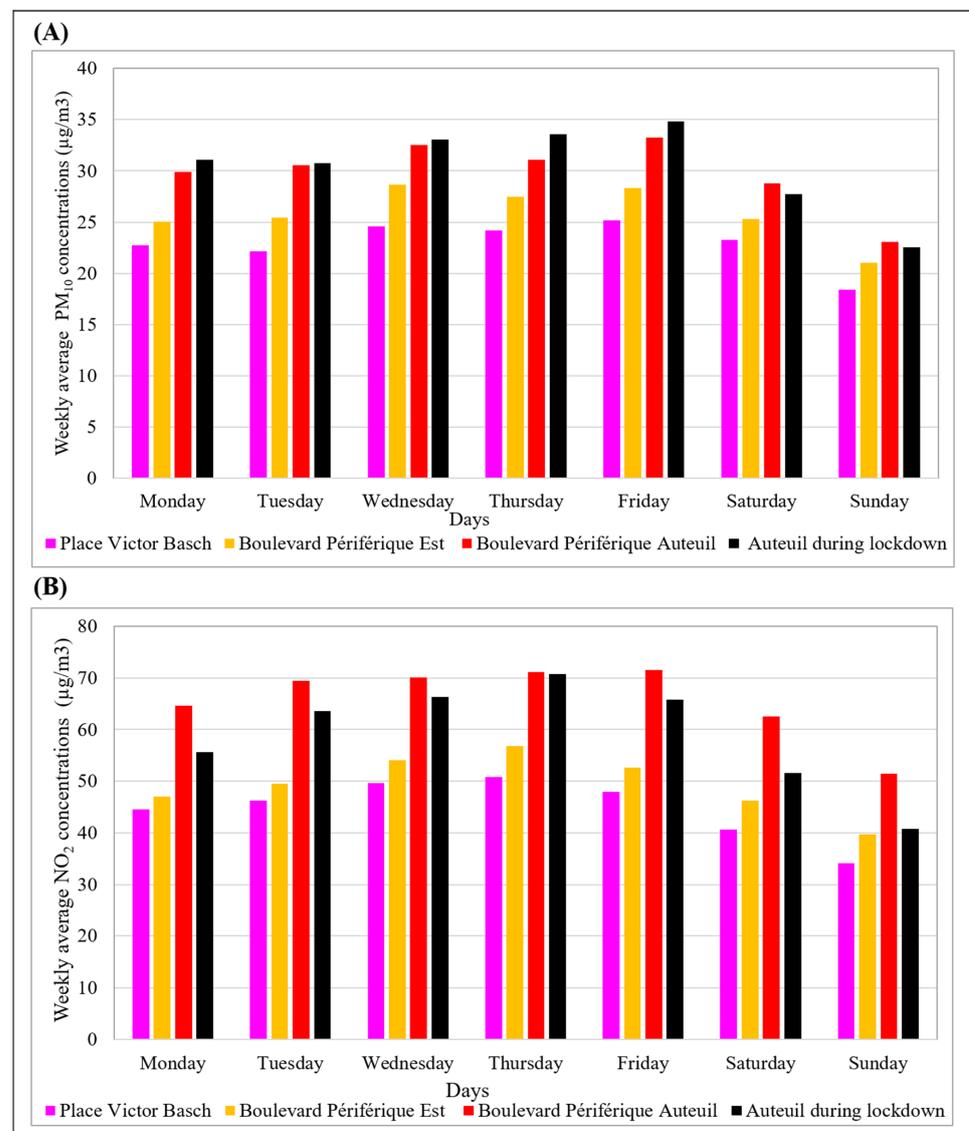


Figure 6. Weekly variations in average concentrations of PM_{10} (A) and NO_2 (B) in the southern part of the Paris conurbation in 2020 (traffic stations: Place Victor Basch, Boulevard Périphérique Est, Boulevard Périphérique d’Auteuil).

4.2. Exceedances of WHO Thresholds

4.2.1. Monthly Exceedances of PM

PM₁₀ pollution episodes are recorded mainly in winter at all stations. The daily standard recommended by the WHO, set at 50 µg/m³ in 2020, was exceeded in particular in March 2013 and December 2016 for two different reasons. In March 2013, after the first 5 days of mild anticyclonic weather, exceptionally cold weather dominated the month.

The deviation from normal average temperatures reached −3 °C, thus increasing heating needs, hence the 20 exceedances of the daily norm at the three traffic stations. The same number of exceedances was observed at a background station in the 12th arrondissement of Paris. In December 2016, anticyclonic situations favoured the accumulation of PM₁₀. Indeed, the meteorological station of Paris Montsouris recorded pressure values between 1020 and 1046 hPa during this month, causing, on average, 14 exceedances (Figure 7).

Some other situations stand out, such as at the Boulevard Périphérique d’Auteuil in September 2014, with 17 days exceeding the WHO standard. This situation is mainly explained by the concomitance of meteorological factors favourable to high-concentration PM and especially by more intense road traffic at this station than at the other two, as explained above.

Analysis of the interannual variation shows that in 2020, compared to the other years, there was a decrease in exceedances during all months. This is particularly noticeable in January, March, September, and November, mainly in Auteuil. This can be explained, on the one hand, by the general trend of air-quality improvement that Paris has experienced for the last 10 years and, on the other hand, by the successive lockdown and curfew periods that France experienced beginning in March 2020.

For PM_{2.5}, in the absence of data recorded by the Place Victor Basch station, we can only analyse the results of the two stations located near the Boulevard Périphérique (Auteuil and Est). The monthly distribution of exceedances of the daily standard recommended by the WHO follows that of PM₁₀. The highest values were recorded between 2013 and 2015 in winter and autumn. Values vary for Boulevard d’Auteuil, from January to March, from 20 to 27 days in 2013, from 13 to 17 days in 2015. Values reach 21 days in September 2014 (Figure A1B). On Boulevard Périphérique Est, this exceedance also occurs but on fewer days in winter 2013 (from 14 to 21 days) and in autumn 2014 (from 7 to 14 days) (Figure A1A).

Few exceedances were recorded in autumn 2019 compared to other years. This is partly due to mild and very rainy weather.

During lockdown periods, exceedances of PM_{2.5} and PM₁₀ were recorded only in November because meteorological conditions referring to data recorded in Paris (Montsouris) were favourable to high concentrations. Although temperatures were, on average, 2 °C above normal, the duration of sunshine was 64% above normal; the weather was dry, with a 73% decrease in precipitation due to the dominance of anticyclonic weather.

4.2.2. Monthly Exceedances of NO₂

NO₂ is primarily influenced by the intensity of road traffic. Among the three stations, the Boulevard Périphérique d’Auteuil station was the most affected by exceedance of the hourly NO₂ threshold, which is set at 200 µg/m³. The maxima were recorded mainly in autumn, spring, and winter (Figure A2C). Interannual variability shows that 2013 was the most polluted year, with 6 to 26 days of exceedances, followed by 2014 (3 to 21 days) and 2015 (1 to 17 days). In contrast, only 15 days of exceedances were recorded during the whole of 2020; all were registered outside the lockdown periods. On the other hand, the Boulevard Périphérique Est and the Place Victor Basch stations recorded fewer exceedances, not exceeding 5 days, particularly in summer and autumn (Figure A2A,B).

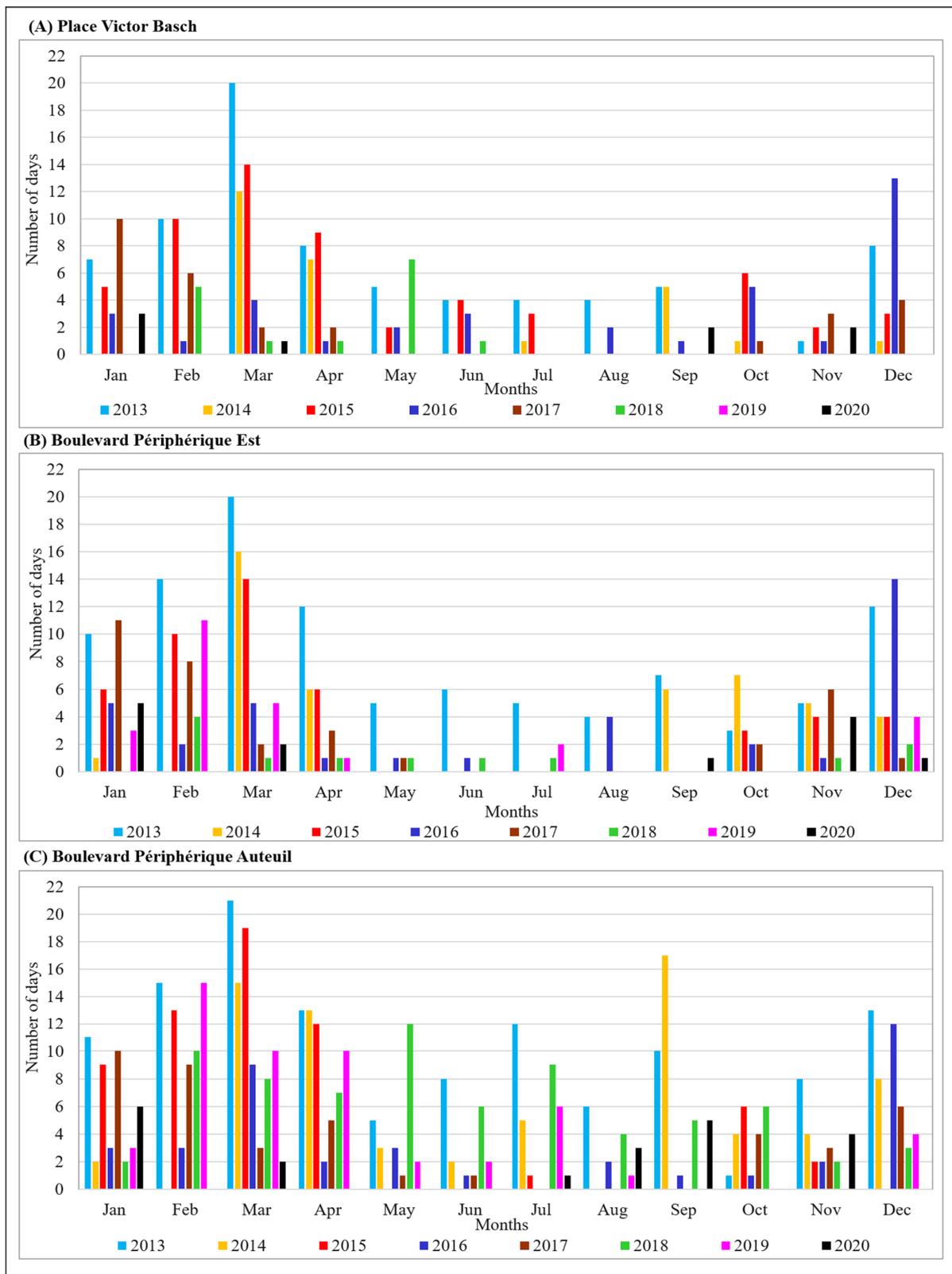


Figure 7. Number of exceedances of the PM₁₀ daily standard on a monthly scale in the southern part of the Paris conurbation from 2013 to 2020 (traffic stations: (A) Place Victor Basch, (B) Boulevard Périphérique Est, (C) Boulevard Périphérique d’Auteuil; (Airparif hourly data).

4.3. Differences between Lockdown and Non-Lockdown Phases

The daily average concentrations of PM_{2.5} and PM₁₀ calculated in 2020 show a strong spatiotemporal variability. While most of the records were below the WHO standard, occasional exceedances were recorded during both lockdowns, as well as in normal (non-lockdown) situations. On a spatial level, the data recorded at the three stations were strongly correlated using the Pearson correlation coefficient (*r*). Moreover, the relationship between the daily averages of each of the two pollutants per station is strong, positive, and significant, with *r* = 0.89 for PM_{2.5} and *r* = 0.94 for PM₁₀. The daily averages of PM_{2.5} and PM₁₀ for the year were 14 and 26 µg/m³, respectively, on Boulevard Est and 13 and 30 µg/m³ on Boulevard d'Auteuil. This average hides a temporal variability. Indeed, the coefficient of variation (standard deviation/mean) * 100) reached about 50% at both stations. On a weekly scale, we calculated the averages for three periods: the first lockdown, from 17 March 2020 to 11 May 2020; the second lockdown, from 31 October 2020 to 15 December 2020; as well as the whole year 2020 (all situations combined). The concentrations of PM_{2.5} and PM₁₀ decreased during weekends, especially on Sundays, due to less road traffic. The daily average concentrations were similar across weekdays.

In 2020, compared to PM₁₀, PM_{2.5} daily exceedances were more frequent at both stations (Figure 8). Indeed, we calculated 43 exceedances Boulevard Est and 30 on Boulevard d'Auteuil for PM_{2.5}, against 13 on Boulevard Est and 22 on Boulevard d'Auteuil for PM₁₀. A large proportion of these exceedances occurred during the two lockdowns, particularly the second one. We counted a total of 18 exceedances during the first lockdown, compared to 27 during the second lockdown for PM_{2.5}, and 4 compared to 9 for PM₁₀. The peaks were slightly higher in east Paris. During the first lockdown, maximum concentrations were recorded on 28 March in anticyclonic weather characterised by a high geopotential height and the northward migration of the Azores subtropical anticyclone, which reached Iceland. A weak north wind and clear skies were observed. Thermal inversion situations were also recorded in the Paris region, according to the Trappes radiosonde and evidenced by thick fog banks that persisted until 5 pm. During the second lockdown, PM peaks were recorded during a long anticyclonic episode that lasted from 20 to 30 November, with maximum values on 26 November marked by a very weak wind (less than 2 m/s) and a thermal inversion. In sum, radiative situations favourable to PM accumulation were spread over 15 days during the first lockdown and 16 days during the second lockdown.

During 2020, for all meteorological situations combined (Figure A3C), the average daily concentration was about 20 µg/m³ on Boulevard Est. A decrease of about 10 µg/m³ was observed on Sundays. Concentrations were higher on Boulevard d'Auteuil, where the daily average varied from 30 µg/m³ on Monday to 33 µg/m³ on Friday; on weekends, a slight decrease was observed on Saturday (28 µg/m³), which was confirmed on Sunday (23 µg/m³). The same trend is observed for Boulevard Est and Place Victor Basch.

During both lockdown periods, the weekly pattern did not change, while the average values during the first lockdown (Figure A3A) were comparable to the average situation (Figure A3C). The PM₁₀ concentration increased by about 3 µg/m³ during the second lockdown compared to the first lockdown between Monday and Thursday (Figure A3B). This increase can be explained by meteorological conditions favourable to high concentrations of pollutants and by the less strict nature of the second lockdown. Indeed, road traffic was reduced by 70% during the first lockdown, compared to 30% during the second lockdown (<https://opendata.paris.fr>, accessed on 26 June 2021). Apart from the weekly averages, the absolute maximum values were higher outside lockdown periods. However, weekly averages show that the thresholds recommended by the WHO were exceeded both during lockdown and non-lockdown periods.

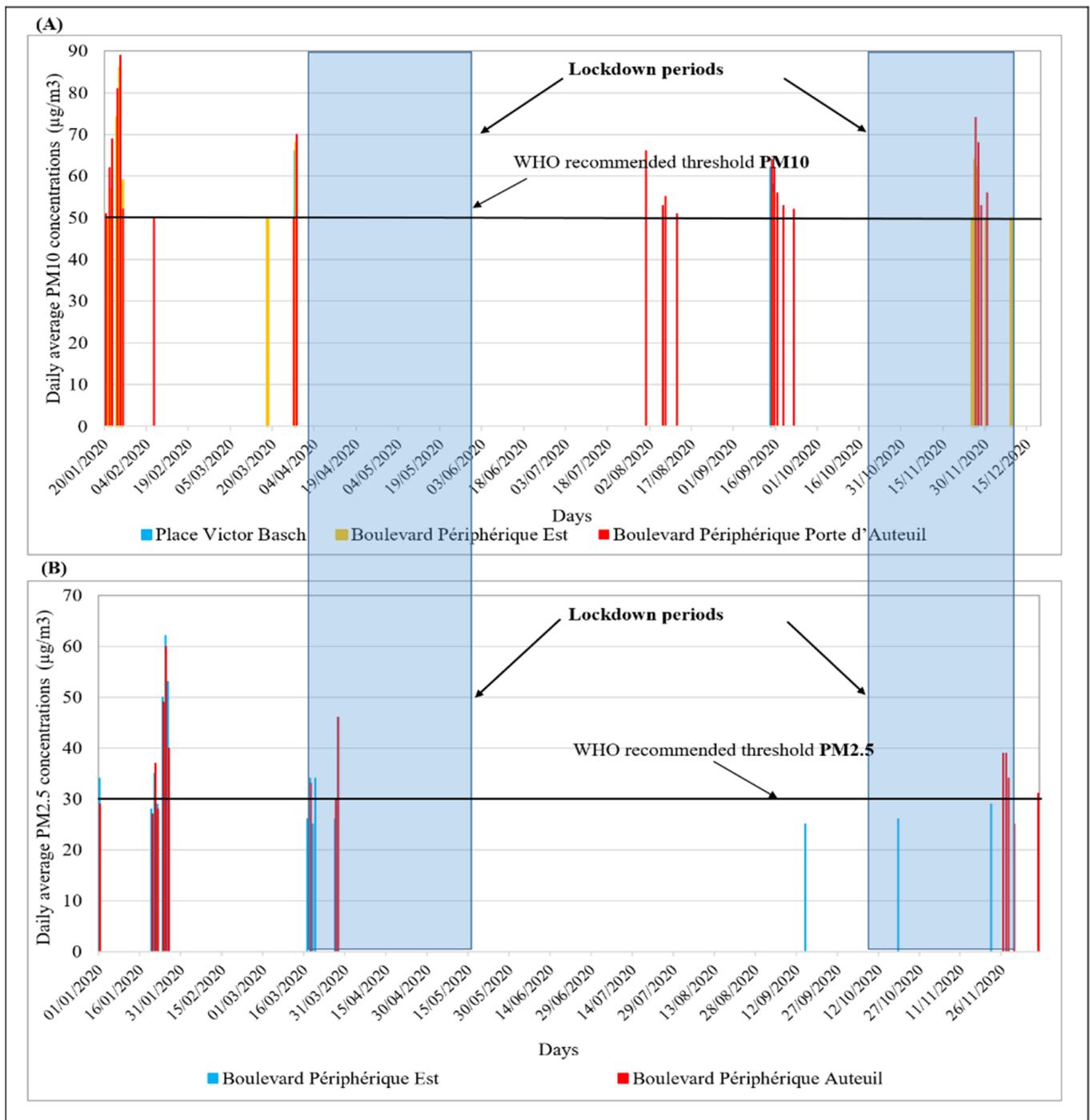


Figure 8. Exceedances of the WHO recommended threshold on an annual scale during lockdown and non-lockdown periods. (A) PM₁₀ at the Place Victor Basch, Boulevard Périphérique Est and Boulevard Périphérique d’Auteuil stations. (B) PM_{2.5} at the Boulevard Périphérique Est and Boulevard Périphérique d’Auteuil stations (Airparif data).

NO₂ concentrations exceeding the hourly standard (200 µg/m³) are rare, unlike exceedances of the daily average recommended by the WHO (25 µg/m³), which are frequent, particularly in September, which is dominated by anticyclonic situations. The same applies to the second lockdown, which was less strict than the first and was marked by more stable weather (Figure 9).

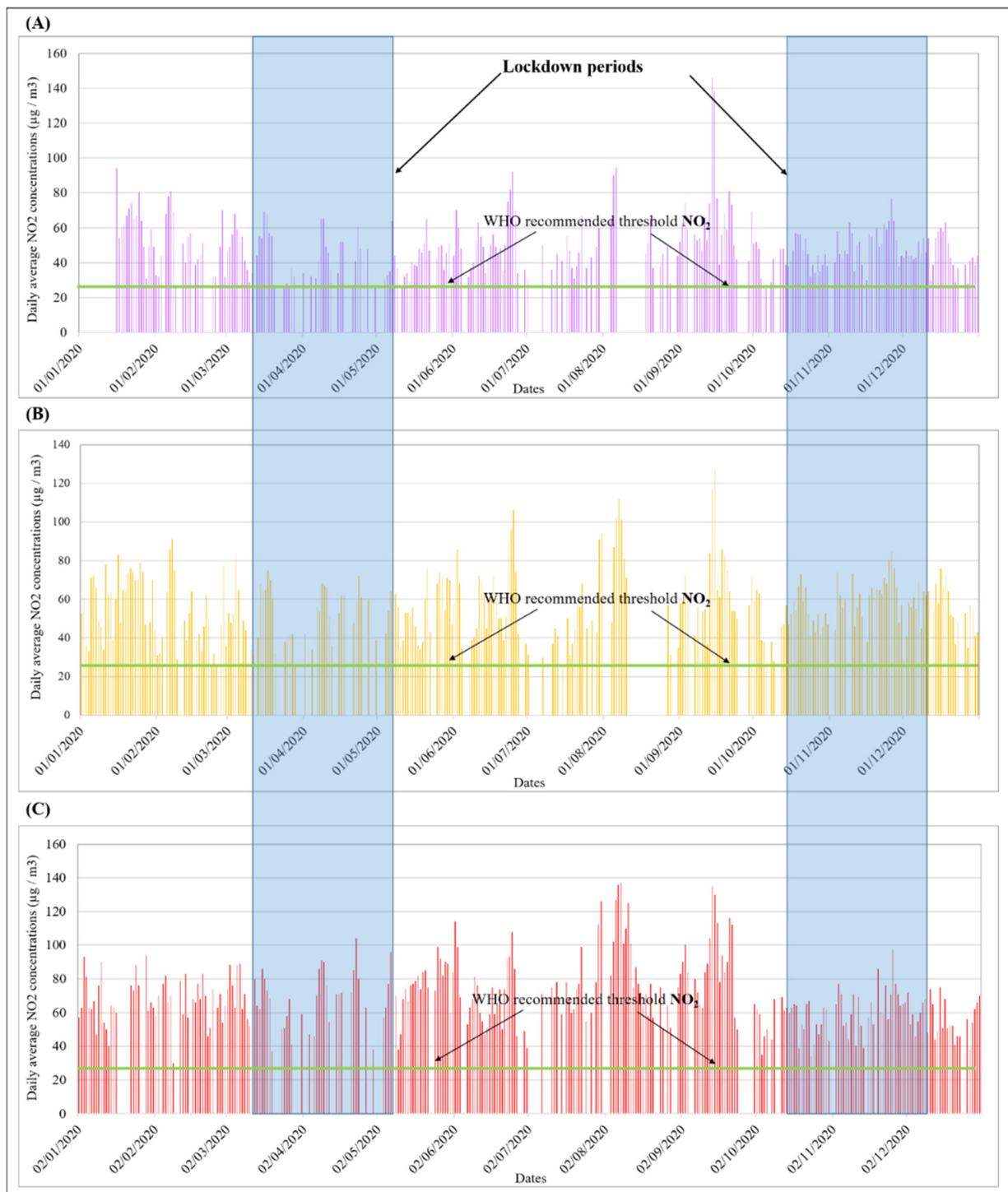


Figure 9. Exceedances of the daily threshold recommended by the WHO for NO₂ during lockdown and non-lockdown periods. Stations: (A) Place Victor Basch, (B) Boulevard Périphérique Est, (C) Boulevard Périphérique d’Auteuil (Airparif data).

4.4. Spatiotemporal Variability of Daily Concentrations of NO₂, PM_{2.5}, and PM₁₀ from Mobile Measurements (Fine Scale)

Mobile measurements collected by portable sensors confirm that the level of air pollution during the second phase of the lockdown sometimes exceeded the thresholds recommended by the WHO. Measurements were carried out in the morning (from 8:00 to 10:00) and in the evening (from 17:00 to 19:00). We separated the measurements made in

stable weather (atmospheric pressure > 1015 hPa, wind < 5 m/s, and cloud cover < 2 octas) from those made in unsettled weather (atmospheric pressure < 1010 hPa, wind > 8 m/s, and cloud cover > 6 octas).

4.4.1. Spatiotemporal Variability of NO₂ Concentrations

Differences in NO₂ during Lockdown by Weather Type: Stable or Unsettled

First, the NO₂ concentrations recorded during the two lockdown periods in 2020 were categorised according to the previously mentioned weather types. Then, the 75th percentile was calculated to locate the highest levels, which correspond to 105 µg/m³ for unsettled weather and 133 µg/m³ for stable weather (Figure 10).

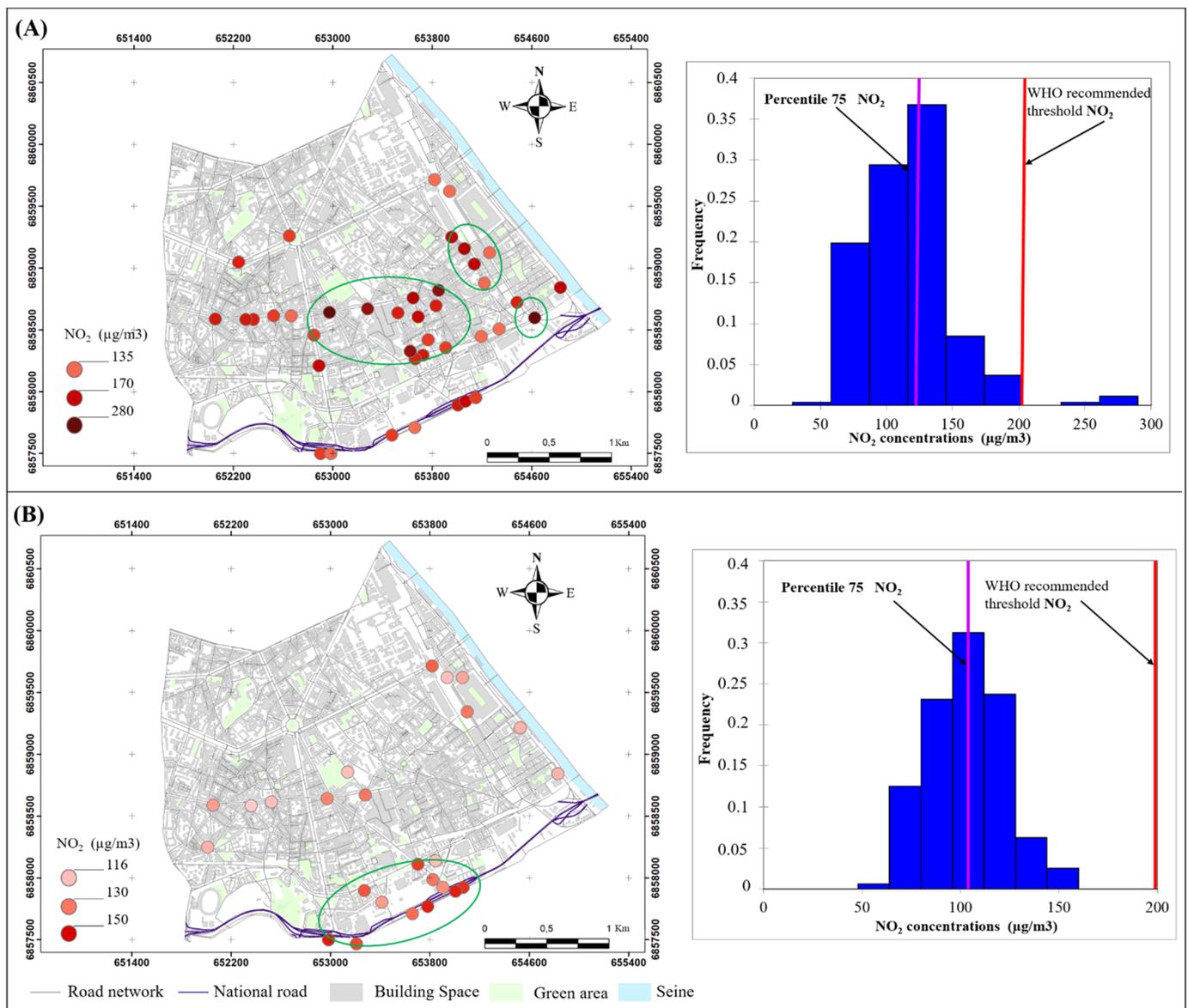


Figure 10. Frequency distribution of NO₂ concentrations in the 13th arrondissement in 2020 and 2021 during lockdown. (A) Stable weather, (B) unsettled weather (measurements by Aeroqual 500 sensors; number of campaigns: 25).

The probability of having high concentrations in stable weather is higher than in unsettled weather. Concentrations did not exceed 160 µg/m³ in unsettled weather. However, they reached 286 µg/m³ in stable weather (Figure 10A).

In order to understand the spatial and temporal variation of NO_2 , we mapped the frequency distribution of concentrations above the percentile for each type of weather. In calm weather, concentrations exceeding the 133 $\mu\text{g}/\text{m}^3$ percentile were homogeneously distributed in the southern part of the 13th arrondissement, particularly near Boulevard Périphérique. Values exceeding 250 $\mu\text{g}/\text{m}^3$ were recorded mainly in three places: the area between Rue Tolbiac and Rue Nationale, Rue de Chevaleret, and Boulevard Périphérique (Figure 10A).

In addition, concentrations ranging from 150 to 170 $\mu\text{g}/\text{m}^3$ were recorded at Boulevard Périphérique, Place d'Italie, and Boulevard Auguste Blanqui (Figure 10A). This configuration was totally different in unsettled weather, where we observed that the highest values, ranging from 130 to 150 $\mu\text{g}/\text{m}^3$, were mainly concentrated near Boulevard Périphérique, at Porte d'Ivry, and at Porte d'Italie. Nevertheless, some lower concentrations (110 to 120 $\mu\text{g}/\text{m}^3$) were found in the centre and east (Rue Tolbiac, Avenue de France) (Figure 10B), probably due to emissions from metro stations. Our map analysis shows that the spatial distribution of NO_2 concentrations changed according to the type of weather.

NO_2 Variations during Non-Lockdown Periods by Weather Type

During non-lockdown periods, we noticed that the value of the 75th percentile changed, increasing from 113 $\mu\text{g}/\text{m}^3$ in unsettled weather (Figure 11B) to 125 $\mu\text{g}/\text{m}^3$ in stable weather (Figure 11A). The absolute deviation between the two types of weather shows a decrease compared to the lockdown phase. We did not record values above the WHO standard for either type of weather if we considered the hourly standard (200 $\mu\text{g}/\text{m}^3$).

Figure 11A shows that in stable weather, two clusters were identified: one to the west, at the Avenue d'Italie, and the other to the south, along Boulevard Périphérique and Avenue de la Porte d'Ivry. These clusters contained concentrations of up to 160 $\mu\text{g}/\text{m}^3$. Between Boulevard Maréchaux, Avenue de la Porte d'Ivry, and Rue Tolbiac, a concentration of 160 $\mu\text{g}/\text{m}^3$ was recorded. In unsettled weather, the situation was mainly marked by concentrations ranging from 140 $\mu\text{g}/\text{m}^3$ to 190 $\mu\text{g}/\text{m}^3$ along the Seine, Avenue d'Italie, and Boulevard Vincent Auriol. The same concentrations were recorded for the centre cluster. Concentrations of 125 $\mu\text{g}/\text{m}^3$ were added to this range to extend this cluster, as at Rue Eugène Oudiné (Figure 11B).

The results of the measurement campaigns were consistent with those obtained for noise: they confirm the correlation between noise levels and road traffic. Potentially, on the scale of the study area, noise pollution decreased with increased distance from national roads, e.g., Boulevard Périphérique, and major roads, e.g., Rue Tolbiac, in parallel with high concentrations linked to road traffic.

4.4.2. Spatiotemporal Variability of Daily PM_{10} Concentrations

PM_{10} Variations during Lockdown in Stable and Unsettled Weather

The results of the measurement campaigns confirm the correlation between road traffic density, noise, and fine particle air pollution. The Bravais–Pearson correlation coefficient between the number of vehicles and PM_{10} concentrations reached 0.56. The correlation is positive and significant. The results also show a variability of the concentrations according to type of weather. Even during the COVID-19 lockdown, some acute pollution episodes were encountered in radiant weather, as was the case on 26 November 2020 at Porte d'Ivry, where concentrations reached 70 $\mu\text{g}/\text{m}^3$ for PM_{10} and 50 for $\text{PM}_{2.5}$ during the morning peak of road traffic, with 835 vehicles in 5 min (Figure 12A).

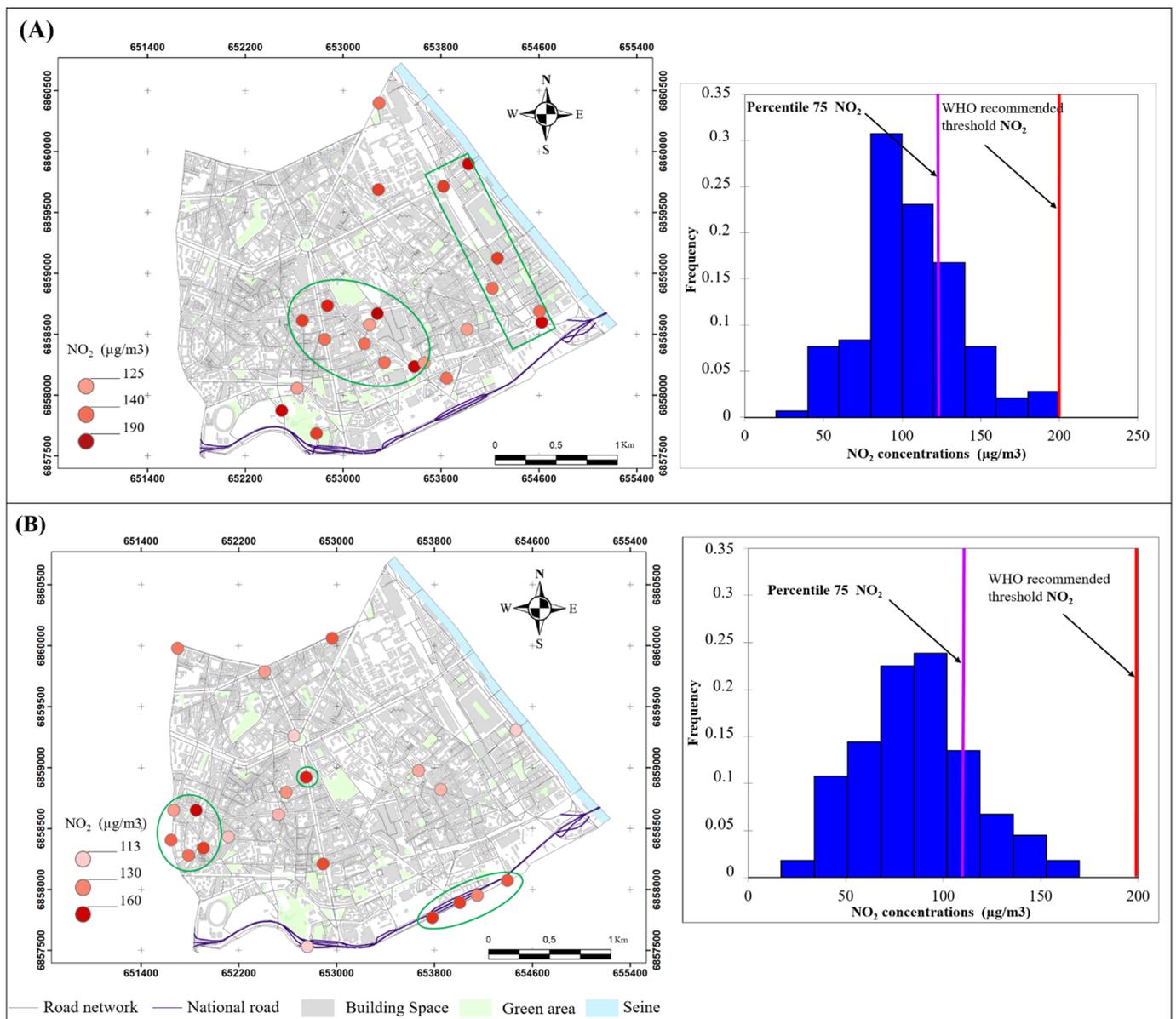


Figure 11. Frequency of NO₂ concentrations in the 13th arrondissement exceeding the 75th percentile during periods non-lockdown periods. (A) Unsettled weather and (B) stable weather in 2020 (measurements by Aeroqual 500 sensors; number of campaigns: 35).

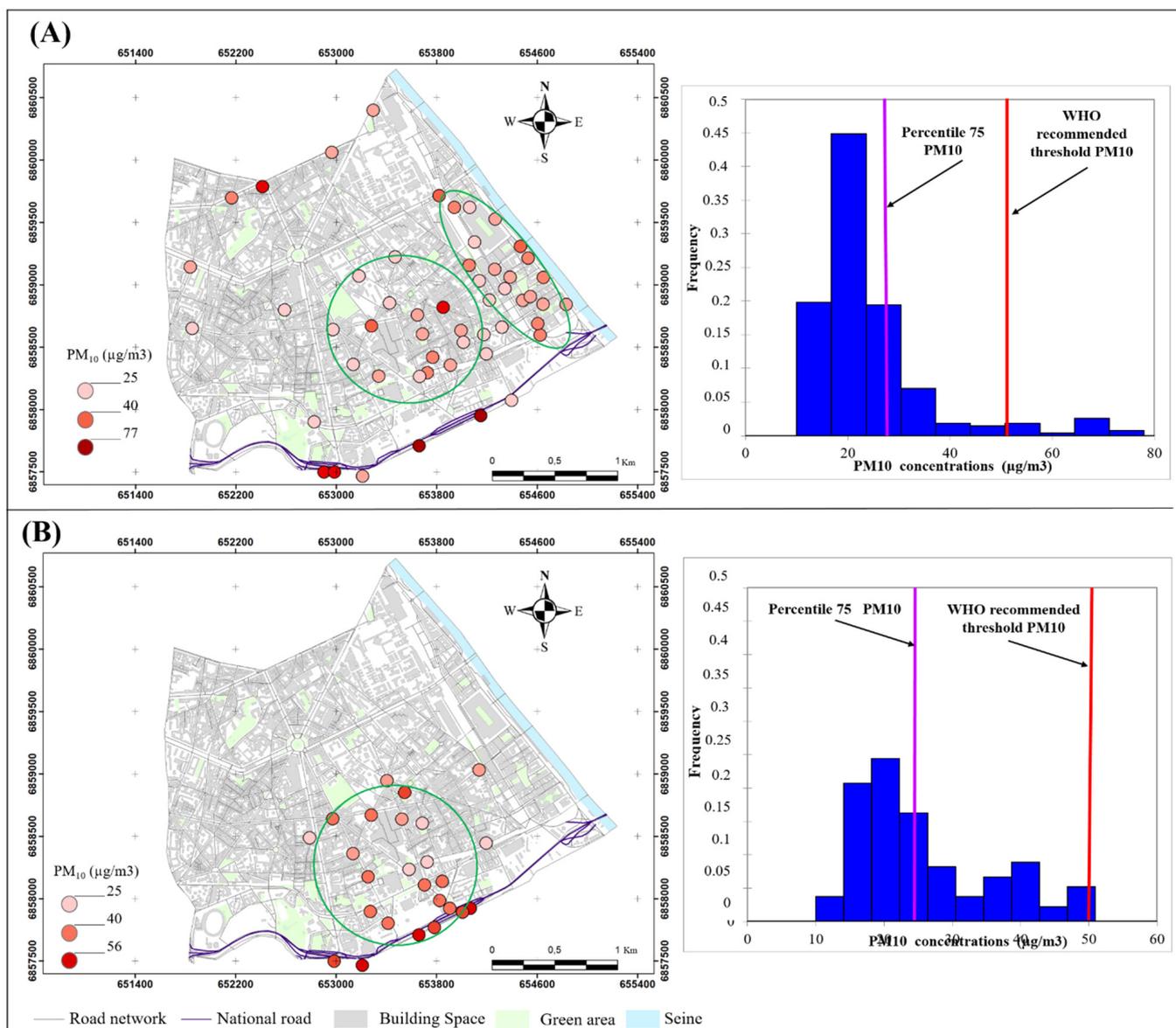


Figure 12. Frequency distribution of PM₁₀ concentrations in the 13th arrondissement exceeding the 75th percentile during lockdown periods. (A) Stable weather, (B) unsettled weather in 2020 and 2021.

During the lockdown, we note that the 75th percentile increased from 22 μg/m³ in unsettled weather to 27 μg/m³ in stable weather (Figure 12B). We recorded higher values in stable weather. Figure 12 shows that in stable weather, two clusters were identified: one in the east, between Rue des Grands Moulins and Avenue de France, and the other in the middle of the 13th arrondissement, at Boulevard Vincent Auriol. These clusters have concentrations up to 77 μg/m³. Along Boulevard Périphérique and at the junction of Rue Tolbiac, concentrations of over 75 μg/m³ were recorded.

On the other hand, when the weather was unsettled, concentrations decreased and ranged from 25 μg/m³ to 56 μg/m³, e.g., Rue Regnault, Rue Château des Rentiers. Boulevard Périphérique, Avenue de la Porte d’Ivry, and Avenue de la Porte d’Italie were the places where the highest values were recorded (Figure 12B).

PM₁₀ variations during Non-Lockdown Periods in Stable and Unsettled Weather

The 75th percentile of PM₁₀ concentrations did not change much, remaining around 25 μg/m³ for both weather conditions (Figure 13). In addition, the frequency of obtain-

ing concentrations above $30 \mu\text{g}/\text{m}^3$ was lower in unsettled weather. Compared to the lockdown period detailed above, the recorded data were comparable, with the exception of the maximum concentrations reached in good weather, which were around $80 \mu\text{g}/\text{m}^3$ when the meteorological conditions were more favourable to the accumulation of particles (Figure 13A).

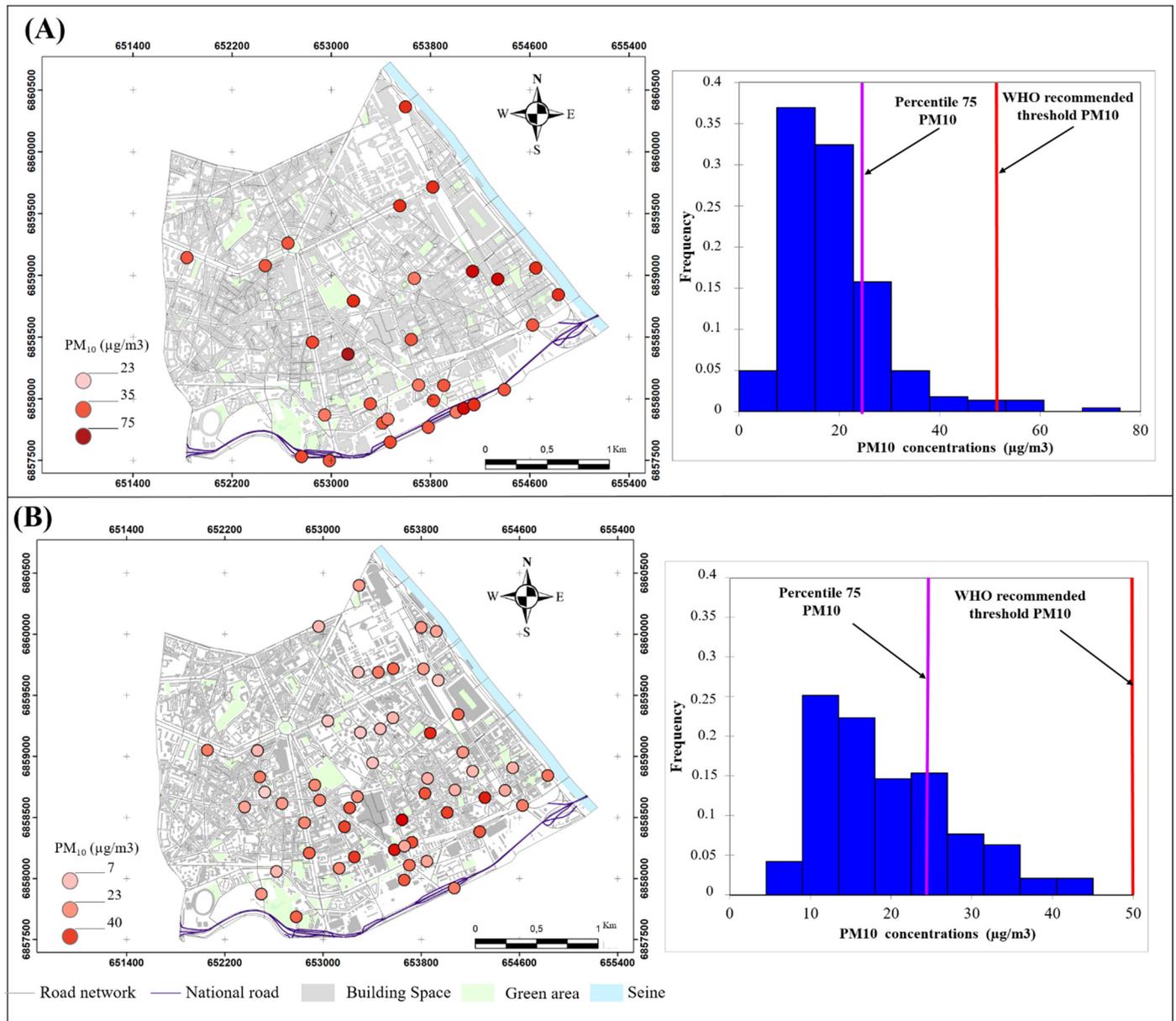


Figure 13. Frequency distribution of PM₁₀ concentrations in the 13th arrondissement exceeding the 90th percentile during non-lockdown periods. (A) Stable weather, (B) unsettled weather in 2020 and 2021 (semi-itinerant measurements).

In stable weather, the highest values, ranging from 50 to $70 \mu\text{g}/\text{m}^3$, were mainly recorded near congested arteries: Boulevard Périphérique, Quai Panhard-et-Levassor, Avenue de France, and Boulevard Vincent Auriol. We also observed relatively high concentrations, exceeding $70 \mu\text{g}/\text{m}^3$, mainly between the junction of Rue de Tolbiac and Rue de Chevaleret, and Avenue de Choisy (Figure 13A), one of the densest areas. Regarding unsettled weather, despite road traffic comparable to that in stable weather (about 700 vehicles per 5-min period), the situation was mainly marked by concentrations ranging from

30 $\mu\text{g}/\text{m}^3$ to 40 $\mu\text{g}/\text{m}^3$ along Boulevard Vincent Auriol, Rue Nationale, and Rue Albert Bayet. The peaks were recorded near the junctions. We recorded lower values, ranging from 20 to 25 $\mu\text{g}/\text{m}^3$, at Rue Bobillot between Avenue de Choisy and Rue Tolbiac, Quai Panhard et Levassor, Boulevard Masséna, and Quai d'Austerlitz (Figure 13B).

5. Discussion

The results of this study, like recent work on the link between problematic pollutants in Paris and COVID-19, are preliminary. We conducted measurement campaigns in 2021 to confirm our results. The spatiotemporal variability of pollutants is systematically explained by meteorological parameters and by the intensity of road traffic, which varies considerably from one street to another in the 13th arrondissement of Paris.

The improvement in air quality in Paris in 2020 cannot be explained by lockdowns alone. The common air pollutants and their precursor's concentrations have been reduced substantially since 2013. For this effect, we chose to compare the situation during lockdowns to that during non-lockdown periods in 2020 only, contrary to other works. Ranjeet et al. studied anomalies in air pollutant concentrations (increases or decreases during 2020 periods compared to equivalent 2015–2019 periods) and reported, in 63 cities covering 25 countries over seven geographical regions of the world, decreases of up to about 70% in mean NO_2 . In our study, this decrease did not exceed 15% because we referred only to 2020 data.

The mobile survey method is effective for capturing the spatial variability of air quality at the neighbourhood scale, such as in the 13th arrondissement of Paris. Unfortunately, we could not compare hourly concentrations of NO_2 and PM_{10} measured by mobile platforms with that measured by nearby Airparif air monitoring stations because the latter do not record these pollutant levels. The measurement campaigns, carried out with the Aeroqual Series 500 portable air quality monitors, clearly show that there were high concentrations of PM, exceeding WHO standards during the second lockdown. These results nuance those of Skirienė et al., who showed an improvement in air quality during lockdown periods in four countries (France, Spain, Italy, England) [26]. These differences are mainly due to the measurement protocol, ours being based on a network of spots covering several sites exposed to heavy road traffic. The use of the median calculated over 16 recordings (for 5 min) avoids the extreme values linked to the passage of lorries or the proximity of metro vents.

The observed peaks of particulate matter are explained by road traffic and wood heating, given that temperatures were slightly higher than normal during the two lockdown periods. PM concentrations were higher during the second lockdown, which was characterized by more intense road traffic than the first and which experienced a long episode of radiative weather favourable to high pollutant concentrations. In other regions, increases of PM concentrations, such as in some Spanish cities, were attributed mainly to the long-range transport of African dust and/or biomass burning [27]. Nevertheless, these justifications are not defensible in Paris.

The case study of the 13th arrondissement in Paris during the second lockdown is representative of what happened on a Paris-wide scale, reporting relatively high values of NO_2 and PM_{10} exceeded the WHO recommended values. Our measurements remain episodic and do not allow for comparison with the WHO daily standards. In 2022, we plan to install fixed ECOSMART stations near spots that have recorded high values and near high-stake locations (schools, hospitals, etc.).

6. Conclusions

This study of the spatial and temporal variability of air pollution has mainly highlighted the particularity of lockdowns in 2020. Despite a slight decrease in fine particle pollution during the first lockdown due to a considerable decrease in road traffic density, peaks exceeding 65 $\mu\text{g}/\text{m}^3$ for $\text{PM}_{2.5}$ and 75 $\mu\text{g}/\text{m}^3$ for PM_{10} were recorded during periods of radiative weather. These results are consistent with those reported in [28] for the first

lockdown. The decline in the number of vehicles circulating in 2020 contributed to a reduction in NO₂ concentrations. However, concentrations of particulate matter increased, as was the case in Italy [29].

The area of the 13th arrondissement recorded significant road traffic during the lockdown, mainly near Boulevard Périphérique. The density of buildings and anticyclonic weather make the wind weak and do not favour the mixing of pollutants.

We concluded from the field measurements that the probability of having high NO₂ concentrations in stable weather was higher than in unsettled weather during lockdown. Values exceeding 250 µg/m³ were recorded mainly in three locations: the area between Rue Tolbiac and Rue Nationale, along Rue de Chevaleret, and on Boulevard Périphérique.

During non-lockdown periods, we did not record values above the WHO standards in unsettled weather. During the second lockdown, we recorded PM₁₀ concentrations above 50 µg/m³ in stable weather, with values reaching 77 µg/m³. In unsettled weather, PM₁₀ concentrations dropped by about 40%. For the two pollutants mentioned above, the maximum concentrations were observed at two junctions: Boulevard Périphérique/Avenue de la Porte d'Ivry and Boulevard Périphérique/Avenue de la Porte d'Italie.

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Appendix A

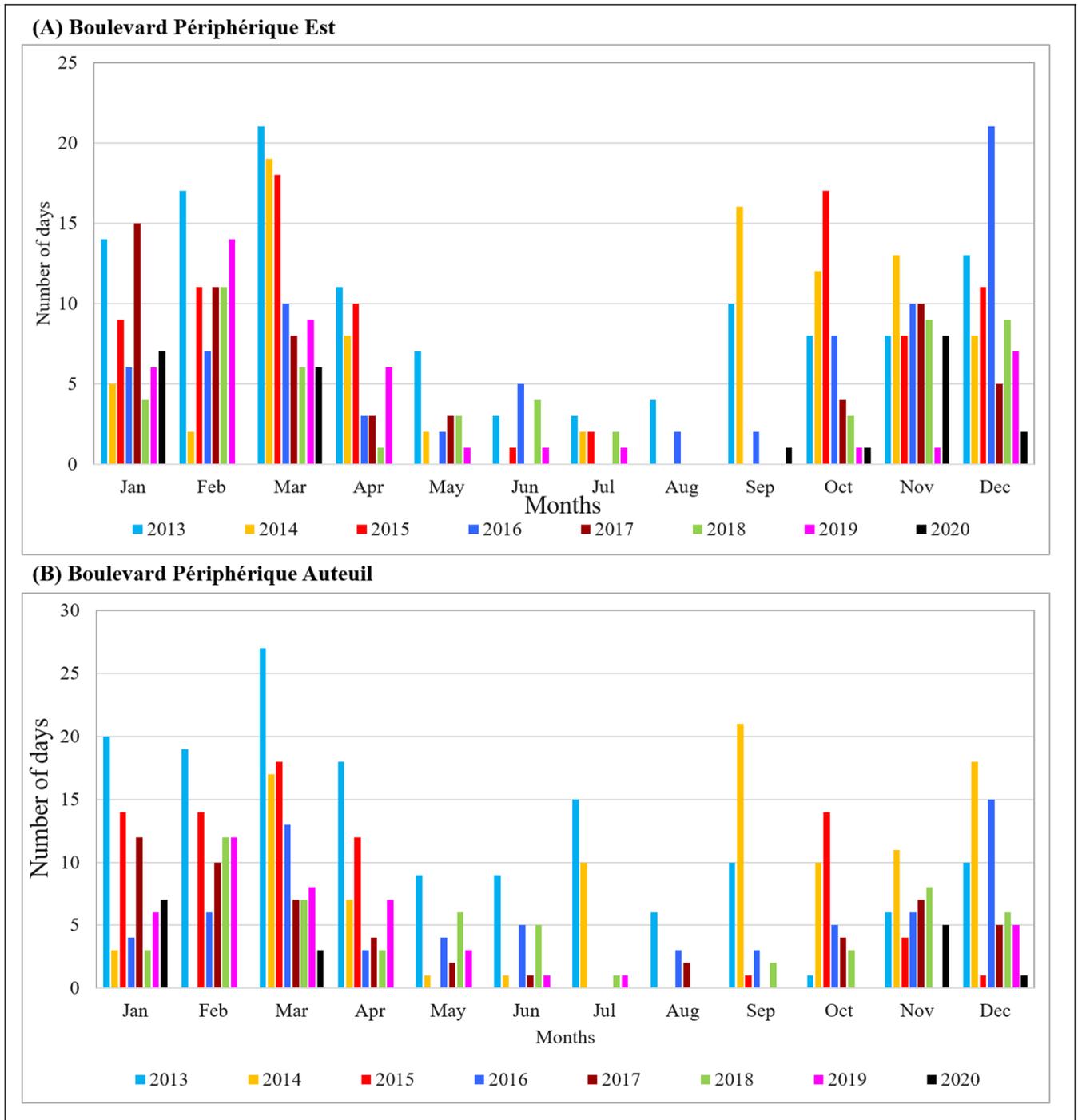


Figure A1. Number of exceedances of the WHO PM_{2.5} daily standard on a monthly scale in the southern part of the Paris conurbation between 2013 and 2020. (A) Boulevard Périphérique Est, (B) Boulevard Périphérique d’Auteuil (Airparif data).

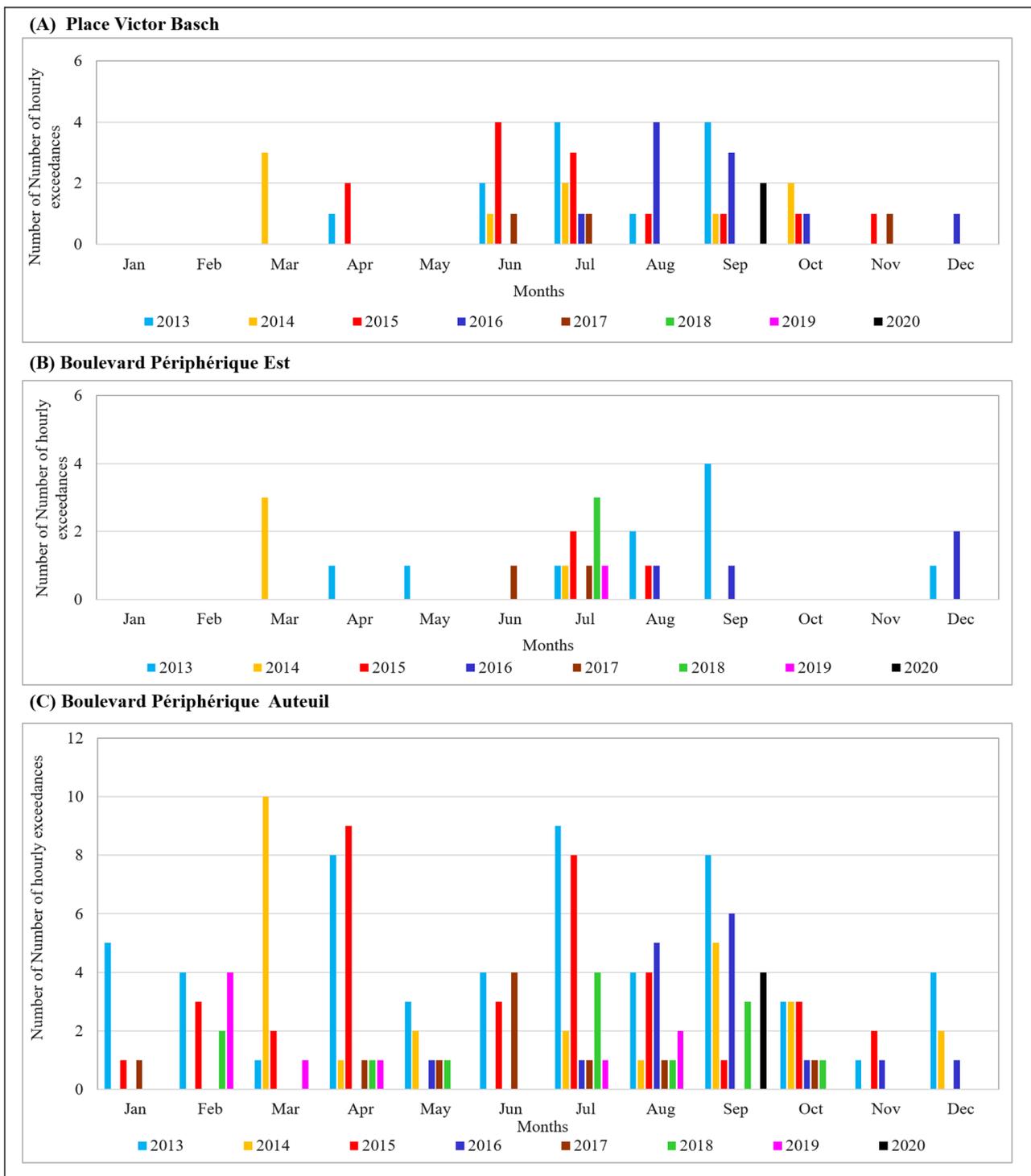


Figure A2. Number of hourly exceedances per month of NO₂ concentrations in the southern part of the Paris conurbation between 2013 and 2020 (traffic stations. (A) Place Victor Basch, (B) Boulevard Périphérique Est, (C) Boulevard Périphérique d’Auteuil (Airparif data).

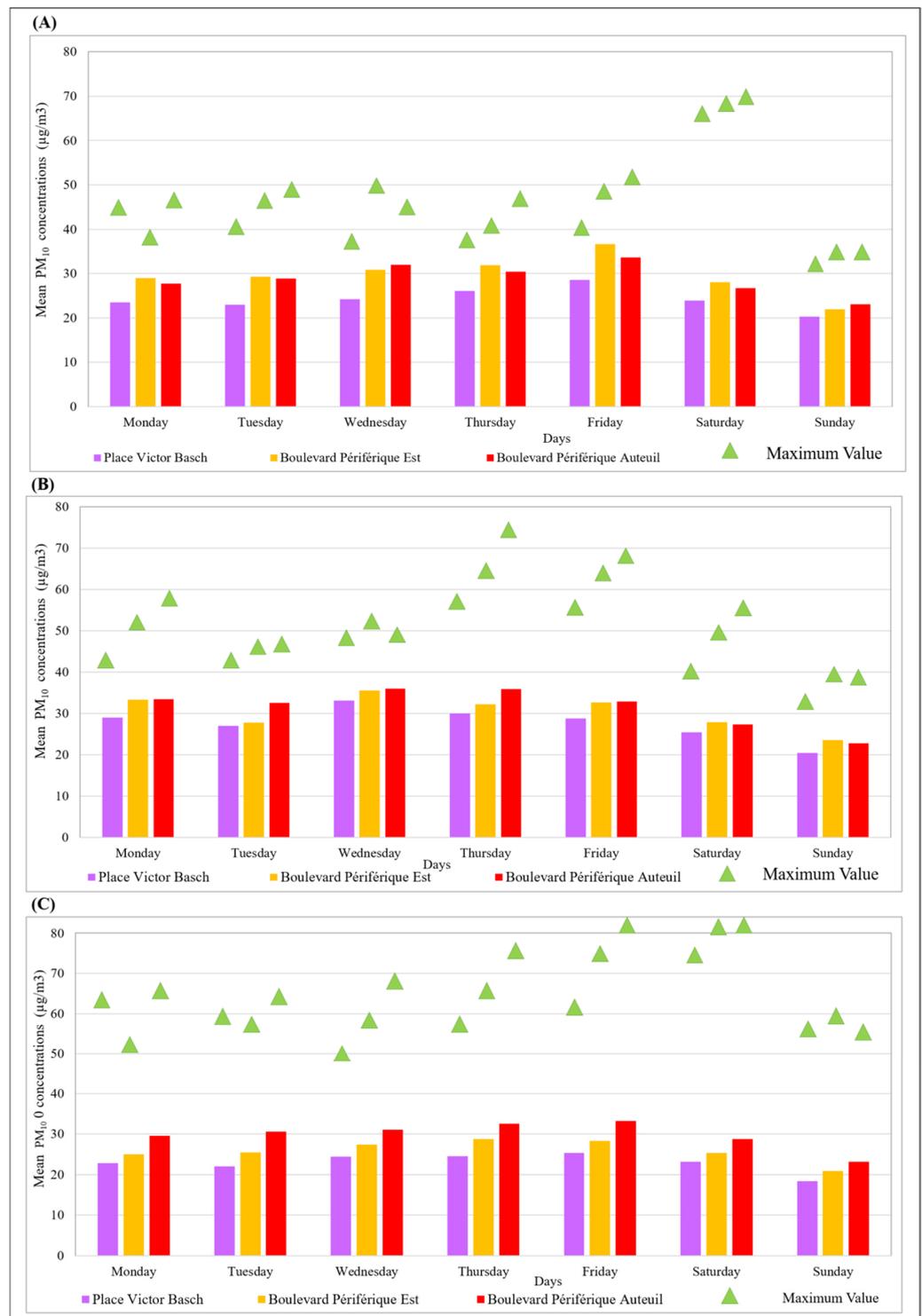


Figure A3. Weekly variation of average and maximum PM₁₀ concentrations in the southern part of the Paris conurbation in 2020 during the first lockdown (A), the second lockdown (B), and throughout the year (C). Traffic stations: (A) Place Victor Basch, (B) Boulevard Périphérique Est, (C) Boulevard Périphérique d’Auteuil (Airparif data).

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