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Micrometeorological Conditions That Influence the Air Quality in Houses Near High Rise Buildings – Field Results

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Abstract

Measurements assessing how micrometeorological conditions—driven by the proximity of large buildings—influence $PM_{2.5}$ levels were conducted in an urban commune of Santiago, Chile, during the winter and spring seasons. This commune is characterized by a mixture of one story houses and high-rise building. These large building may have an influence on the air quality because they alter wind circulation or lower the temperature due to the shadow of the building. In this work, $PM_{2.5}$ and meteorological parameters were measured outside three pairs of houses in winter of 2021, one of which received shadow from a nearby building and the other was under the sun. In one pair, $PM_{2.5}$ was larger in the house located under the shadow of the building only during the winter months, the result was attributed to the lower temperature generated by the shadow, which inhibited $PM_{2.5}$ dispersion. In another pair of houses, the result was attributed to the difference in wind speed in one of the houses, because the building acts as a windbreak. In the third pair of houses no effect was observed in $PM_{2.5}$, this is probably due to the lack of significant micrometeorological differences between the two sites.

Keywords: $PM_{2.5}$; high-rise building; permanent shadow; temperature

1. Introduction

Between January 2013 and July 2018, the Estación Central building department granted permits for 81 high-rise projects, totaling 38,956 apartments. According to the 2019 Official Cadastre of High-rise Buildings, these structures range from 20 to 41 stories (52 to 106 meters), with 30 exceeding 30 stories. By May 2019, 60 of these "towers" were completed, concentrated within a 23.6-hectare area on the western side of Santiago—a density of 3.4 towers per hectare.

The proliferation of high-rise buildings in close proximity significantly degrades the internal environmental quality of the urban fabric. This density results in poor acoustic insulation, diminished privacy, restricted airflow, and a chronic lack of sunlight [1,2]. A primary factor affecting inhabitant well-being is the "shadow cone" cast by these structures, the length of which is a function of building height and latitude. This shading causes a localized drop in ambient temperature as solar radiation is blocked and shaded surfaces cool. For the 81 permitted buildings in this area, the combined shadow length reaches 2,937 meters. This condition peaks between the March and September equinoxes, reaching a critical maximum during the winter solstice (June 21–22). At this time, a solar angle of 33°46′ at solar noon causes each building to project a shadow to the south equivalent to twice its own height.

There is a well-established inverse relationship between ambient temperature and air pollutant concentrations: higher temperatures typically correspond to lower concentrations, while colder

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conditions favor the accumulation of pollutants [3]. High-rise structures further complicate this dynamic by altering wind patterns. When airflow strikes a building's facade, it is redirected; while some air escapes upward, a significant portion is forced downward—a phenomenon known as the "downwash effect"—creating turbulence and gusts at street level [4,5]. As building height increases, the magnitude of this downward airflow intensifies . [6,7]. Given that wind speed is the primary meteorological driver of $PM_{2.5}$ dispersion, the localized increase in velocity caused by tall buildings can lead to a reduction in particulate concentrations at the base.

We can infer that the greater amount of shade and, therefore, at lower temperature and higher humidity, there is a higher concentration of pollutants at ground level, to the south of these buildings, even more so in the presence of very low rainfall [8]. Consequently, $PM_{2.5}$ concentration depends fundamentally on the dispersion conditions of the atmosphere [9], that is, the transport of pollutants depends on the state of the atmosphere and the meteorological conditions (atmospheric turbulence, wind speed and direction, radiation solar, etc.). On the contrary, atmospheric stability hinders the dispersion of pollutants and contributes to their accumulation near emission sources, as is the case with thermal inversion. In addition, there is an evident relationship between the intensity of the wind and the concentration levels of the pollutants. The dispersion of contaminants increases with wind speed and turbulence.

In this study, six low cost monitors (LCMs) were built and used to study the difference in ambient conditions in houses with and without shadow from a high rise building. In each site, the LCM had sensors to measure $PM_{2.5}$, temperature, humidity, wind speed and direction. The results show that the location of the house with respect to the shadow makes a difference in temperature and humidity, but $PM_{2.5}$ is sensitive to several conditions, such as wind speed, location with respect to the building, time of day, sun irradiation, etc.

2. Materials and Methods

2.1. Instrumentation and Measurement Period

Seven custom low-cost monitoring stations were developed to measure $PM_{2.5}$, PM_{10}, temperature, humidity, wind velocity and direction. Each unit features a **Plantower PMS7003** laser particulate sensor (λ=680±10 nm) [10,11]. While the manufacturer specifies capabilities for both PM_{10} and $PM_{2.5}$, research indicates that laser particle counters often exhibit a nonlinear response to larger particles; therefore, only the $PM_{2.5}$ fraction was treated as highly accurate [12–14]. Environmental parameters were captured using a **Sensirion SHT30** sensor (typical accuracy: ±3% RH; ±0.3∘C), while wind data were gathered with a **Shenzhen Fine Offset Electronics** station (resolution: 22.5∘ direction; 0.5 m/s speed). These components were integrated with an **ESP32 microcontroller** onto a custom interface plate and housed in a compact 12×10×8 cm^3 enclosure. Data were logged locally to an SD card and, where connectivity permitted, transmitted to a university web server via WiFi.

$PM_{2.5}$ concentration was measured continuously with a 1 min. interval in all sites. Deployment of the instruments and measurements started in May and ended in October of 2021. The measurement period corresponds to winter and spring, a time of the year with the lowest temperatures, highest humidity, lowest wind velocity and highest PM2.5 concentrations.

2.2. Study Area

The study was located in the commune of Estación Central in Santiago de Chile, towards the west of the city. This area is known to have higher levels of $PM_{2.5}$ in winter because dispersion conditions are very poor and there significant emissions from wood burning [15–17]. The area has a lot of commercial and retail activity, but it is also a residential area. Because the area does not have direct influence from emission sources and it is located in the middle of the city, all sites can be considered as an urban background. As mentioned in the introduction, this commune has seen a significant increase in the number of very tall buildings in the last 10 years.

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Figure 1 shows a map of the commune in which the pink shapes indicate buildings with more than 50 m in height. Three tall buildings were selected to study the influence of the permanent shadow on the environmental conditions of the place. The monitors were located in pairs, one of them close to the permanent shadow of a building and the other in a nearby site but away from the shadow. The blue dots in Figure 1 indicate these sites. Each monitor had a sensor for $PM_{2.5}$, temperature, humidity, wind velocity and direction. The height of the building and houses in the area were determined from the Google Earth program.

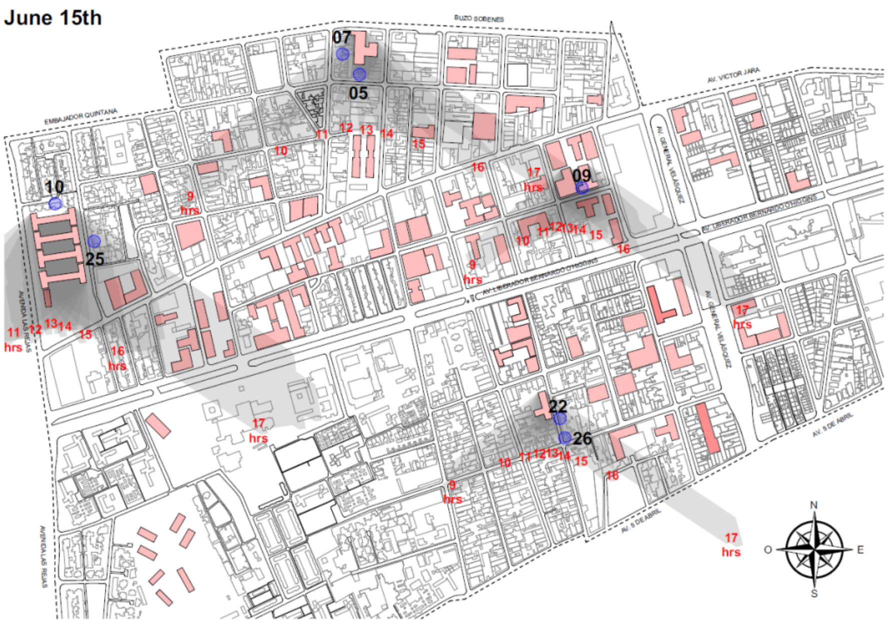

Figure 1. Map of the commune of Estación Central indicating the buildings and measurement sites. The shadows of the buildings are indicated for several hours during the day for June 15th. The arrow shows the wind direction from 12 pm to 7 pm.

2.3. Shadow Determination

The program used to calculate the shape and length of the shadows from the buildings was Archicad, which is a BIM (Building Information Modeling) drawing and modeling software. The program allows creating parametric designs of the elements, with a data bank that contains the complete life cycle of the construction, from concept to creation. The software has a georeferencing function (spatial positioning technique of an entity in a unique and well-defined geographic location in a specific coordinate and datum system) which locates the project in the respective city (in this case Central Station, Santiago) and simulates the position and path of the sun.

2.4. Precalibration

An inter-comparison of the instruments was performed before the start of the campaign, from April 29th until May 3d, 2021 at the university site (USACH) to determine the variability among them. 6 instruments were placed side by side during 3 days to measure temperature, humidity, $PM_{2.5}$, wind speed and direction. The one minute data from all instruments was averaged to obtain 1 point per hour. A linear calibration factor was applied to some of the instruments in order to minimize the Pearson correlation coefficient and the normalized root mean square error, nRMSE [18]. Several previous studies have found that the Plantower data has to be multiplied by a number close to 0.5 to match the data from reference instruments. Holder et al., [19] found a correction factor of 0.51 for the Plantower PMS 5003 in a study of multiple wildfires. Barkjohn et al. [20] also found a correction factor of 0.51 across multiple locations in the US. A study of domestic woodburning in Armindale, New South Wales, Australia [21] found that a multiplier of 0.55. The data in this study was compared with a reference monitor Metone model 1020 located in Parque O'Higgins Station that belongs to the Ministry of the Environment [22] for the same dates. The station is located 4 km south-east of the monitoring sites, consequently $PM_{2.5}$ data is not necessarily the same, but a comparison can still be performed. The five-day $PM_{2.5}$ 1-hour data measured at Parque O'Higgins was compared to the average measured at the university with the Plantower monitors. The correction factor found was 0.5, which is very close to the previous studies [19–21]. A plot of $PM_{2.5}$ for all sensors after the correction is shown in Figure 2 along with the reference monitor at Parque O'Higgins. The highest correlation obtained was 0.9977 and the lowest was 0.9655 between Plantower monitors. These values are consistent with previous studies that found good correlation between similar sensors [10,14,23].

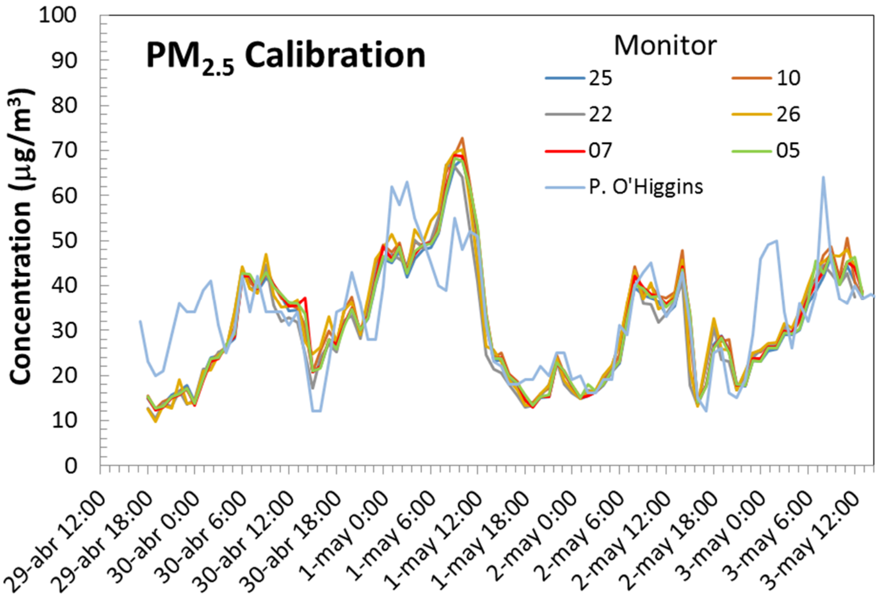

Figure 2. $PM_{2.5}$ Calibration data for the 6 monitors at USACH, along with the reference instrument (METONE 1020) at Parque O'Higgins station.

2.5. Wind Characteristics of the Area

Wind speed and direction are very relevant to $PM_{2.5}$ concentrations because they determine how pollution is dispersed. In a city, the wind pattern changes drastically depending on the location and orientation of buildings, streets, low rise constructions, etc. There is a vast literature on the relationship between buildings and wind flow in architectural and engineering literature [4,24–26]. For this reason, it is necessary to have wind speed and direction measurements in a place free from obstacles. In Santiago, the Parque O'Higgins station has a wind speed and direction monitor that can be used as a reference for the area, because it is located in a large park, far from buildings or trees. In contrast, the monitors installed on the houses are close to building or trees and are only representative of the meteorological microenvironment. The average wind speed in Parque O'Higgins is shown in Figure 3 for several months. A pattern that is very common in central Chile (Gramsch et al., 2006) can be seen, in which the speed increases during the afternoon and decreases at night and early morning. The figure shows that the wind speed is very low from May to July, with speeds higher than ~ 0.5 m/s only between 12 and 6 pm. In the months of August through October, the wind speed increases and there are speeds larger than ~ 0.5 m/s between 12 and 8 pm. Because of this pattern, only during the afternoon hours the wind can affect the pollution near buildings, because during the night and early morning hours, the wind speed is too low.

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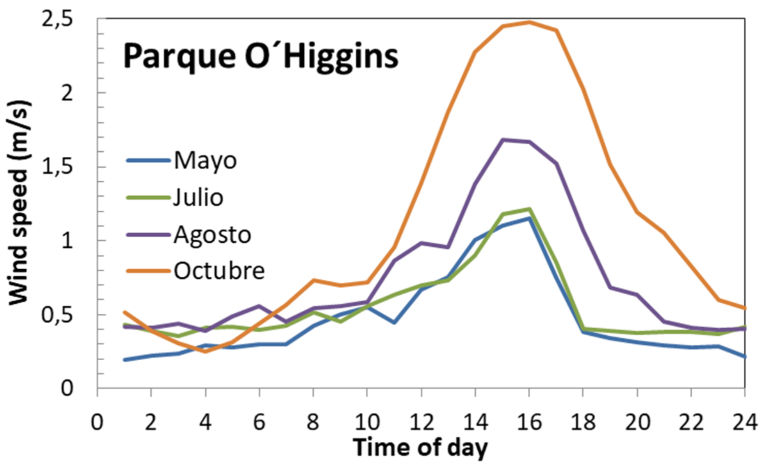

Figure 3. Wind speed in Parque O'Higgins station for four months of the year 2021.

3. Results

3.1. Monitors 010 and 025

Figure 1 shows the location of monitors 010 and 025 and a more detailed picture is shown in Figure 5. The first house (UTM: 341527 E 6297163 S) is located within a gated community, approximately 80 meters east of a large street (Gral. Velazquez), 40 m west of a smaller street (Sta. Petronila) and less than 10 m north of a large building approximately 76 m tall and an area of 130 x 150 m^2. In its immediate surroundings there is no commercial activity and little traffic because it is a gated community. The house where monitor 10 is located is never shadowed by the building because it is located to the north of it. Due to the low-profile surrounding residential area (3–6 m), there are few barriers to air circulation. This suggests that the wind that approach the building closely resembles the data from the Parque O'Higgins station (see Figure 3 and Figure 4). Monitor 025 is located about 80 south-east of the previous monitor, very close to Sta. Petronila st. Near this site there is a residential kiosk 15 meters to the north and several other small businesses, including 3 minimarkets and a liquor store. In the southwest sector, another cluster of 4 minimarkets is located at the base of the building. Within a radius of 15 to 30 meters to the north, 2 minimarkets and a hair salon are identified, while 30 meters to the south, there is a preschool. Monitor 25 is located on the east side of the building and receives shadow from the building during the afternoon, but sun during the morning.

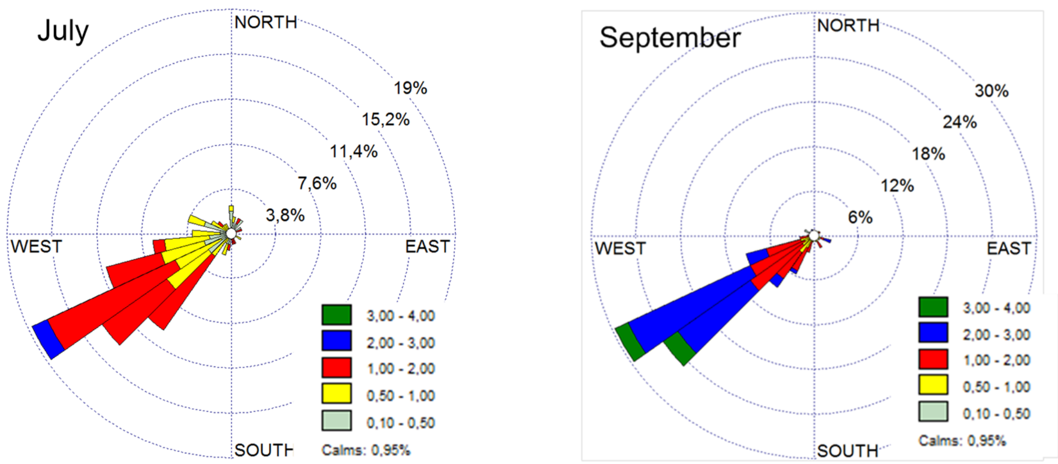

Figure 4. Wind direction and speed in Parque O'Higgins station for the hours 11 to 5 pm, in a winter and a spring month.

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Figure 5. Location of houses 010 and 025 with respect to the building and predominant wind direction.

The wind speed profile has been plotted for two months for monitors 010 and 025 in Figure 5. It can be seen that the wind speed is larger in house with monitor 010 than monitor 025, during the afternoon. This higher speed in house 010 is probably due to wind being deflected towards the north and then goes around the building. This effect is well known and has been documented before [6,27]. In contrast, monitor 025 is located behind the building with respect to the incoming wind; therefore it causes the wind speeds to probably decrease in the vicinity of monitor 025. The wind direction shown in Figure 7 also confirms the observation above, the wind direction in monitor 010 goes along the side of the building, and the wind direction in monitor 025 goes in the opposite direction, that is after passing the building, the wind is redirected towards the ground, causing a flow moving downwards, generating recirculation at the ground level. The arrows in Figure 5 show the most probable wind pattern during the afternoon, when the speed is higher.

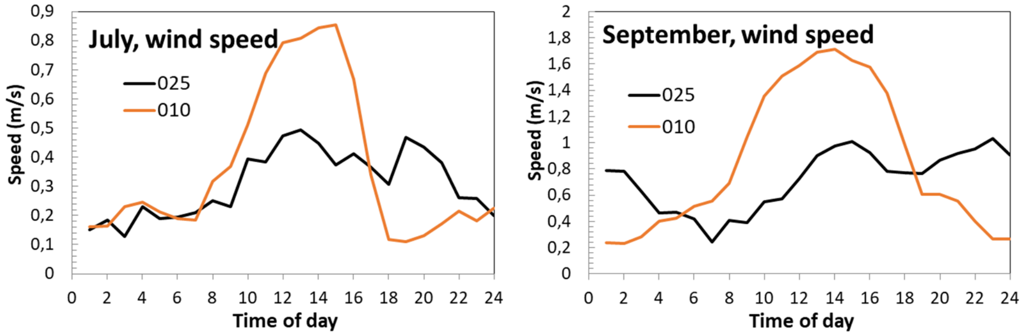

Figure 6. Wind speed profile for July and September for monitors 025 and 010.

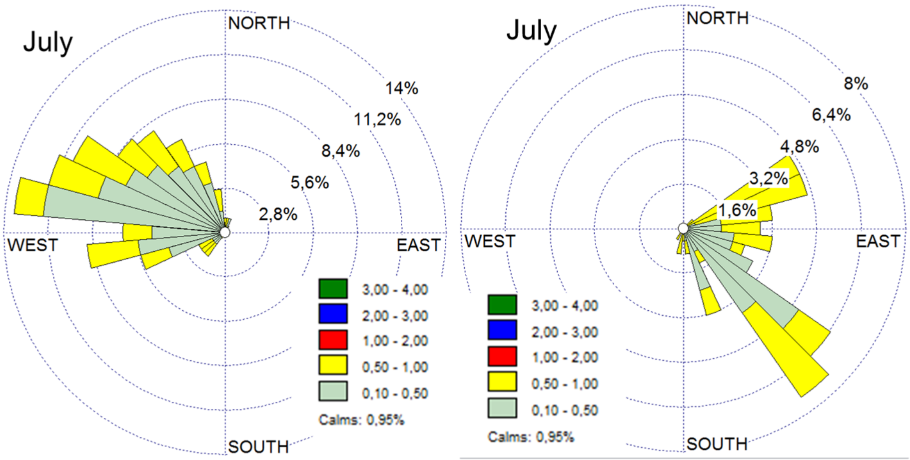

Figure 7. Wind rose for monitor 10 (left) and monitor 25 (right) for the month of July and hours 11 am to 5 pm.

The location of the houses with respect to the building, also affects the shadow that they receive. House 010 receives sun during the whole day in during the measurement period. House 025 receives sun light from the morning until 3 – 4 pm and only after 4:00 pm is under the shadow of the building. The calculated shadows for June 15th are indicated in Figure 1 for several hours of the day, for the other months, the calculation gives similar results. As a result of these shadow characteristics, the temperature difference between houses 010 and 025 is almost non-existent. The mean temperature that is shown in Figure 8 confirms that there is no difference between the houses. It has to be noted that after ~ 4 pm, house 025 starts receiving the shadow of the building, but it does not make house 025 to have lower temperature than house 010. This indicates the heating the sun has an effect on the house vicinity only when it is more intense. At later times the heating is lower and it is not enough to make a difference in the temperature.

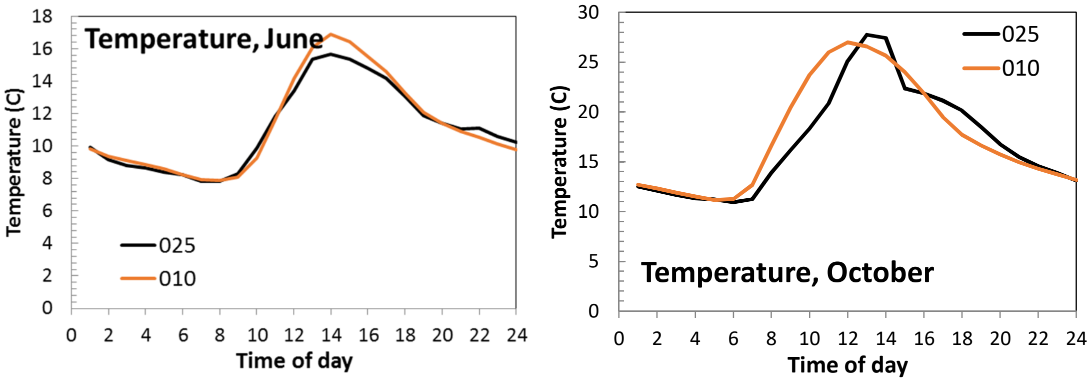

Figure 8. Mean diurnal variation of temperature for houses 005 (shadow) and 007 (sun) for the months of June and October.

The time series of the daily $PM_{2.5}$ average for the houses with monitors 010 and 025 is shown in Figure 4. Both curves are very similar because the sensors are only separated by 90 m, and most of the $PM_{2.5}$ is determined by the overall pollution in that sector of the city and not by local conditions. It can also be seen that there is a decrease in $PM_{2.5}$ during the months of September and October, which is related to improved ventilation conditions. The beginning of spring brings higher temperatures and faster wind speeds, which improves the vertical and horizontal dispersion of contaminants.

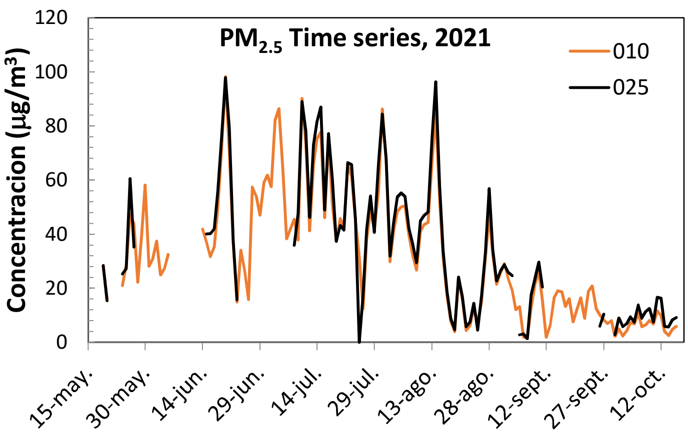

Figure 9. Time series of the $PM_{2.5}$ daily average for the three pairs of houses. The $PM_{2.5}$ for the house located in the shadow of the building is plotted with a black line and the house in the sun with an orange line.

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The diurnal variation of $PM_{2.5}$ is shown in Figure 10 for the monitors in houses 010 and 025 for two months, July (Winter) and September (Spring). The diurnal profile has some features that are similar to all houses. During the morning, approximately from 8:00 to 11:00 there is an increase in $PM_{2.5}$ which is related to low wind speeds and emissions from vehicles during the morning rush hour. This characteristic has been reported in many previous studies [28–30]. In the afternoon (12 pm–6 pm) there is a decrease in $PM_{2.5}$ because there is an increase in the wind speed that brings clean air coming from the west and disperses contaminants. There is also an increase in $PM_{2.5}$ during the evening, (~ 8 – 10 pm). In the colder months (May, June, July) the maximum in the evening is larger than in warmer months and shows the influence of the evening rush hour and the reduction of atmospheric turbulence [31] that reduces dispersion of pollutants. As shown in previous studies [28,29] the wind speed at night decreases to 0.5 – 1 m/s. In addition, during winter there are emissions from wood stoves used for space heating. All these factors lead to a well-known accumulation of pollution in this area of Santiago [28,32].

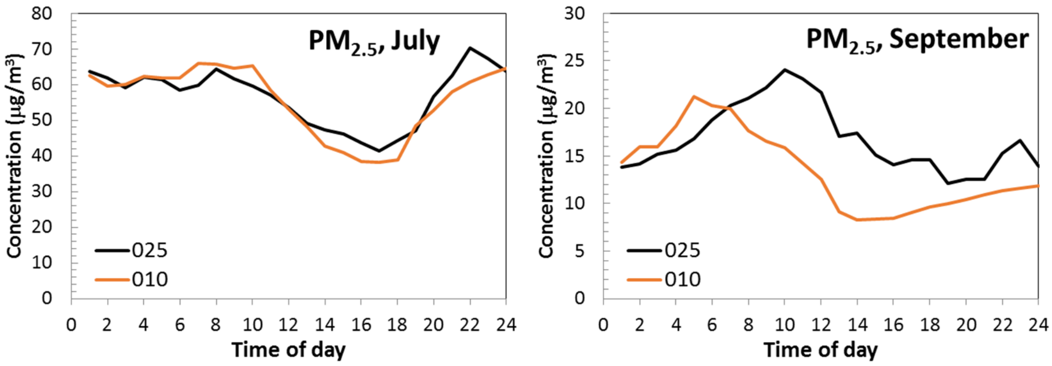

Figure 10. $PM_{2.5}$ mean diurnal variation for the pair of houses in the shadow (025) and sun (010).

The figure shows no difference in $PM_{2.5}$ for the month of July, which could be explained because the wind speed during this month is very low, with house 010 having slightly larger velocity during the afternoon, but not enough to make a difference in $PM_{2.5}$. In addition there is little difference in the shadow between both houses. However, Figure 10 also shows that in September, house 010 has lower $PM_{2.5}$ during most of the day, which is probably related to the location of the houses with respect to the building. In this month, the wind speed in both houses is almost twice as in July, but the wind in house 025 is still very low and the wind speed in house 010 is large enough to generate more dispersion of pollution than in house 025. Thus in this month, the difference in $PM_{2.5}$ is probably related to the difference in micrometeorological conditions generated by the building.

3.2. Monitors 005 and 007

Figure 11 shows the location of monitor 007 and monitor 005. The first is located in Benedicto XV Street which has little traffic and about 30 m west of a large building 94 m tall and an area of approximately 77 x 25 m^2. It has a minimarket on the north side and, across the street, warehouses dedicated to mechanical activities. As shown in Figure 1, monitor 7 is shadowed by the building during the morning, but from around 12:00 pm it only receives sun, Because is located at the base of the building, which acts as an obstruction, it may cause the causing wind to be deflected downward [6,27]; as a result the wind speed may increase in the afternoon with respect to the surroundings.

Figure 11. Location of houses 005 and 007 with respect to the building and predominant wind direction.

Monitor 005 is located on Embajador Quintana, which is also a secondary street with little traffic. The house where monitor is located is adjacent to a bakery, fifteen meters to the east; there is a metal mold manufacturer, and 15 meters to the west, a fast-food outlet. Additionally, 30 meters across the street, there is a grocery store. The equipment is located about 10 m south of the building, and is it always under its shadow. Because of the angle between the wind direction and the surface of the building, the airstream may get deflected towards the north and not towards monitor 005 and the wind velocity at this site may not increase. But the building will probably not affect the wind speed or direction in house 5 because the building is located at the side of the house.

The wind speed has been plotted for two months for monitors 005 and 007 in Figure 5. It can be seen that for these houses there is no difference in wind speed, indicating that the building has no effect on the speed in this case, because one house is located before the wind reaches the building and the other is located at the side of the building. For the other months, the profiles are similar.

The wind rose for the monitor in house 005 shown in Figure 13 confirms that the building has little influence on the direction of the wind, because the rose is similar to the rose in Parque O'Higgins, which is a site that has no obstacles around (see Figure 4). For house 007 the wind rose is slightly different than Parque O'Higgins, because it also has wind going towards the north. In this case, the building seems to have an effect on the direction because it deflects the wind towards the north. The arrow in Figure 11 shows an estimated diagram of the wind pattern.

For these two houses, the location of the building does have a clear effect on the shadow, because as shown in Figure 1, house 005 is always in the shadow, and house 007 receives direct sun light from about 11:00 am until the end of the day. The shadow has a direct effect on temperature, as shown in Figure 14.

Figure 14 clearly shows that the house located in the sun has higher temperatures only during the afternoon, i.e., when the solar radiation is more intense, and no difference is seen for other hours of the day. This is probably reason that no difference in temperature was observed between houses 010 and 025, because when the solar radiation was more intense, both houses were under the sun. And when only one house was in the shadow of the building, the sun was nor very intense. This is an indication that only when the solar radiation is intense, a difference in temperature is seen between the houses. The mean diurnal variation for relative humidity (not shown) has the opposite shape as the temperature, but it also has large differences between sun and shadow, with lower RH in the house that is facing the sun.

The diurnal variation of $PM_{2.5}$ is shown in Figure 15 for the monitors in houses 005 and 007 for two months, July (Winter) and September (Spring). The $PM_{2.5}$ profiles in Figure 15 show that in July, house 005 which is in the shadow has slightly higher $PM_{2.5}$ than house 007 that is located in the sun. During the early morning, the evening and at night there is no difference in $PM_{2.5}$ between the houses. As seen in Figure 12 in these pair of houses there is no difference in wind speed, so probably it does

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not play a role in the difference in $PM_{2.5}$. However, the temperature is higher in house 007 than in house 005 between 11 am and 6 pm, because house 007 receives more radiation. If the temperature is higher in one house than the other, vertical dispersion of the air is probably higher in the house that receives more sun, which can remove contaminants. So in this case, it seems that the shadow is the responsible for the higher $PM_{2.5}$ observed in house 005.

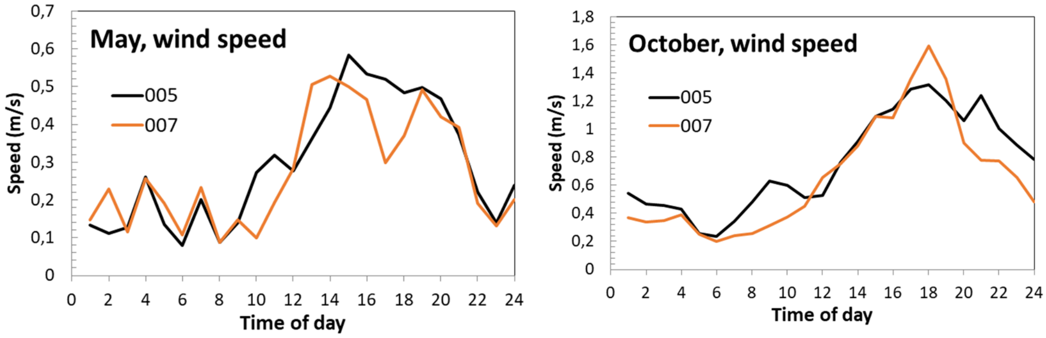

Figure 12. Mean wind speed for houses 005 and 007, for two months.

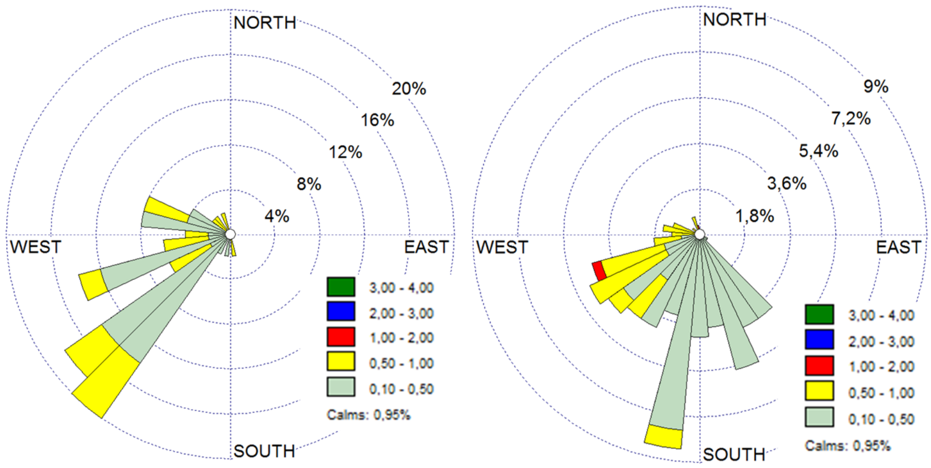

Figure 13. Wind rose for monitor 005 (left) and monitor 007 (right) for the month of May and hours 11 am to 5 pm.

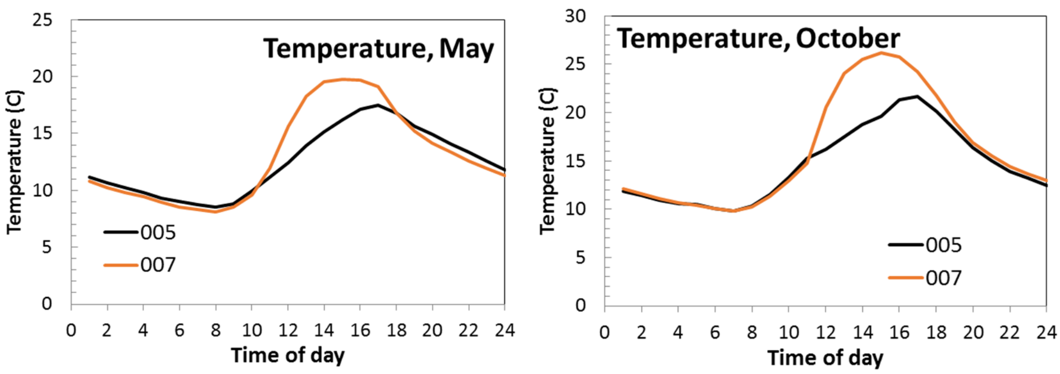

Figure 14. Mean diurnal variation of temperature in houses 005 (shadow) and 007 (sun). The other months have similar shapes.

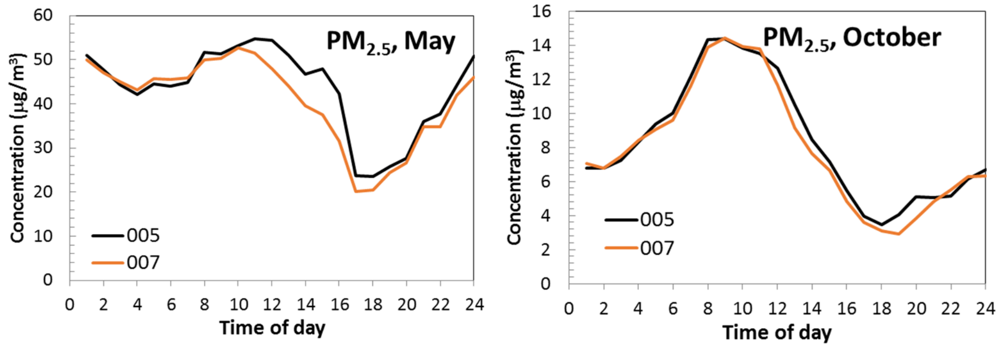

Figure 15. Mean diurnal variation of $PM_{2.5}$ for houses 005 (shadow) and 007 (sun) for the month of July (winter) and October (Spring).

In October, there is no difference in $PM_{2,5}$ between the houses. During this month, the mean temperature is also lower in house 005 than house 007, but both temperatures are significantly higher than the previous months. The wind speed is also higher for both houses, so it seems that these higher temperatures and higher wind speeds help dispersion of contaminants in both houses. Thus it seems that for the shadow (and temperature) to affect $PM_{2.5}$ in one house and not the other there has to be low wind speeds.

3.2. Monitors 022 and 026

As shown in Figure 16 monitors 022 and 026 are located in the same side of a street with low traffic (Placilla St.) in the south-east side of a building with a height of 47 m and an area of approximately 51 x 22 m2. North of monitor 022 there is a vacant lot designated for future construction. Thirty meters to the south, close to the location of monitor 026, there is a car repair company. In its surroundings, there are mostly residential houses. As shown in Figure 1, the house where monitor 022 is located receives shadow from the building during the afternoon, but sun during the morning. Monitor 026 also receives sun during the morning and shadow during the afternoon, but a little later than monitor 022 because it is located further south away from the shadow. As shown in Figure 16, both monitors are located in houses with similar micrometeorology and shadow characteristics. Considering the predominant wind direction, the building probably slightly blocks the wind from reaching monitor 022, but not monitor 026. In this pair of houses wind speed or direction were not measured.

Figure 16. Location of houses 022 and 026 with respect to the building and predominant wind direction.

For houses 022 and 026, a clear influence of the shadow on the temperature is not easily observed. For the months of July and October, house 022 which is located on the side of the building, only receives the shadow after 2 – 3 pm. House 026 is located further south from the building and also receives shadow after 2 – 3 pm on July, but in October, this house does not receive the shadow because it is too short. The temperature data shown in Figure 17 indicates that in October it increases in house 022 after ~ 10 am and decreases rapidly after 2 pm when it starts to receive shadow. Also, in October, at 2 pm, house 026, which was in the shadow, starts receiving sunlight and its temperature increases above that of the house 022, indicating that when the solar radiation is high the temperature raises very quickly.

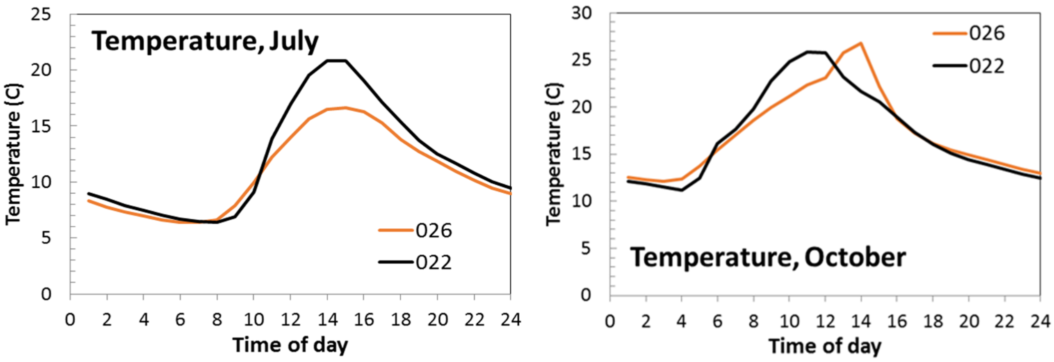

Figure 17. Mean diurnal variation of temperature for houses 026 (sun) and 022 (shadow) for the months of September and October.

For the pair of houses 026 / 022, there is no difference in the mean $PM_{2.5}$ for any month, as can be seen in Figure 18. However, the location of the houses is such that during July, both houses are under the sun until 2 pm. At 3 pm both houses are under the shadow of the building and after 4:30 pm house is 022 is situated in the shadow and house 026 in the sun. Thus there is a period of only 2 – 3 hours when one house is in the shadow and the other in the sun. For the other months, the situation is similar, and only after 4:00 pm house 22 is in the shadow and house 26 in the sun. In October, house 022 is in the shadow and house 26 in the sun after 3:00 pm and 2:00 pm respectively. Assuming that the wind approaching the building, has the same direction as Parque O'Higgins (Figure 4) then, between 12 and 6 pm, the wind has south-west direction and the building does not obstruct the air circulation during the afternoon, so probably the influence of the wind on $PM_{2.5}$ is the same for both houses. For these pair of houses the micrometeorological conditions are similar and no difference in $PM_{2.5}$ can be seen between them.

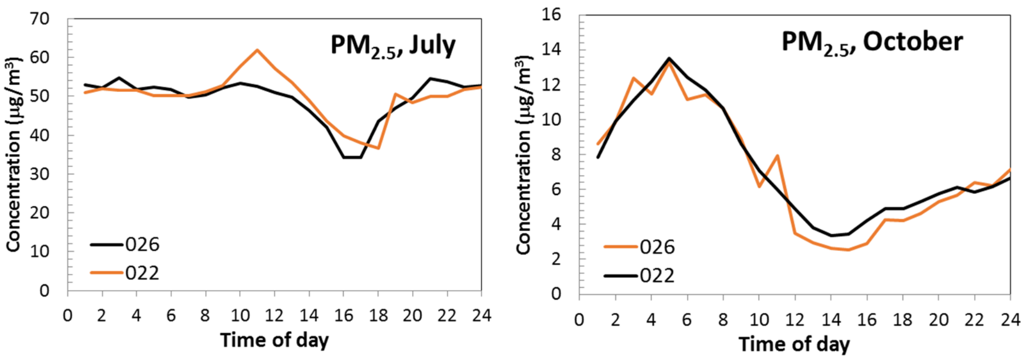

Figure 18. Mean diurnal variation of PM2.5 for houses 022 and 026 for the month of July (winter) and October (September).

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4. Discussion

In order to assess the statistical significance of the difference in $PM_{2.5}$ between the houses, a t-Student analysis was performed for each pair of houses. Because the influence of the shadow, temperature and wind speed could only be seen during daytime hours, the t-Student test was applied to the average $PM_{2.5}$ between the hours of 11:00 am to 5:00 pm and the results are shown in Table 1. In the second line of the table, the number in the left indicates the house in the shadow and the number in the right the house in the sun. The calculation was done with ProUCL statistical analysis software which is provided by the EPA for use with ambient data (EPA2024). For each month, all hours between 11:00 am to 5:00 pm were used to perform the analysis. The p value of the t-Student calculation is shown in Table 1 for each pair of houses. "=" means that there is no statistical difference in the means with a 90% confidence, ">" indicates that the $PM_{2.5}$ mean for the house in the shadow is larger than the mean for the house in the sun. Table 2. shows the mean temperature and wind speed for the pair of houses and the calculation using the t-Student analysis.

Table 1. t-Student assessment of PM2.5 mean from the house in the sun versus the house in the shadow, between the hours of 12 pm to 6 pm. The number in the left indicates the house in the shadow and the number in the right the house in the sun. ">" indicates the average for the house in the shadow is greater that the house in the sun. "=" means the averages are equal.

$PM_{2.5}$	**p-value for the houses indicated below**		
Houses	**005 / 007**	**022 / 026**	**025 / 010**
May	0.044 (>)		
June	0.002 (>)		0.963 (=)
July	0.007 (>)	0.817 (=)	0.049 (>)
August	0.032 (>)	0.105 (=)	0.102 (=)
September	0.627 (=)	0.998 (=)	0.001 (>)
October	0.19 (=)	0.990 (=)	0.001(>)

Table 2. Mean temperatures and mean wind speed from the house in the sun versus the house in the shadow only between 11 am to 5 pm. Using t-Student calculation, ">" (<) indicates the average for the house in the shadow is greater (lower) that the house in the sun. "=" means the averages are equal.

	Mean temperatures for the pair of houses (ºC)		
Houses	**005 / 007**	**022 / 026**	**025 / 010**
May	14.7 (<) 17.7		
June	12.6 (<) 16.1		14.4 (=) 15.0
July	13.6 (<) 17.1	18.3 (>) 15.2	16.7 (<) 17.7
August	13.2 (<) 17.9	17.7 (>) 15.8	17.1 (=) 17.7
September	17.5 (<) 21.3	20.8 (=) 20.3	19.6 (<) 21.2
October	18.6 (<) 23.0	21.9 (=) 22.3	23.8 (=) 24.3
		Mean wind speed (m/s)	
Houses	**005 / 007**		**025 / 010**
May	0.434 (=) 0.396		
June	0.428 (=) 0.443		0.473 (=) 0.670
July	0.500 (=) 0.518		0.421 (<) 0.713
August	0.610 (=) 0.708		0.705 (<) 0.923
September	0.835 (=) 0.805		0.840 (<) 1.582

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October	0.890 (=) 0.895	0.882 (<) 1.318

Table 1 shows that for the pair of houses 005/007, the average $PM_{2.5}$ for the house in the shadow (005) is greater than $PM_{2.5}$ for the house in the sun (007) for the months of May through August. During the same months, the average temperature in the afternoon hours(Table 2) is lower for house 005 than 007 and the mean wind speed is similar for the same months. Thus, for these months, the larger $PM_{2.5}$ in house 005 than in house 007 is most likely due to lower temperatures during the afternoon that prevent vertical dispersion of contaminants. The shadow in house 005 started approximately at 10 am until 3 pm in May and June. During July, the shadow was approximately from 11 am until 3 pm. In August it started at 11 am until 2 pm. In September and October there was shadow from approximately 12 pm until 2 pm. For September and October, the mean temperature is also lower in house 005 than house 007, but both temperatures are significantly higher than the previous months(Table 2). Thus, $PM_{2.5}$ was similar because the higher temperatures generated the same dispersion of contaminants in both houses.

For the pair of houses 026 / 022, the t-Student analysis indicates that there is no difference in the mean $PM_{2.5}$ for any month. In this case, the location of the houses is such that during July, both houses are under the sun until 2 pm. At 3 pm both houses are under the shadow of the building and after 4:30 pm house is 022 is in the shadow and house 026 in the sun. Thus there is a period of only 2 – 3 hours when one house is in the shadow and the other in the sun, which is not enough to make a difference in $PM_{2.5}$. For August, the situation is similar, and only after 4:00 pm house 22 is in the shadow and house 26 in the sun. In September and October, the situation is similar, with house 022 being in the shadow and house 026 in the sun after 3:00 pm and 2:00 pm respectively.

For the pair of houses 025 / 010, $PM_{2.5}$ is higher for July, September and October. For these pair of houses, it seems that the reason for the higher PM2.5 is the difference in wind speed, not shadow or temperature. For these months, the wind speed is higher in house 025 as shown in Table 2. At house 025, the building acts as a windbreak. This lack of ventilation prevents PM2.5 from dispersing, resulting in higher concentration levels. The temperatures in house 025 are also lower than in house 010 for all months, which also can contribute to less vertical dispersion in house 025, with the consequent rise in $PM_{2.5}$.

The previous results show that $PM_{2.5}$ is very sensitive to the location and influence of micrometeorological parameters, such as wind speed, temperature and shadow. In the pair of houses 005 and 007, PM2.5 was higher in house 005 the shadow resulted in lower temperature which prevented vertical dispersion of contaminants. In the pair of houses 010 and 025, PM2.5 was higher in house 025 because the wind speed was lower, preventing horizontal dispersion of contaminants. In houses 022 and 026, there was no difference in PM2.5, the probably because the micrometeorological parameters were not different enough to make a difference.

5. Conclusions

A large variability was observed in the $PM_{2.5}$ measured in the pairs of houses adjacent to large buildings, depending on the specific location and micrometeorological conditions. A clear difference in $PM_{2.5}$ between the houses was found only between the hours of 11 am to 5 pm, which was the period when sun radiation and wind speed was higher. The difference in the concentrations was found to be related to the difference in temperature conditions between the houses or the difference in wind speed between the houses. In one pair of homes, $PM_{2.5}$ was larger in the house located under the shadow of the building during the winter months, this result was attributed to the lower temperature generated by the shadow, because the wind speed was similar in both houses. In another pair of houses, the $PM_{2.5}$ was larger in the house under the shadow for 3 out of 5 months, but in this case, the result is attributed to the difference in wind speed and temperature in one of the houses. In the third pair of houses the wind speed was the same for both of them, but no difference was observed in PM2.5, probably because the house was under the shadow for only a few hours each day. Even between houses in close proximity, the data show sharp differences in micrometeorological parameters, highlighting the impact of hyper-local conditions.

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