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Urban vegetation and particle air pollution: Experimental campaigns in a traffic hotspot☆

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ABSTRACT

This work presents the main results of two experimental campaigns carried out in summer and winter seasons in a complex pollution hotspot near a large park, *El Retiro*, in Madrid (Spain). These campaigns were aimed at understanding the microscale spatio-temporal variation of ambient concentration levels in areas with high pollution values to obtain data to validate models on the effect of urban trees on particulate matter concentrations.

Two different measuring approaches have been used. The first one was static, with instruments continuously characterizing the meteorological variables and the particulate matter concentration outside and inside the park. During the summer campaign, the particulate matter concentration was clearly influenced by a Saharan dust outbreak during the period 23 June to 10 July 2016, when most of the particulate matter was in the fraction $PM_{2.5\text{-}10}$. During the winter campaign, the mass concentrations were related to the meteorological conditions and the high atmospheric stability.

The second approach was a dynamic case with mobile measurements by portable instruments. During the summer campaign, a DustTrak instrument was used to measure PM_{10} and $PM_{2.5}$ in different transects close to and inside the park at different distances from the traffic lane. It was observed a decrease in the concentrations up to 25% at 20 m and 50% at 200 m. High PM_{10} values were linked to dust resuspension caused by recreational activities and to a Saharan dust outbreak. The highest PM values were measured at the *Independencia* square, an area with many bus stops and high traffic density. During the winter campaign, three microaethalometers were used for Black Carbon measurement. Both pollutants also showed a reduction in their concentrations when moving towards inside the park. For PM_{10} and $PM_{2.5}$, reductions up to 50% were observed, while for BC this reduction was smaller, about 20%.

1. Introduction

Air pollution is estimated to be the cause of 400 000 deaths per year in the EU (WHO, 2018) and citizens living in urban areas are particularly vulnerable to this threat, due to the high concentration of population and their proximity to numerous emission sources. Within cities, areas with higher air pollutant concentrations than those in the surrounding areas are known in air quality terms as “hotspots”. These places are usually characterized by large spatial and temporal concentration gradients and people working or living in these areas have the possibility of being exposed to elevated levels. Therefore, it is important to understand this spatial and temporal distribution of airborne pollutants in urban hotspots for a risk assessment study taking into account actual and representative air pollution levels and exposure.

Ozone and particles, especially those below 2.5 μm, are

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considered to be the most threatening air pollutants for human health. Pascal et al. (2013) found that complying with the WHO guideline of 10 $\mu g/m^3$ in annual mean for $PM_{2.5}$ (particle matter with aerodynamic diameter < 2.5 μm) would add up to 22 months of life expectancy, corresponding to a total of 19,000 deaths delayed in 25 European cities. Nature-based solutions are becoming increasingly important for human societies facing the broad range of challenges in urban areas. Green infrastructures provide essential ecosystem services that can be vital for city sustainability. A number of studies have explored the link between urban vegetation and their positive effects on air pollution as one of the most relevant ecosystem service (Pearlmutter et al., 2017). Beckett et al. (1998) provide an interesting revision of woodlands role in reducing the effects of PM_{10} (particle matter with aerodynamic diameter < 10 μm) pollution. For instance, they established that already in Manning and Feder (1980) forest canopies were more effective at capturing particles than any other vegetation type, due to their much greater surface roughness that increases turbulent deposition and dry deposition processes by causing localized increases in wind speed. In some experiments in windtunnels, Beckett et al. (2000) confirmed that the particle removal efficiency is related with the particle Stokes number, the particle inertia, so more complex structures of canopies can remove more pollution. In urban parks, Silli et al. (2015) found similar results, higher removal for PM_{10} than for $PM_{2.5}$. The vegetation cover effect on the particles has been modelled by several authors in more recent studies. McDonald et al. (2007) modelled the effect of urban tree planting on concentrations and depositions of PM_{10} and predicted that increasing total tree cover in West Midlands (UK) from 3.7% to 16.5% would remove an additional amount of 110 ton per year of primary PM_{10} from the atmosphere. Tallis et al. (2011) estimated the removal of atmospheric particulate pollution by the urban tree canopy of London between 852 and 2121 tons of PM_{10} annually; representing between 0.7% and 1.4% of the suspended PM_{10} from the urban boundary layer. Fares et al. (2016) studied the reductions in PM_1 (particle matter with aerodynamic diameter < 1 μm) in a Mediterranean area, Rome, with vegetation similar to Madrid. This study was later enlarged to the Latium region by using image mapping to estimate the ecosystem services to obtain the Leaf Area Index, modelling the PM_{10} and ozone concentrations. No differences were observed between the air pollutant removal in the urban center and in the region (Fusaro et al., 2017). For gaseous pollutants, Alonso et al. (2011) demonstrated the effect of a periurban forest as a significant O_3 sink for the Madrid city and Santiago et al. (2017) for NO_2. Yli-Pelkonen et al. (2017) also found that concentrations of O_3 were significantly lower in tree-covered habitats than in adjacent open habitats, but concentrations of NO_2 did not differ significantly between tree-covered and open habitats. A review of the O_3 removal by trees can be found in Sicard et al. (2018). Although this is not an exhaustive review of the studies on the influence of the vegetation cover on the atmospheric pollutants, these references provide an indication of the experimental work on this subject and its link with modelling aspects. However, the number of direct empirical studies is limited, fewer than modelling studies. Pearlmutter et al. (2017) compiles an updated review of ecosystem services provided by urban forests as green infrastructures. Nevertheless, unlike other types of infrastructures, these are more dynamic, more heterogeneous, and often more fragile – because they are alive, and because of their complexity, their effect can be extremely variable depending on the species used in urban forests. A review on urban vegetation and air pollution by Janhäll (2015) concludes that although some studies publish limited datasets to validate models, extensive experimental datasets, including a thorough description of the vegetation inside urban areas, are needed to improve existing models.

The TECNAIRE-CM (Innovative technologies for the assessment and improvement of urban air quality) research project is aimed at providing new methods for monitoring and modelling air pollution that can consistently describe urban pollution dynamics from continental to street scale in Madrid (Spain), a city seriously affected by pollution problems with PM_{10} annual average values of 38 $\mu g/m^3$ and $PM_{2.5}$ annual average values of 20 $\mu g/m^3$ (Casquero-Vera et al., 2019; Kassomenos et al., 2012; Ayuntamiento de Madrid, 2016). In the framework of this project, several activities have been performed, including an analysis of the application of the short term air quality action plan of the city council (Borge et al., 2018). Also the development of intensive experimental campaigns has been carried out in two different hotspots for a better understanding of urban pollution and its sources. The first case study focused on *Plaza de Fernández Ladreda*, whose results can be found in Borge et al. (2016). The second location, the *Escuelas Aguirre* area, is a complex urban environment where some of the main streets in Madrid converge in the vicinity of a large park (*El Retiro*), with a clear influence of road traffic (Santiago et al., 2017).

This paper assesses the impact of an urban park on a heavily trafficked area in Madrid, for one of the main urban pollutants, particulate matter, by measuring two parameters: particle mass concentration (PM_{10}, $PM_{2.5}$ and PM_1) and Black Carbon (BC). This last component (BC) is directly related to traffic emissions and not affected by other particulate sources as dust outbreaks and soil resuspension. This work is based on experimental data from two field campaigns performed in summer 2016 and winter 2017. The data obtained in these campaigns will be used to validate models on the effect of urban trees on particulate matter concentrations, in a similar way as in Santiago et al. (2017) for the NO_2 case.

2. Material and methods

2.1. Study area description

The Madrid metropolitan area is located in the center of the Iberian Peninsula and has more than 5.5 million inhabitants, while the city is limited to 3.2 million (2017). The region comprises a car fleet of 4.5 million vehicles, a high percent of which are diesel powered, accounting for 70.6% of total mileage within the city (Ayuntamiento de Madrid, 2018). Since the industry installed in the region consists essentially of light factories, the Madrid plume is typically urban, fed by traffic emissions and also by heating systems in winter. The climate in Madrid is typical of a mid-latitude continental area, with hot dry summers and cold winters, most days being under stability and clear-sky conditions.

The experimental campaigns have been performed in an urban area in downtown Madrid that includes El Retiro Park, one of the largest and most popular parks in the city, a main landmark in the city that is frequented by many people to work out and for other leisure activities. It has 125 ha where more than 19 000 trees grow. More than 6500 trees are horse chestnut trees, representing 34.5% of the total forest mass. In a lower quantity, it is possible to find plane trees (5%), Judas trees (4.1%) and the windmill palm (3.4%). There are also abundant field maples, Atlas cedars, Mediterranean cypresses, European nettle trees, honey locusts, holm oaks, stone pines, privets, almonds and some others, being more than 300 trees for each type. Most of the paths inside the park are unpaved so dust resuspension is common, especially during small van transects and some recreational activities like running. Differences were observed when there was a pedestrian, a runner and a group of runners, from light to intense dust resuspension. Traffic is not allowed to general public inside the park although maintenance vehicles circulate occasionally and cycling and skating are common activities.

In the study area, there are several main streets and avenues around Retiro Park with intense road traffic and one of the main squares in the city, *Independencia* Square (Fig. 1). An air quality monitoring station (*Escuelas Aguirre*, EA) belonging to the municipal network is located in a small garden close to the intersection of the two most important avenues in the area (*Alcalá* and *O'Donnell* Streets). In this station, there were 15 daily exceedances for PM_{10} limit value (50 $\mu g\ m^{-3}$ not to be exceed >35 times a year) in 2015 and recorded some of the highest annual averages (22, 24 and 25 $\mu g\ m^{-3}$) and maximum daily values (68, 97 and 71 $\mu g\ m^{-3}$) in Madrid, for the years 2013–2015 (Ayuntamiento de Madrid, 2016), after discarding those attributed to the natural sources like African dust outbreaks by a contrasted methodology (Escudero et al., 2007), according to the EU Directive.

2.2. Periods of campaign and instrumentation

The first campaign (summer) was carried out in summer from 15 June to 15 July 2016, when the temperatures were high, with no rain, and a well developed mixing layer during daytime. The second one (winter) took place from 25 February to 20 March 2017, with colder temperatures, clear skies most of the time and a shallower mixing layer. Besides meteorological conditions, the vegetation and pollutant characteristics were also rather different in both campaigns, giving a wide range of scenarios to be studied.

The atmospheric particle mass concentrations for the size fractions PM_{10}, $PM_{2.5}$ and PM_1 were measured in diverse locations in the study area. Several instruments were deployed to reach this goal (Fig. 1). An Optical Particle Counter Grimm 1107 instrument (Grimm and Eatough, 2009; Marcq et al., 2010), G1, was installed inside the park, 30 m South of the park fence and at the roof of a 3 m high building. A second Grimm 365, G2, was located close to the municipal monitoring station located in *Escuelas Aguirre* outside the park and 2 m high. Both instruments measured the particle mass concentrations in the three size ranges simultaneously throughout the campaign.

Additionally to the fixed monitoring instruments, some dynamic measurements were also performed in the area. A TSI DustTrak DRX instrument (Tasić et al., 2012; Rivas et al., 2017; Viana et al., 2015; Fares et al., 2016) was used to measure particulate matter (PM_{10} and $PM_{2.5}$) concentration levels. This was achieved by measuring at several points around the experimental area and by walking with the instrument around this area at a mean adult height respiration level. These transects were done during both campaigns and took between 15 and 30 min, depending on the selected transect, and covered 1 km and 2 km length respectively. Because the area is large, the transects have been divided in four: two longitudinal ones along the *Alcalá* Street (the first transect is from *Independencia* Square to *El Retiro* underground station and the second case from this last point to *Menéndez Pelayo* Avenue, both are shown in section 3.1.3), a perpendicular transect to *Alcalá* Street and inside the *El Retiro* Park (not discussed and shown in this paper). Several paths inside the park, mainly parallel to *Alcalá* street were covered to understand concentration changes depending on the distance to *Alcalá* street: in the street itself, 20 and 200 m away from it. Some other short transects and measurements at singular points like a bus stop in *Independencia* square have also been performed. The bus stop selected was one located in the Southwestern sector of the *Independencia* square (shown in Fig. 1), a heavily trafficked roundabout with very frequent bus transit (one bus every two minutes on average during the measurements). In total 13 transects during 6 different days were made, covering both weekdays and weekends, as well as 3 measurement series in the bus stop during 3 days. The data collection frequency was 6 s and the data obtained for every transect were averaged to represent that transect. Among all these transects, the most interesting cases have been selected and discussed in the following sections.

Prior to the campaigns, the optical instruments and the DustTrak were compared to a High Volume Samplers (HVS) and the correction factors obtained were used to correct the raw measurements. The comparison between HVS and the optical instruments showed good correlations. The main results can be found in the supplementary material. The TSI DustTrak DRX instrument was used in both campaigns: summer and winter.

Black Carbon (BC) measurements were also obtained in a dynamic measurement pattern only during the winter campaign with three microaethalometers (microAeth® model AE51, Aethlabs; Cai et al., 2014; Viana et al., 2015) at $\lambda = 880$ nm and a cut-off size of 2.5 μm. The flow rate was 0.1 $L\ min^{-1}$ and the sampling time 60 s. Prior to the campaigns, these microaethalometers were compared to a multi-wavelength aethalometer (Magee Sci. mod. AE33, Aerosol d.o.o) ($\lambda = 370$, 470, 520, 590, 660, 880, and 950 nm) with a

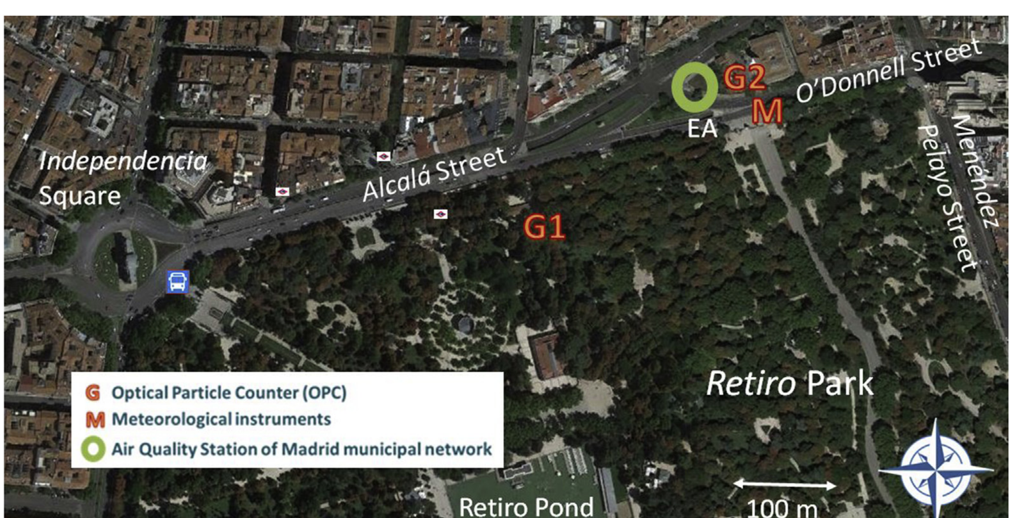

Fig. 1. Study area. It includes the locations of Grimm instruments (G1 inside the park and G2 in *Escuelas Aguirre*), the bus stop (in blue), the local meteorological station (M) and an air quality station (green circle). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

cut-off size of 10 μm and a flow rate of 5 L min^{-1} obtaining good correlations (R^2 around 0.75) and a correction factor for every microaethalometer (slopes between 1.17 and 1.24) that has been applied to all the raw data. The main results concerning this correction can be found in the supplementary material, Fig. S2. Although both instruments have different cut-off sizes, as the BC is usually found in the finer fraction of particles, no differences should be observed because of this reason.

These aethalometers allowed a different approach during four days to the dynamic measurements performed in the summer campaign. For two days, aethalometers were installed in three different points parallel or perpendicular to the *Alcalá* Street. These points were moved progressively after a sampling period towards inside the park. While these sensors remained in their positions, the DustTrak was moving in a similar way as in the summer campaign performing different transects. A third day was dedicated to the *Independencia* Square at the bus stop location, and a fourth day was spent in some of the streets in the Northern side out the park. As BC is directly related to traffic emissions, these particles can show the role of green areas in mitigating these emissions.

A meteorological station was also installed at the experimental area to fully characterize the local meteorological conditions (Fig. 1). It was composed of three instruments: Vaisala Weather Transmitter, thermohygrometer and pyranometer. Firstly, a *Vaisala Weather Transmitter WXT520* provided six weather parameters: wind speed, wind direction, precipitation, atmospheric pressure, air temperature and relative humidity. Besides, a pyranometer (*Apogee SP-100*) recorded the downward short wave radiation (direct and diffuse radiation) and a thermohygrometer (*Rotronic HC2-S3*) completed this set of measurements with additional temperature and relative humidity data. Turbulent parameters were evaluated from a *Young 8100* sonic anemometer data, which corresponded to the three wind components (u,v,w), and estimated air temperature from the air density. This instrument worked at a high sampling frequency (20 Hz) in order to obtain a really good temporal resolution. The typical climatological variables (1981–2010) in the area for the summer campaign period are 23.9 °C, 16 mm of rain, 41% relative humidity, 2 days with precipitations above 1 mm. For the winter campaign, these variables are: 11.2 °C, 25 mm of rain, 55% relative humidity, 4.1 days with rains above 1 mm (AEMET, 2018).

Long range transport processes of dust laden African air masses affected all the observed PM concentrations during both campaigns. These phenomena have been documented by a robust methodology (Escudero et al., 2007; Viana et al., 2010) and their impact on the Madrid area is well documented (MAPAMA, 2017).

3. Results and discussion

3.1. Results and discussion for summer campaign

3.1.1. Meteorological conditions

Figure S3 shows both the local measurements and the regional situation in the Madrid area. The results obtained in both stations were similar, except for the wind speeds and directions. This campaign took place during a warm period, warmer than usual, coinciding with air masses coming from North Africa and with maximum temperatures up to 35 °C, and with an average relative humidity around 35% and minima of 20% in the local measurement site. Such dry and hot weather provides favorable conditions for soil particle resuspension. The regional wind speed was moderate, with an average value of 3.7 ms^{-1} and without long calm periods (wind speed below 2 ms^{-1} in the regional measurements) during the campaign. Most of the days, it was possible to reach values of 4 ms^{-1} during several hours with peaks close to 10 ms^{-1} around the 26th. No significant rain occurred during the whole campaign.

3.1.2. PM ambient concentrations

It is clear that the highest PM_{10} concentrations, see Table 1, were measured inside the park. This was caused by the resuspension of the particles from the soil as it is unpaved and mainly in the coarse fraction $PM_{2.5\text{-}10}$. Several activities, like sports, and the wind effect produced this resuspension. $PM_{2.5}$ and PM_1 were less affected by resuspension and the concentrations were similar in both sites. The particulate matter concentration measured was significantly related to the Saharan dust outbreak that occurred over the period 23 June to 10 July, as shown in Fig. 2. This can be observed given that most of the particulate matter (75% for G1 and 50% for G2 averaged during the period 23 June to 5 July) was in the coarse fraction $PM_{2.5\text{-}10}$. The number of daily and hourly exceedances in both Grimm instruments can be found in Table S1. The PM_{10} series in both instruments started to increase their values before the African air masses arrived at the site because of unknown reasons, while both, the $PM_{2.5}$ and PM_1 started to be affected at the approximate time that the air masses arrived according to the models (MAPAMA, 2017). The highest impact is observed in the PM_{10} fraction indicating that the Saharan particles are mostly included in the size range between 2.5 and 10 μm, although they are also measured in PM_1. Another interesting aspect is that during the Saharan dust period, the lowest concentrations, measured by *El Retiro* Grimm during nighttime were high, reaching hourly values above 25 μg m^{-3} several nights with a maximum concentration of 50 μg m^{-3}, being mainly affected by this dust and very little by local emissions. The influence of Saharan dust outbreak was confirmed by the measurements from the DustTrak instrument as it will be discussed in the next section. At the end of this period, it was a cleaning up of the lower troposphere by ventilation caused by stronger winds that reduced surface concentrations for all the size fractions.

The Saharan dust outbreak hampered the influence of other different sources. Only in the case of *El Retiro* Grimm, dust resuspension caused by human activities like gardening or running had a significant impact on observed PM_{10} values. As these activities are not continuous, they are detected by a noisier series for both instruments: Grimm and DustTrak.

3.1.3. Dynamic measurements of particulate matter

A DustTrak was used during walking transects in the area, see Fig. 3.

Some results regarding PM_{10} for the two longitudinal transects during 21 and 24 June are shown in Fig. 3 (a) and (b), respectively and some statistical analyses can be found in the supplementary material, Tables S2 and S3 and Figs. S4 and S5. The PM_{10} concentrations were high according with the values obtained by the Grimm instruments those days. The 21 June was previous to the Saharan dust event, but during the 24 June high dust concentrations due to the Saharan outbreak were already detected. The 21 June, the DustTrak data showed that the highest values were measured at the *Independencia* Square (left in Fig. 3a), a heavily trafficked area, with high intensity of (mostly diesel) buses. The measurements taken at the bus stop selected for the study in this square revealed high PM_{10} values when the diesel buses stopped and lower for Compressed Natural Gas (CNG) buses. The high values obtained in the opposite side of the square (marked A in the figure) can be explained by the formation of a vortex because of the wind direction and the presence of buildings. This vortex drags the particles emitted in the bus stop area to the other side of the square. The *Alcalá* Street side closer to *El Retiro* showed lower values pointing to an influence of the vegetation in the particulate matter levels inside the park.

Table 1
Average concentrations, standard deviation (SD), maximum and minimum particulate matter concentrations in the fractions PM_{10}, $PM_{2.5}$ and PM_1 during the summer campaign period in both sites.

		Average values	SD	Maximum	Minimum
El Retiro Grimm (G1)	PM_{10} ($\mu g\ m^{-3}$)	79.3	71.5	564.9	9.3
	$PM_{2.5}$ ($\mu g\ m^{-3}$)	15.4	6.4	53.9	5.8
	PM_1 ($\mu g\ m^{-3}$)	9.6	4.0	25.1	2.5
Escuelas Aguirre Grimm (G2)	PM_{10} ($\mu g\ m^{-3}$)	27.9	20.5	264.5	6.2
	$PM_{2.5}$ ($\mu g\ m^{-3}$)	13.2	6.6	48.6	3.1
	PM_1 ($\mu g\ m^{-3}$)	7.2	2.9	19.7	1.9

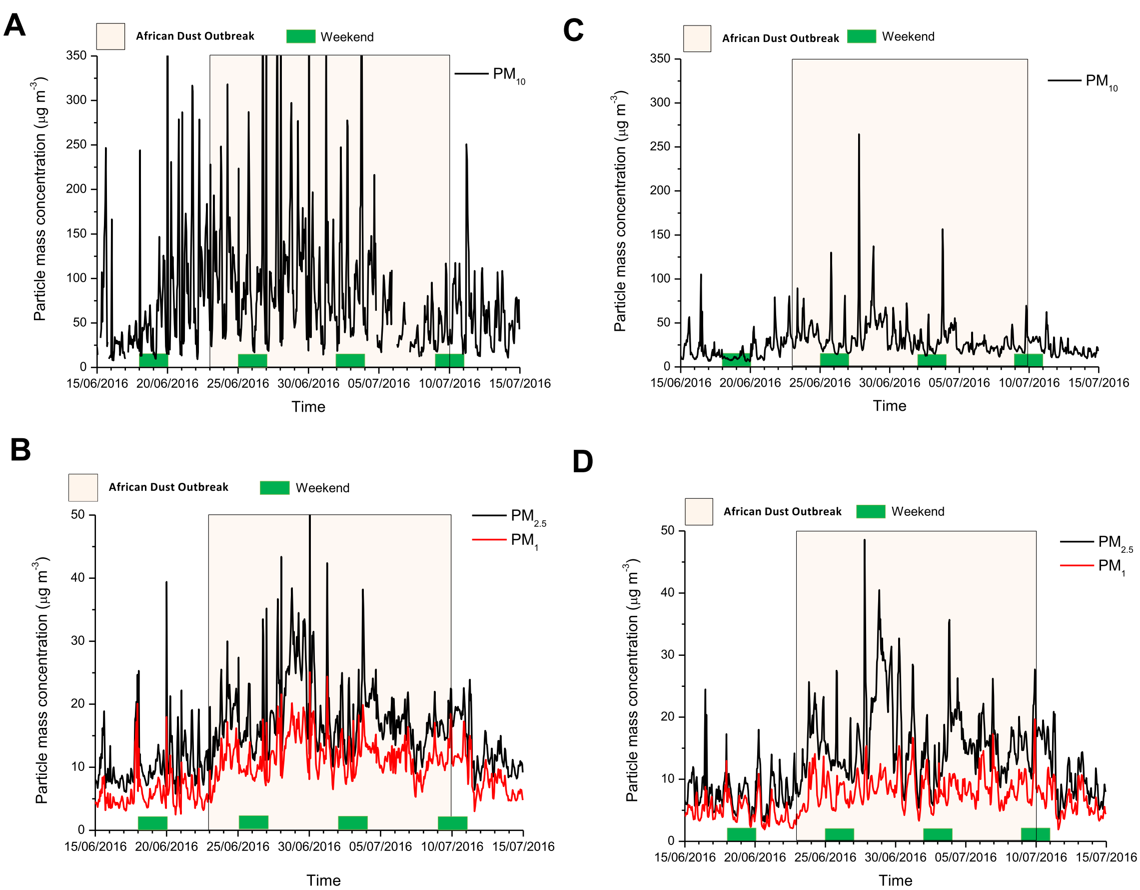

Fig. 2. PM_{10}, $PM_{2.5}$ and PM_1 concentration measured in (a–b) *El Retiro* and (c–d) *Escuelas Aguirre* sites measured by the two Grimm instruments during the summer campaign. The period with Saharan dust outbreak is marked.

This result contrasts with the results for the 24 June, when higher concentrations were measured inside the park (marked B) than outside (marked C) (except a point affected by some works on the pavement). This could be also caused by the formation of a vortex as during the 21 June. In this case the wind direction is the opposite transporting the particles from the street to the park.

Some additional measurements were carried out the 1st of July to clarify this point, following transects parallel to the *Alcalá* Street at different distances from it. The results obtained can be observed in Fig. 4 for (a) PM_{10} and (b) $PM_{2.5}$, and some statistical analyses can be found in the supplementary material, Table S4 and Fig. S6. Both results are similar, with the maximum values along the *Alcalá* Street sidewalk which decrease as we moved away from this and inside the park. In the street sidewalk, the PM_{10} average concentrations for some transect fractions were higher than 100 $\mu g\ m^{-3}$, and they decreased down to around 85 $\mu g\ m^{-3}$ in the first park path, around 20 m inside. These PM_{10} values decreased much more at 200 m down to even 50 $\mu g\ m^{-3}$. The highest concentration at this distance was observed in the area between the main gate (*Independencia* square) and the pond, where more pedestrians and runners were found, together with a dry sand soil. $PM_{2.5}$ measurements (Fig. 4b) showed a similar behavior, with the maximum values found in the points close to the traffic lane of the street (around 45 $\mu g\ m^{-3}$) and in the area with higher pedestrian activity. These concentrations decreased as the sampling location was moved away from the traffic lanes, being 30 $\mu g\ m^{-3}$ at 20 m and 20 $\mu g\ m^{-3}$ at 200 m. This meant that the urban plant cover together with the distance can produce a reduction in the particle concentration around 50% under the meteorological situation corresponding to these measurements.

3.2. Results and discussion for winter campaign

During the winter campaign, the plant cover density was

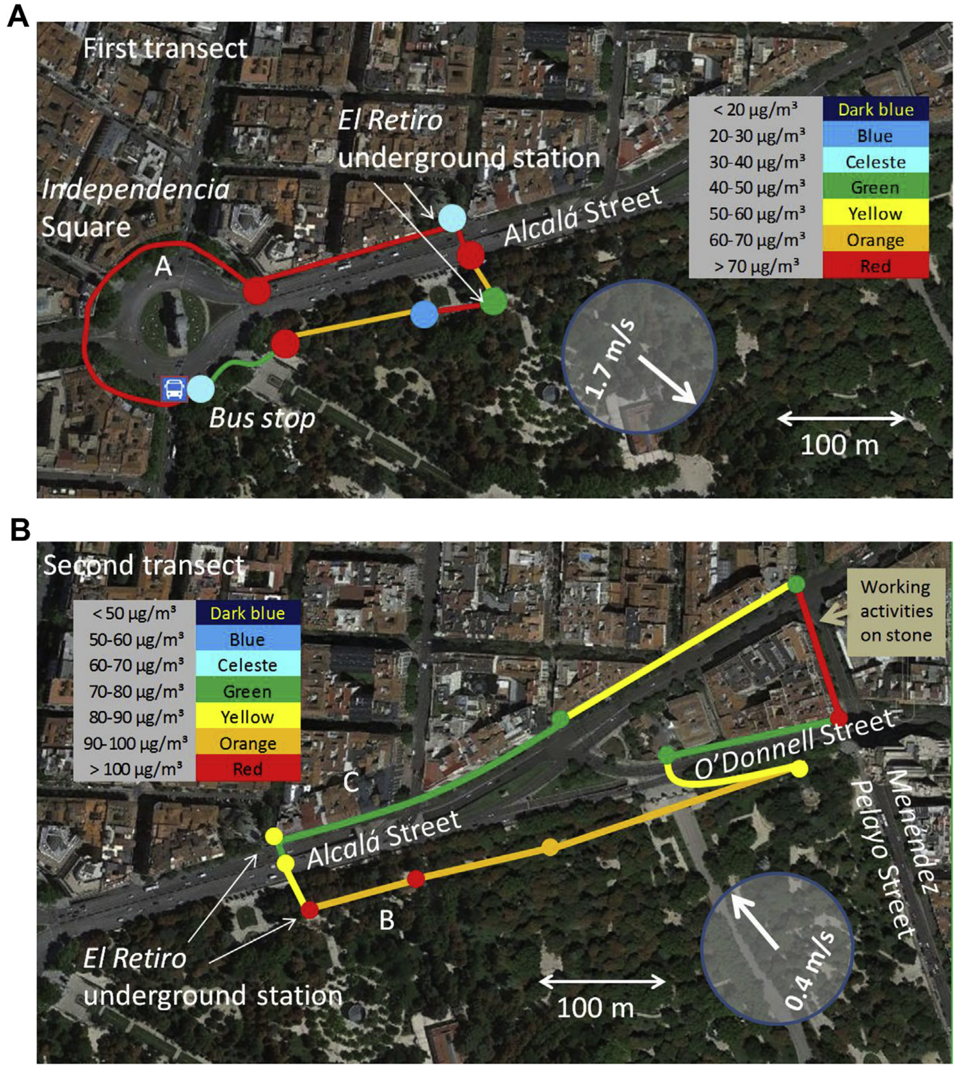

Fig. 3. PM_{10} measured with the DustTrak during the longitudinal transects performed along the *Alcalá* Street (a) 21 June 2016 10:05-10:30 UTC and (b) 24 June 2016 08:03-08:37 UTC. This figure includes points, where the measurements were static for a short period (1 min), and lines, where the measurements were dynamic, while walking. It includes the averaged wind speed and direction measured at regional scale during that period as it is more representative for vortex formation.

smaller than in the summer, as the deciduous species have lost their leaves, especially the plane trees, which show a very important activity during the summer. However, the evergreen species are also numerous (21% of the trees), so the vegetation cover is not negligible at all during this period.

3.2.1. *Meteorological conditions*

The 2017 winter was rather mild in Madrid, warmer than usual, as it can be seen in the data measured by the regional and local meteorological stations (Fig. S3). As in the summer campaign the results obtained in both stations were similar, except for the wind speeds and directions. Maxima daily temperatures above 20 °C were reached over the periods 7–11 and 14–20 March, at the same time that the wind speeds were low at regional scale, with maximum values of $4\,ms^{-1}$ during some short times. There were other colder periods, with temperatures generally below 10 °C and high wind speeds, with values close to $10\,ms^{-1}$ and constant wind direction (from NE), especially in the period 12–14 March. The relative humidity remained relatively low during the central period characterized by high temperatures and stronger wind speeds and high during the initial and ending periods of the campaign. Weak-rainy events were observed only during a day of the campaign (3 March). Its effects can be observed in PM concentrations.

3.2.2. *PM ambient concentrations*

Average, standard deviation, maximum and minimum concentrations can be found in Table 2 During this campaign the particle mass concentrations measured by the Grimm instruments, see Fig. 5, were lower than during the summer campaign, but again PM_{10} concentrations measured inside the park, with unpaved paths, were significantly higher than those measured outside because of the same reason, the soil resuspension. During 25–26 February and 3 March, there was a Saharan dust outbreak and particulate mass concentrations were high. It was not a strong outbreak (MAPAMA, 2017), so the instruments did not measure the maximum PM_{10} values during these periods, but the $PM_{2.5}$ and PM_1 values were high, with $PM_{2.5}$ and PM_1 hourly concentrations close to $50\,\mu g\,m^{-3}$. During the warmer days, an accumulation period occurred and high concentrations were reached. The Grimm instrument located at *Escuelas Aguirre* showed its highest values in these days, the periods 8–12, 14–16 and 18–20 March. Between these periods, the concentrations decreased due to the ventilation

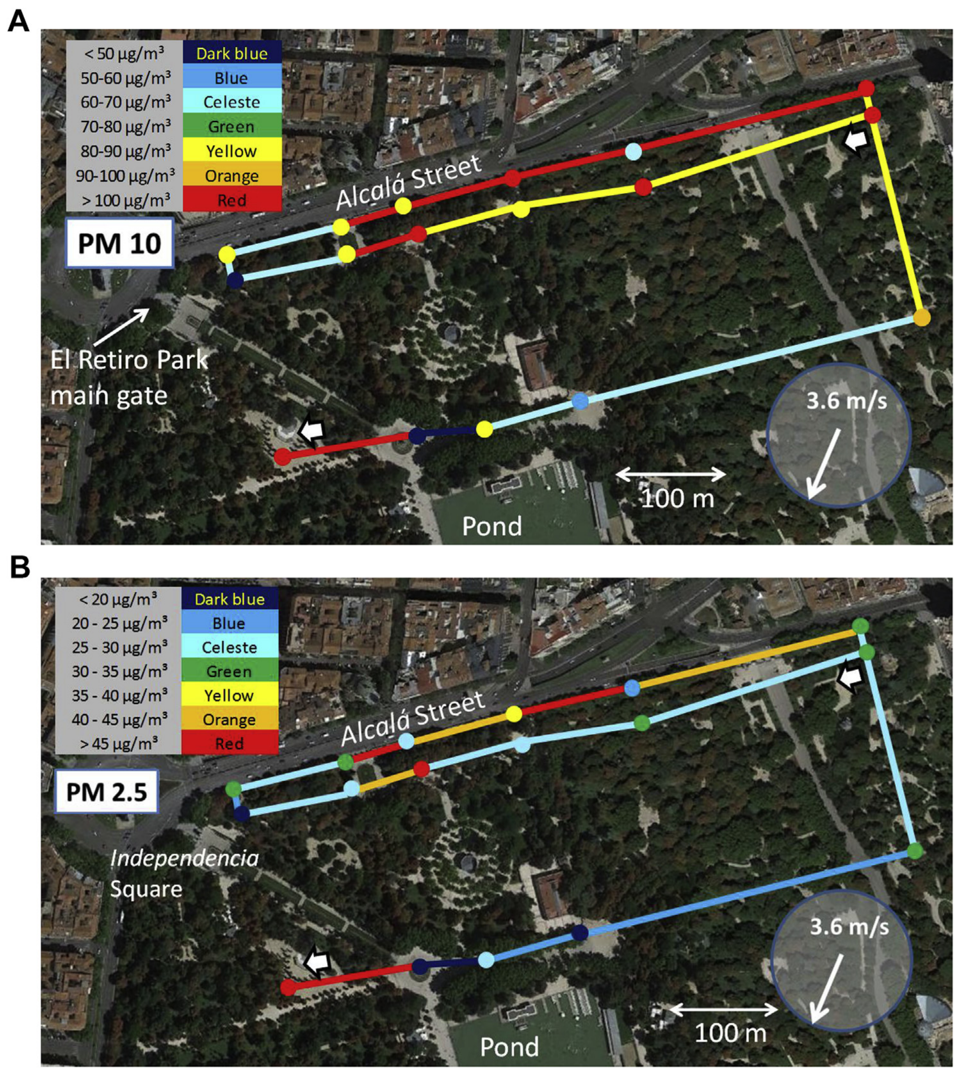

Fig. 4. (a) PM_{10} and (b) $PM_{2.5}$ measured with the DustTrak during the transects performed inside *El Retiro* park on 1 July 2016 10:17-11:10 UTC. This figure includes points, where the measurements were static for a short period (1 min), and lines, where the measurements were dynamic, while walking. The white arrows indicate the initial and final points of the transect.

Table 2
Average concentrations, standard deviation (SD), maximum and minimum particulate matter concentrations in the fractions PM_{10}, $PM_{2.5}$ and PM_1 during the winter campaign period in both sites.

		Average values	SD	Maximum	Minimum
El Retiro Grimm (G1)	PM_{10} ($\mu g\ m^{-3}$)	65.3	78.6	912.7	8.6
	$PM_{2.5}$ ($\mu g\ m^{-3}$)	16.6	8.8	55.2	5.1
	PM_1 ($\mu g\ m^{-3}$)	12.6	8.3	51.2	2.3
Escuelas Aguirre Grimm (G2)	PM_{10} ($\mu g\ m^{-3}$)	29.0	24.1	232.5	5.5
	$PM_{2.5}$ ($\mu g\ m^{-3}$)	18.9	12.2	71.3	3.6
	PM_1 ($\mu g\ m^{-3}$)	14.0	9.5	53.0	2.2

of the area due to the higher wind speeds. The accumulation episode is clear in the $PM_{2.5}$ and PM_1 values; in both cases the daily minimum concentrations were higher than during other periods. $PM_{2.5}$ reached values of 40 and PM_1 of 30 $\mu g\ m^{-3}$. The Grimm instrument located inside *El Retiro* showed a similar behavior.

3.2.3. Dynamic measurements of particulate matter

The most interesting results were those obtained for the measurements inside the park showing a better repeatability along time than during the summer campaign. An example of the results can be found in Figs. 6 and 7 and some statistical analyses can be found in the supplementary material, Tables S5 and S6 and Figs. S7 and S8.

The transects done with the DustTrak during the 16th March can be found in Fig. 6 for PM_{10} and $PM_{2.5}$. These results gave high concentrations in the sides close to the *O'Donnell* and *Menéndez Pelayo* streets and lower as the transects were towards inside the park. For example in Fig. 6a, PM_{10} in both streets reached values of

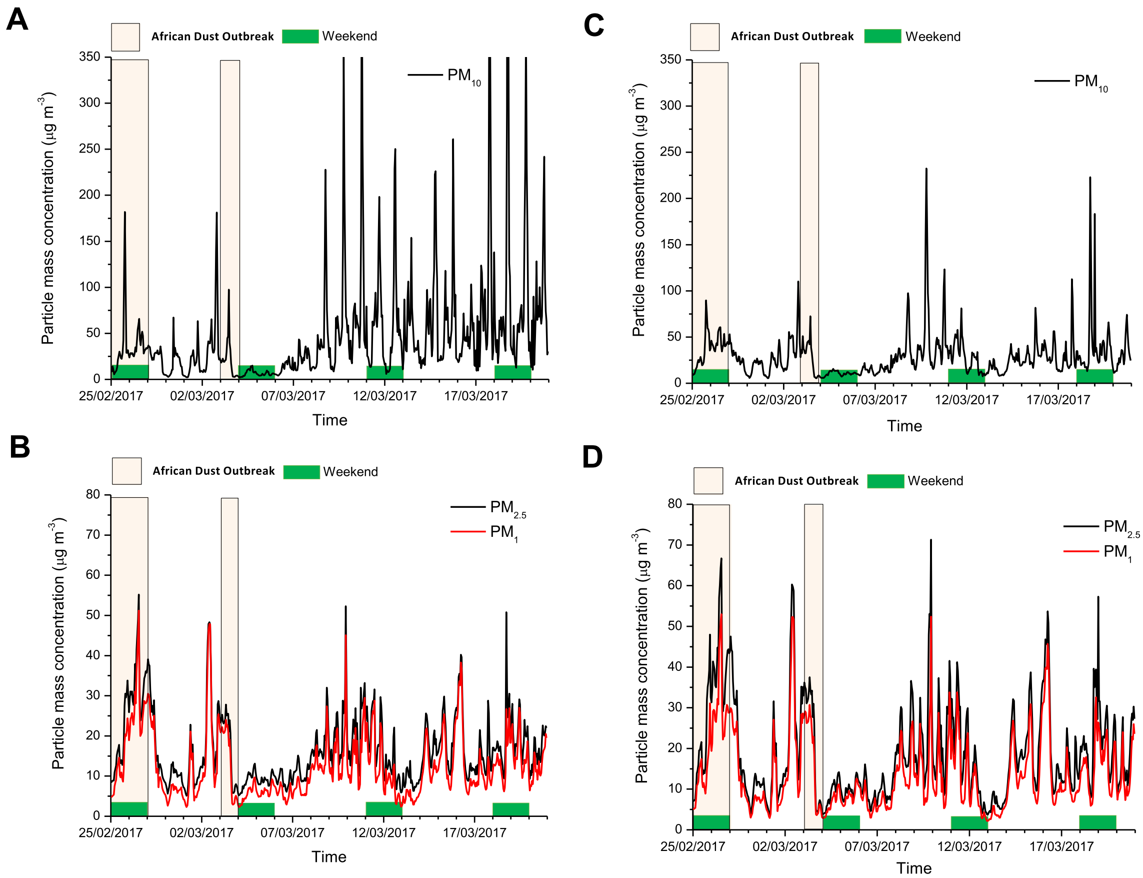

Fig. 5. PM_{10}, $PM_{2.5}$ and PM_1 measured in (a–b) *El Retiro* and (c–d) *Escuelas Aguirre* sites by two Grimm instruments during the winter campaign. The periods with Saharan dust outbreak are marked.

70–80 μg m^{-3} while inside the park values as low as 25–30 μg m^{-3}could be measured. This means that reduction up to 60% could be observed in particular cases. In Fig. 6b, the $PM_{2.5}$ could reach values close to 30 μg m^{-3} in both street sides, but it was reduced to 15-10 μg m^{-3} inside the park. This 50% of reduction could be caused by the distance to the emission points, i.e. by dry removal, and the barrier effect caused by the plant cover located in the area.

The results obtained with the microaethalometers also showed the same trend as the DustTrak. The BC measurements provided an interesting picture with the highest values in the *Menéndez Pelayo* street (that perpendicular to *O'Donnell* street, at the East side of *El Retiro* park) and decreasing as moving towards inside the park. In the North-South direction, the decrease in the BC concentration was also clear, from 1530 to 1220 ng m^{-3} at 100 m, which represents a 20% reduction for these measurements. The lower decrease in the BC concentration in PM_1 compared with the decrease in the particulate matter in $PM_{2.5}$ can be caused by the presence of resuspended particles, not emitted by cars and with low BC concentration in the fraction $PM_{1\text{-}2.5}$. This fraction is easier to remove by inertia mechanisms when the wind interacts with the tree canopies producing a stronger decrease. The higher concentration gradients for PM_{10} could also be explained because particles included in this fraction are easier removed by this same mechanism than $PM_{2.5}$.

These results indicate a more pronounced effect of vegetation on air quality with higher reductions than those published in the literature. It has been previously published that urban vegetation can have a small effect to remove air pollutants in northern climates, and did not differ between seasons (Setälä et al., 2013). Janhäll (2015) reported that several modelling studies on dry deposition have shown PM_{10} reductions of a few percent, while $PM_{2.5}$ concentrations varied less within urban areas. An example is the work by Tallis et al. (2011) where a maximum value of 2.6% was calculated to be reached for PM_{10} in London when increasing the vegetation land to 30%. The particle size is a key factor in PM removal, so exhaust particles (sizes below 0.6 μm) can be reduced a 40% just after a conifer barrier (Al-Dabbous and Kumar, 2014). Dust and coarse particles ($PM_{2.5\text{-}10}$) can have a smaller reduction; Tiwary et al. (2008) found collection efficiencies of 35% for a hawthorn hedge and lower for yew and holly. Fares et al. (2016) found reductions in PM_1 up to about 20% in Rome, the same maximum values we have measured for BC, which is mainly in the PM_1 fraction.

For BC, Brantley et al. (2014) found that behind a tree barrier maximum reductions of 22% could be reached when winds were directly from a road and of 12.4% in average. These results are closer to those shown here, with a maximum decrease of 20%. In summary, all these works show certain dispersion in the results because of the relative influence of many parameters such as particle size, flow recirculation, vegetation properties (hairiness, stickiness, thickness of leaves, porosity, etc), meteorology, nearby emissions and others. There are also different kinds of approaches, with long periods of measurements obtaining average values or with short periods obtaining values easier to relate to the boundary conditions, i.e. meteorological conditions. Individual analysis for every case is required to understand the parameters influencing the effects of vegetation on air pollution and the distance effect.

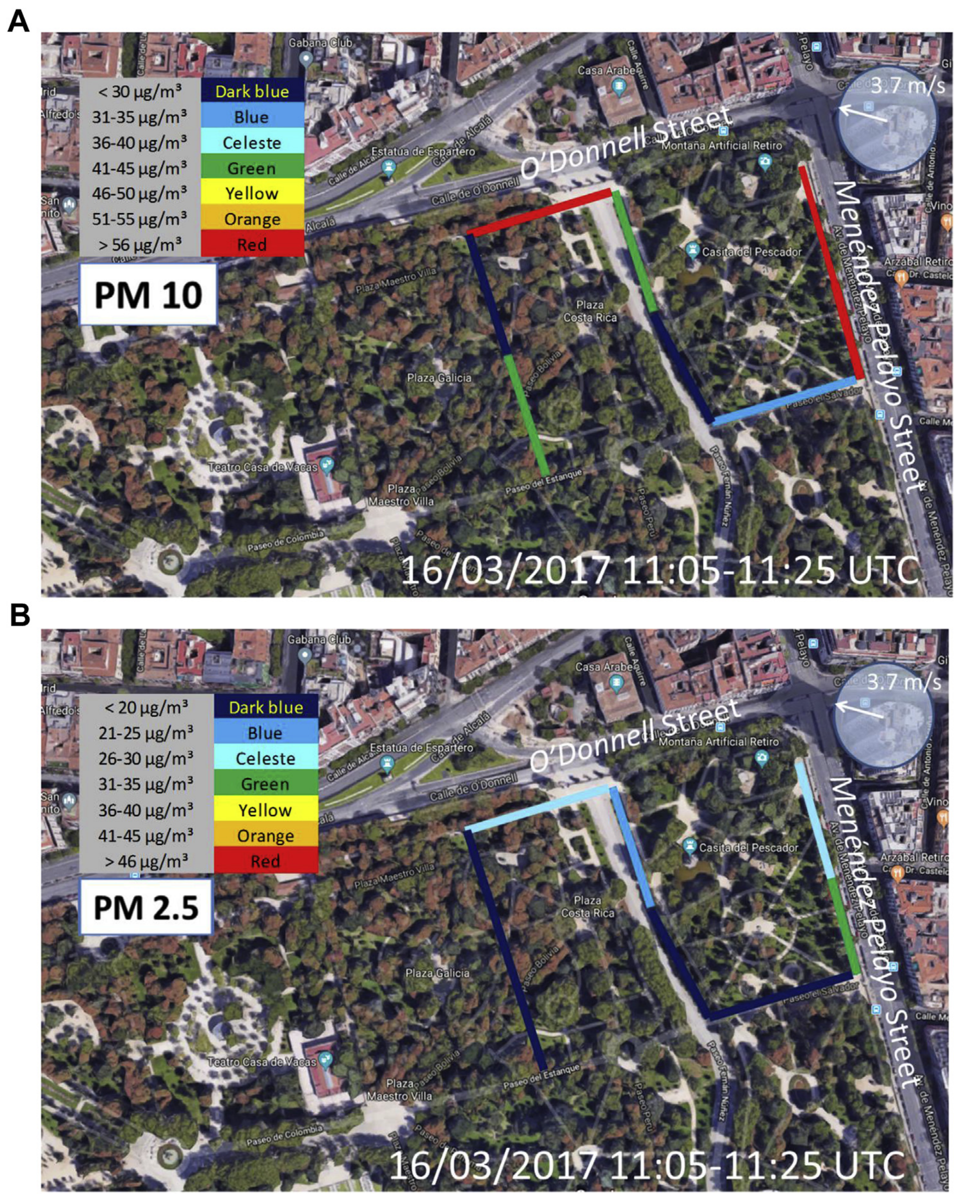

Fig. 6. (a) PM_{10} and (b) $PM_{2.5}$ measurements during the 16 March 2017 11:05-11:25 UTC inside the *El Retiro* park for different transects.

4. Conclusions

Two field campaigns in different seasons of the year (summer and winter) have been carried out in a complex hotspot in Madrid, very close to a large urban park (El Retiro). In both of them, a positive impact of vegetation reducing air pollution has been clearly observed as measured PM_{10}, $PM_{2.5}$ and BC concentrations in points affected by traffic were higher than those measured inside the park, 200 m away from the street.

During the summer campaign, higher particulate mass concentrations were measured linked to some Saharan dust outbreaks. It was possible to observe that the highest values were measured in the *Independencia* square, an area with high traffic density, especially affected by buses. In the transects inside the *El Retiro* park, a decrease in the PM_{10} and $PM_{2.5}$ concentrations of up to 25% at 20 m and 50% at 200 m was observed. High PM_{10} values inside the park were linked to dust resuspension caused by human activities like garden maintenance or running.

The winter campaign showed similar results. Observed concentrations were strongly conditioned by atmospheric stability. Maxima values were observed during accumulation periods associated to these stability events during 8–12, 14–16 and 18–20 March when the pollutants reached the highest values. Similarly to the summer campaign, strong spatial concentration gradients were observed near the borders of the park. For PM_{10} and $PM_{2.5}$, reductions up to 50% were observed at 200 m from the street, while for the BC case was smaller, only 20%. The possible reason for the smaller BC removal is that it is included in the PM_1 fraction, less affected by the inertia mechanism for particle removal by the tree canopies.

Although there is a high scattering in the results published in previous works on the effect of vegetation on air pollution, the reductions measured in this work are globally larger than those observed or modelled in those previous cases. The probable reason is that the short sampling time used in this work indicates periods where maximum values were reached instead of an average value

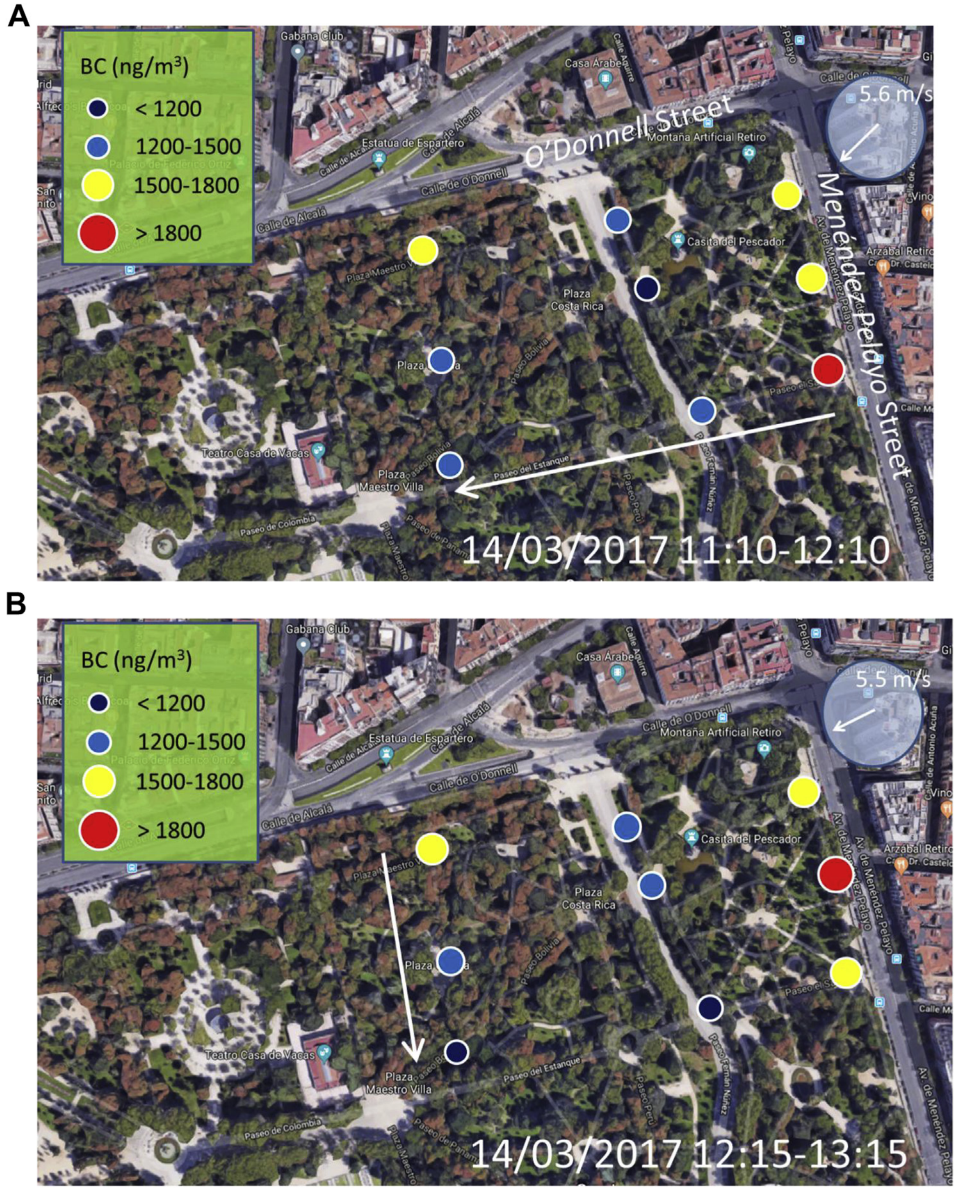

Fig. 7. BC concentrations measured the 14 March 2017 along the arrow direction and sense. The circle area is directly related to the concentration, while the circle color indicates the concentration range. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

as it is usually performed in other experimental studies. For a better understanding, to know what extent concentration reduction is due to vegetation or simply to distance from the source it would be necessary to perform modelling exercises to evaluate whether these pollution reductions are only caused by the vegetation cover or also other factors like distance are influencing the concentration values. CFD (Computational Fluid Dynamics) modelling considering different permeability for the vegetation barriers may be particularly relevant.

Declarations of interest

None.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envpol.2019.01.016.

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