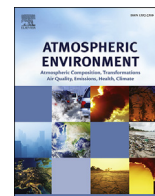




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Factors controlling particle number concentration and size at metro stations



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HIGHLIGHTS

- Particle number size distribution recorded at 9 different metro platforms.
- Mean $N_{0.3-10}$ correlate with the depth of the platforms in the old metro lines.
- UFP may be partly governed by outdoor emissions through mechanical ventilation.
- At operating hours, coarse particles less abated than UFP by tunnel ventilation.
- The control of coarse particles should be a priority at the metro system.

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ABSTRACT

An extensive air quality campaign was performed at differently designed station platforms in the Barcelona metro system, aiming to investigate the factors governing airborne particle number (N) concentrations and their size distributions. The study of the daily trends of N concentrations by different size ranges shows that concentrations of $N_{0.3-10}$ are closely related with the schedule of the metro service. Conversely, the hourly variation of $N_{0.007-10}$ (mainly composed of ultrafine particles) could be partly governed by the entrance of particles from outdoor emissions through mechanical ventilation. Measurements under different ventilation settings at three metro platforms reveal that the effect on air quality linked to changes in the tunnel ventilation depends on the station design. Night-time maintenance works in tunnels are frequent activities in the metro system; and after intense prolonged works, these can result in higher N concentrations at platforms during the following metro operating hours (by up to 30%), this being especially evident for N_{1-10} . Due to the complex mixture of factors controlling N, together with the differences in trends recorded for particles within different size ranges, developing an air quality strategy at metro systems is a great challenge. When compared to street-level urban particles concentrations, the priority in metro air quality should be dealing with particles coarser than $0.3 \mu\text{m}$. In fact, the results suggest that at narrow platforms served by single-track tunnels the current forced tunnel ventilation during operating hours is less efficient in reducing coarse particles compared to fine.

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1. Introduction

Metro systems are main transportation modes and typically serve billions of commuters annually in metropolitan areas

worldwide. In major cities, metro can be viewed as a transport lifeline, relieving road traffic congestion (Vasconcellos, 2001). They also reduce air pollution above ground, thus Silva et al. (2012) concluded that a metro strike in São Paulo led to a significant increase in daily mean particulate matter (PM) mass concentrations due to extra road traffic. However, the underground system is a confined space that may cause a concentration of contaminants, either infiltrating from the outside atmosphere or generated internally. In this context, a number of studies have been conducted

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to assess the levels of air pollutants and their chemical compositions. Generally, PM mass concentrations in metro systems, whether on platforms or inside trains, have been found to be higher when compared to those in adjacent outdoor air (Martins et al., 2015a and references therein).

It has been argued that current levels of PM in metro systems are unlikely to lead to any significant excess health effects in commuters (Nieuwenhuijsen et al., 2007 and references therein). Moreno et al. (2017) reported a low oxidative potential in metro samples from Barcelona compared with outdoor air. Conversely, some studies have shown evidences of a significant toxicity. For example, Steenhof et al. (2011) concluded that the underground PM samples caused the largest decrease of metabolic activity compared to traffic and urban background PM. Karlsson et al. (2008) also reported that, compared to outdoor PM, metro PM is more genotoxic and induces oxidative stress in cultured human lung cells. In the Paris metro system, Bachoual et al. (2007) concluded that lung inflammatory and structural cells could be targets of metro PM exposure. Consequently, it is reasonable to conclude that PM concentrations at metro systems should be controlled and reduced where possible.

The first comprehensive metro air quality study was conducted in Boston at the end of the 1980s (Chan et al., 1991) and focused on exposure to gasoline-related volatile organic compounds (VOCs). This work was followed by further studies assessing levels of different air pollutants in metro systems. After more than a decade of research, different air pollutants such as different size modes of PM mass (Furuya et al., 2001; Seaton et al., 2005; Park et al., 2012; Querol et al., 2012), PAHs (Furuya et al., 2001), CO (Cheng and Yan, 2011), NO₂ (Klepczyńska-Nyström et al., 2012), O₃ (Wad, 2002), metals (Kang et al., 2008; Karlsson et al., 2008; Park et al., 2012; Querol et al., 2012; Moreno et al., 2014; Martins et al., 2016a,b), and different biological pollutants (Wad, 2002; Hwang and Park, 2014; Triadó-Margarit et al., 2016) have all been measured using off-line samplers and/or real-time monitors. A search on SCOPUS using the combined keywords “air quality”, “metro system”, and “exposure” results in more than 65 publications in the past 10 years. However, publications on particle number (N) concentrations in metro systems both at platforms and inside trains are more limited (Levy et al., 2002; Birenzvige et al., 2003; Aarnio et al., 2005; Seaton et al., 2005; Cheng et al., 2009; Ma et al., 2012; Klepczyńska-Nyström et al., 2012; Gustafsson et al., 2012; Midander et al., 2012; Onat and Stakeeva, 2013; Colombi et al., 2013; Suárez et al., 2014; Cusack et al., 2015). Commuting studies have reported a higher particle size mode in metro systems compared with other transport modes and with those reported for urban backgrounds (Moreno et al., 2015).

Several studies have concluded on a lack of correlation of PM mass and N concentrations, which implies different sources and/or formation processes for particles in different size ranges (Morawska et al., 1998; Mejía et al., 2008). PM mass is dominated by coarse particles (>1 μm) and provides little information about

ultrafine particles (UFP; <0.1 μm). UFP often contribute only a few percentage to the mass, at the same time contributing to over 80% of N. Therefore, the focus of a study differs widely when measuring one or another parameter.

The main goal of this study is the characterization of N concentrations in different size ranges in the metro system of Barcelona (Spain) in order to assess the influence of key parameters, mainly station design, ventilation settings, number and location of ventilation grills and train frequency. Thus, intensive monitoring campaigns have been carried out at 9 different platforms and different seasonal periods, accounting for specific features.

2. Methodology

2.1. Instrumentation

Different particulate matter size distribution instruments are often used to extend the measured size range within a single study, thus implying that the values they provide are comparable and complementary (Price et al., 2014). For this study, an Optical Particle Sizer (OPS 3330; TSI) and an Electrical Low Pressure Impactor (ELPI; Dekati) were used. Specifications on each instrument are summarized in Table 1. Maintenance services were routinely performed, including the cleaning of the charger and the impactor of the ELPI, in order to avoid changes in the cut points and particle bouncing effects. It is important to note that while OPS is based on the optical diameter, ELPI classifies particles according to their aerodynamic diameter. Different types of particles have distinct relationships between optical and aerodynamic diameters (Chien et al., 2016), which could result in important differences between instruments which are necessary to be characterized and taken into account when interpreting measurements.

The linear regression shows poor agreement between both pieces of equipment OPS and ELPI for N concentrations calculated over similar size ranges (0.374–10 μm as reported by OPS, and 0.384–10 μm as reported by ELPI; Figure S1). The study of the relationships by size ranges reveals that temporal trends between OPS and ELPI are more similar when each range of the OPS is compared with the immediately higher one of the ELPI. The R² of the linear regression between equipments increases by 25% and the slope is closer to one when the selected size range for ELPI is 0.616–10 μm (the lower selected stage being 0.616–0.953 μm instead of 0.384–0.616 μm; Figure S1). As the aerodynamic diameter is highly affected by density, one possible reason for this is that ELPI could slightly overestimate particle sizes due to the high density of metro particles, which ranges from 2.3 to 3.1 g cm⁻³, based on their chemical composition (Martins et al., 2015b). On the other hand, the occurrence of particle re-entrainment (bounce), as the surface was not coated during sampling, could also lead to certain errors in the size classification in spite of the routine maintenance. Accordingly, regarding data reported by the ELPI, the interpretation will mainly focus on total

Table 1
Specifications of the instruments deployed for this study.

	ELPI	OPS
Measurement principle	Impactor technology with particle charging and electrical detection	120° light scatter and filter sampling
Particle size range	0.007–10 μm	0.3–10 μm
Size uncertainty	4% in cut-off diameter ^a	5% at 0.5 μm
Size channels	12 (0.007–0.056; 0.056–0.094; 0.094–0.156; 0.156–0.263; 0.263–0.384; 0.384–0.616; 0.616–0.953; 0.953–1.61; 1.61–2.4; 2.4–4.01; 4.01–6.62; 6.62–10)	16 (0.300–0.374; 0.374–0.465; 0.465–0.579; 0.579–0.721; 0.721–1; 1–1.2; 1.2–1.4; 1.4–1.732; 1.732–2.156; 2.156–2.5; 2.5–3.343; 3.343–4.162; 4.162–5.182; 5.182–6.451; 6.451–8.031; 8.031–10)
Flow rate	30 L min ⁻¹	1.0 L min ⁻¹ ; ±5% accuracy

^a Pagels et al., 2007.

particle N concentrations ($N_{0.007-10}$), which mostly accounts for UFP (>80%).

All the instruments were placed at the end of each platform corresponding to the train entry point, far from the passengers' access-to-platform point, and behind a light fence for safety protection. This location was selected to minimize obstruction to the commuters while representative measurements were performed without interruption. The aerosol inlets were placed at roughly 1.5 m above the platform ground level.

Continuous measurements (24 h day⁻¹; 7 days per week) with a 5-min time resolution were performed using the OPS. On the other hand, the ELPI was scheduled to measure only two weekdays each week to avoid impaction substrate saturation (which can cause the equipment to shut down), with a 5-s time resolution. The particle collection into each impactor stage of the ELPI was carried out onto one aluminium foil per week. Particles on the aluminium foils were extracted using cotton soaked with ethanol. The resulting substrates corresponding to the particle size ranges between 0.007 and 4 µm were acid digested (HF:NO₃:HClO₄, 2.5:1.25:1.25 mL) and subsequently analyzed by Inductively Coupled Plasma Atomic Emission Spectrometry (ICP-AES) and Mass Spectrometry (ICP-MS) to determine major and trace elements, respectively. Substrates corresponding to the two highest stages (4–10 µm) were not considered. A lower surface retention of particles was observed for those larger sizes due to particle re-entrainment (bounce), as the surface was not coated to avoid contaminating the later chemical analyses. Laboratory blanks were routinely analyzed to account for contamination potentially introduced during sampling or analysis. In addition, a standard reference material (NIST 1633b) was added to a fraction of a blank substrate as additional sample quality control. In spite of the described limitations associated with the ELPI size classification, the availability of results on chemical composition represents a good approach to describe differences between size ranges in order to identify potential sources. Thus, the relative abundance of key components for the 0.007–0.094 (UFP) and the 0.953–4.01 µm fractions has been compared and will be discussed.

Data on N concentrations recorded at an urban background station (41°23'14" N, 02°06'56"E, 78 m.a.s.l.) were used for comparisons. In spite of representing urban background conditions, this station is affected by road traffic emissions from the Diagonal Avenue (approximately 200 m distance), one of the largest avenues in the city (100000 vehicles/working day; [Ajuntament de Barcelona, 2015](#)). At this station, N concentrations were recorded with a 3787 TSI WCPC, measuring total particles from 0.005 to 1 µm.

2.2. Sampling sites

The Barcelona metro system (managed by Transports Metropolitans de Barcelona, TMB) absorbs around 50% of the urban commuting load, transporting 1.25 million commuters on weekdays, with the average journey time being 15 min (TMB data). Trains run from 5:00 h until midnight every day, with additional services on Friday nights (finishing at 2:00 h on Saturday) and Saturday nights (running all night long), and with a frequency between 2 and 15 min, depending on the day (weekend or weekday), metro line and time of day. Structural differences between lines are notable, making this system especially interesting in terms of air quality.

Currently, the Barcelona metro system comprises eight lines with a total length of 124.5 km and including 157 train stations. The new stations, in lines 9 and 10 (L9 and L10), have platforms separated from the tunnel by a wall with mechanical doors (PSDs) that are simultaneously opened with the train doors. Nine underground

stations accounting for distinct designs and located at six different metro lines were selected for continuous monitoring ([Fig. 1](#)): Joanic (L4), Santa Coloma (L1), Tetuan (L2), Llefià (L10), Sagrera, Sant Ildefons (L5), Palau Reial, Maria Cristina and Tarragona (L3). The architecture of the stations and tunnels is different for each station: one wide tunnel with two rail tracks separated by a middle wall in Joanic, Palau Reial and Maria Cristina stations, and without a middle wall in Santa Coloma, Tarragona and Sant Ildefons, a single narrow tunnel with one rail track in Tetuan, two wide tunnels with one rail track separated by a middle platform at Sagrera, and a single tunnel with one rail track separated from the platform by a wall with platform screen door systems (PSDs) in Llefià (see [Table 2](#) for further details about the selected stations). The study was carried out during warmer (April–September) and colder periods (October–March; [Table 2](#)), according to TMB ventilation protocols to assess seasonal differences, as ventilation rates at tunnels are higher during the warmer period.

2.3. Statistical methods

Non-parametric Mann-Whitney-Wilcoxon tests were carried out in R programming language (www.R-project.org) to determine the statistical significance of variations in N concentrations during operating hours at a selected metro platform after modifying specific parameters, namely:

- Ventilation protocol.
- Night conditions (affected or not by intense maintenance/renewal works).

3. Results

3.1. Particle number concentrations at platforms: characterization by size range

A summary of N concentrations reported for different metro systems worldwide, including those recorded in this study, is shown in [Table 3a](#) and [b](#). The selected particle size ranges in the available studies varies widely, highly determining the reported concentrations. As previously discussed, a lower cut size above 0.1 µm implies not accounting for UFP. UFP generally represent over 80% of total N concentrations ([Morawska et al., 1998](#)). Thus, studies in [Table 3](#) are shown in two groups based on the lower cut size of the selected measurement methods, finer (a) or coarser (b) than 0.1 µm, in order to facilitate the comparison of N concentrations by similar size ranges. UFP at platforms have usually been found to be lower or similar to those reported in ambient air (e.g. [Cheng et al., 2009](#); [Midander et al., 2012](#)) and in other transport modes ([Suárez et al., 2014](#); [Moreno et al., 2015](#)).

[Table 4](#) shows median concentrations recorded by OPS ($N_{0.3-10}$) and ELPI ($N_{0.007-10}$) at each station during metro operating hours and distinguishing the colder and the warmer periods, as described in [Table 2](#). As can be observed, $N_{0.3-10}$ concentrations vary widely among stations, ranging between 62 and 148 #cm⁻³ during the colder period and between 48 and 183 #cm⁻³ during the warmer period. The highest concentrations were measured in those stations belonging to the oldest metro tunnels of the system (L1, L3), while the lowest concentrations were recorded in the newest metro station with PSDs (Llefià). For the old stations under study, a moderate correlation was obtained between $N_{0.3-10}$ concentrations and the depth of each station ($R^2 = 0.72$; [Figure S2](#)).

In four of the selected stations, $N_{0.3-10}$ measurements were available both in the colder and in the warmer period. It is important to note that ventilation rates at tunnels are always higher during the warmer months (April–September) in all stations,

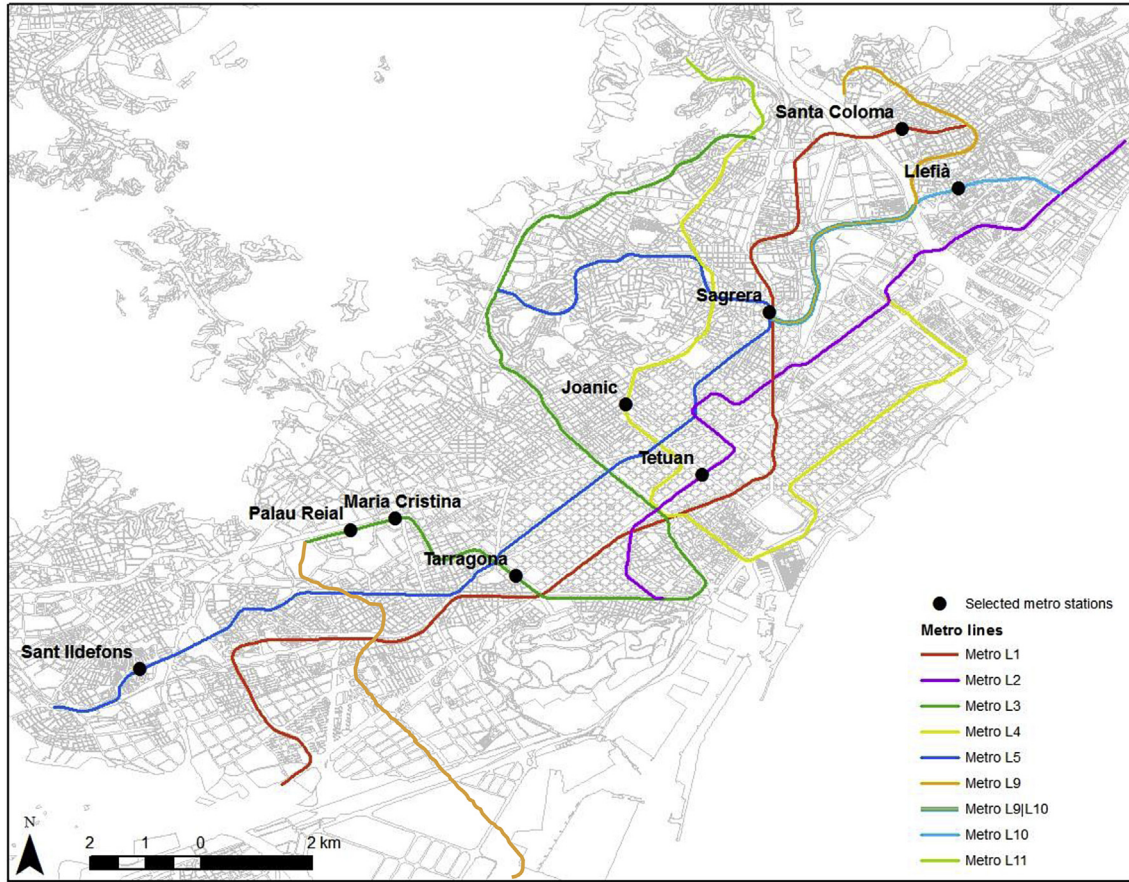


Fig. 1. Map of the metro system of Barcelona indicating the selected metro stations.

Table 2
Main characteristics of the metro stations selected for this study.

Subway station	Line	Depth (m)	Design	Trains in the metro line (frequency) -Mean for weekdays-	Number of accesses to platform	Measurement period	
						Warmer	Colder
Joanic	L4	-7.6		17 (4:36 min)	1	2 Apr-2 May 2013	28 Oct-25 Nov 2013
Llefià	L10	-43.6		9 (6:00 min)	1	31 May-1 Jul 2013	13 Jan-10 Feb 2014
Santa Coloma	L1	-14.6		25 (3:53 min)	1	1 Jul-30 Jul 2013	10 Feb-10 Mar 2014
Tetuan	L2	-12.5		17 (3:55 min)	1	2 May-31 May 2013	25 Nov-20 Dec 2013
Sagrera	L5	-10.5		25 (3:38 min)	2		20 Jan-31 Mar 2015
Palau Reial	L3	-14.2		24 (3:43 min)	2	1 Apr-14 May 2015	
Maria Cristina	L3	-13.7		24 (3:43 min)	2	14 May-10 Jun 2015	
Tarragona	L3	-14		24 (3:43 min)	1	10 Jun-1 Jul 2015	
Sant Ildefons	L5	-10.5		25 (3:38 min)	2		3 Feb-29 Feb 2016

Table 3

N concentrations reported for different metro systems worldwide, including concentrations recorded during this study (distinguishing the colder and the warmer measurement periods). Studies have been classified in two groups based on the lower cut size of the selected measurement methods, finer (a) or coarser (b) than 0.1 μm .

City	Study	N ($\#\text{cm}^{-3}$) on platforms	Method
(a)			
Barcelona (Spain)	Moreno et al., 2015	23 000 (0.01–0.3 μm)	Electrical charging of particles
Boston (USA)	Levy et al., 2002	25 000 (0.02–1 μm)	Condensation nucleus counter
Helsinki (Finland)	Aarnio et al., 2005	31 000 \pm 14000 (0.01–0.5 μm)	Condensation nucleus counter
London (UK)	Seaton et al., 2005	14 000–29 000 (0.02–1 μm)	Condensation nucleus counter
Prague (Czech Republic)	Cusack et al., 2015	11 500 (0.014–0.637 μm)	Scanning mobility particle sizer
Stockholm (Sweden)	Klepczyńska-Nyström et al., 2012	8 960 \pm 660 (0.01–0.1 μm)	Scanning mobility particle sizer
Stockholm (Sweden)	Gustafsson et al., 2012	900–6000 (0.01–0.7 μm)	Scanning mobility particle sizer
Stockholm (Sweden)	Midander et al., 2012	7500–20 000 (0.014–0.33 μm)	Scanning mobility particle sizer
Taipei (Taiwan)	Cheng et al., 2009	15 500 (0.02–1 μm)	Condensation nucleus counter
Barcelona (Spain)	This study	Colder: 12 500 (0.007–10 μm)	Electrical low pressure impactor
(b)			
Fukuoka (Japan)	Ma et al., 2012	108–145 (0.3–>5 μm)	Laser optical counter
Istanbul (Turkey)	Onat and Stakeeva., 2013	54–209 Rush hours 49–184 Non-rush hours (0.3–>0.5 μm)	Optical counter
Milan (Italy)	Colombi et al., 2013	124–220 (0.3–>5 μm)	Optical counter
Washington D.C. (USA)	Birenzvige et al., 2003	100–1000 (>1 μm)	Laser optical counter
Barcelona (Spain)	This study	Warmer: 116 (0.3–10 μm) Colder: 100 (0.3–10 μm)	Optical sizer

Table 4

Summary of median and the interquartile range (25th–75th percentile) of $N_{0.3-10}$ (OPS) and $N_{0.007-10}$ (ELPI) concentrations at each station during metro operating hours, distinguishing the colder and the warmer measurement periods.

Metro station	Colder period						Warmer period		
	$N_{0.007-10}$ ($\#\text{cm}^{-3}$)			$N_{0.3-10}$ ($\#\text{cm}^{-3}$)			$N_{0.3-10}$ ($\#\text{cm}^{-3}$)		
	Median	25th percentile	75th percentile	Median	25th percentile	75th percentile	Median	25th percentile	75th percentile
Joanic	17 520	8984.2	25 527	89	66	110	75	52	104
Llefià	7060	4910	11 000	62	45	83	48	37	72
Santa Coloma	9246	6585	13 820	126	93	167	150	133	192
Tetuan	16 175	10 700	26 360	148	120	195	105	60	133
Sagrera				105	76	144			
Palau Reial							183	145	220
Maria Cristina							122	98	156
Tarragona							130	102	155
Sant Ildefons				80	55	110			

according to TMB ventilation protocols. The comparison of $N_{0.3-10}$ concentrations by the different size ranges in these four stations is shown in Fig. 2 and Table S1. For the sake of simplicity, N concentrations for each size range at each station have been normalized by the average value for all stations to allow the combined comparison of all size ranges between stations in Fig. 2. Namely, the mean N concentration for a given size range and station has been divided by the mean N concentration for the given size range at all the stations (see Table S1 for absolute N concentrations). The most important differences between the colder and the warmer seasonal periods were observed in Tetuan and Llefià stations, where $N_{0.3-10}$ concentrations were by 30–40% lower in the warmer period compared to the colder, which is consistent with the higher ventilation rates during the warmer period. It is especially remarkable the case of Tetuan; while concentrations at this station were the highest in all size ranges during the colder period, this was only true for particles coarser than 1.4 μm during the warmer period. The importance of ventilation rates at tunnels to air quality in Llefià is somehow surprising considering the presence of brand new full-length PSDs which would be expected to inhibit air exchange between platform and tunnel. However, recent works have already indicated that PSD systems are not as effective at preventing contamination of the platform by tunnel air (Martins et al., 2015a; Kwon et al., 2016). In Joanic, decreases were recorded for all the considered size ranges

except for $N_{0.3-0.37}$, which were by 55% higher in the warmer period. Conversely, in Santa Coloma, N concentrations for all size ranges were always higher (by 20%) during the warmer period. Thus, the influence of changes in ventilation rates differ widely between stations, the reasons for these discrepancies may be related to the design, depth and volume of the platforms, but further research is needed.

The lowest $N_{0.3-10}$ concentrations in all size ranges measured in Llefià station during both seasonal periods could be partly attributable to the design of the station equipped with PSDs, and especially to the lower train frequency and more advanced ventilation setup.

$N_{0.007-10}$ data was only available during the colder period and in four stations, with concentrations ranging between 7060 and 17520 $\#\text{cm}^{-3}$, which is in the range of those measured in the outdoor urban background of Barcelona (14 000 $\#\text{cm}^{-3}$ on average during the same period for $N_{0.005-1}$). The highest concentrations were recorded at Joanic station, opposite to what was observed for $N_{0.3-10}$, and the lowest in Llefià (Table 4), when comparing the same measurement periods. This variability could be due to the expected distinct origin of particles in different sizes ranges.

Fig. 3 shows the averaged diurnal variation of $N_{0.007-10}$, $N_{0.3-1}$; $N_{1-2.5}$ and $N_{2.5-10}$ concentrations for the whole sampling period. Similar daily trends of $N_{0.007-10}$ concentrations, which mainly

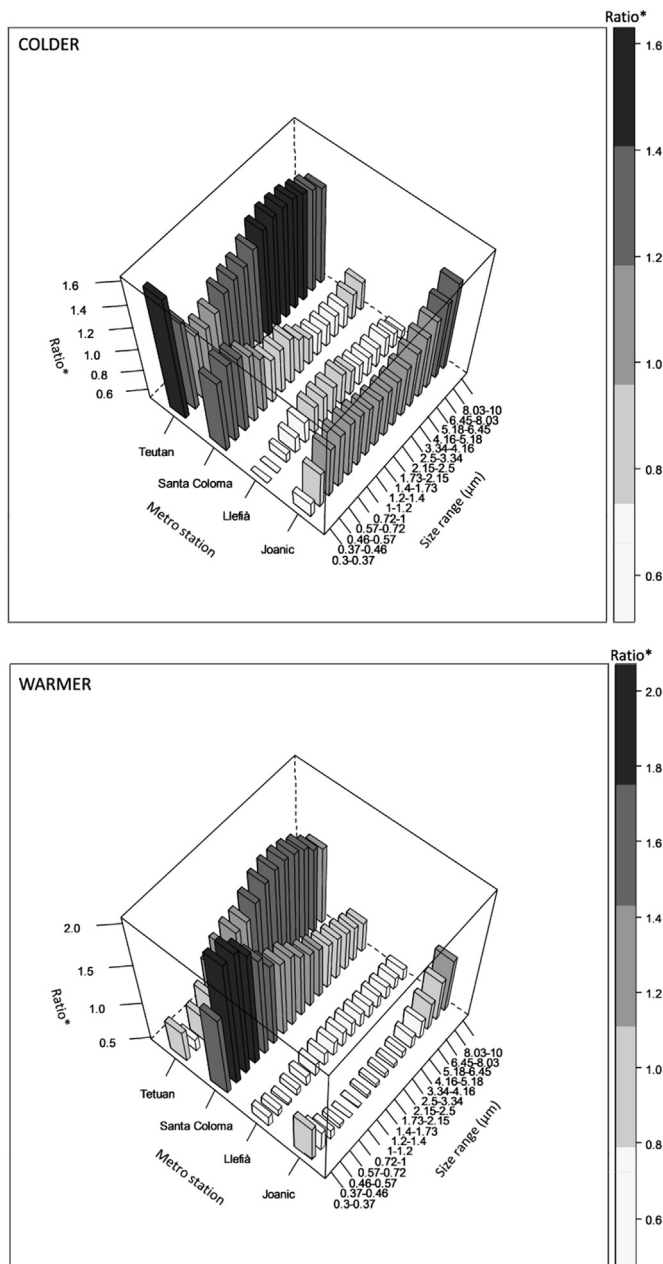


Fig. 2. Comparison of N concentrations between stations for different size ranges (0.3–10 μm) as measured by OPS during the colder and the warmer period.

*To better compare each size range between stations, N concentration, expressed as $\text{dN}/\text{d}\log\text{Dp}$, for each size range at each station has been normalized by the average value for all stations. See Table S1 for further information.

represent UFP, were recorded at all the old stations, closely related with the daily ventilation protocol. The typical ventilation protocol at the old stations accounts for two periods: a) 7:00–22:00 h: impulsion of outdoor air at platforms and extraction of indoor air in tunnels, and b) 22:00–7:00 h: no ventilation at platforms and impulsion of outdoor air in tunnels. The lowest concentrations of UFP were recorded from 3:00–6:00 h, depending on the station, which differ from the daily cycle of $\text{N}_{0.3-10}$, whose concentrations start increasing earlier, coinciding with the beginning of the metro service. Important peaks of $\text{N}_{0.007-10}$ were recorded from 8:00 to 10:00 h and from 19:00 to 21:00 h. Concentrations of $\text{N}_{0.007-10}$ considerably decrease at 22:00 when the ventilation at the

platforms stops, while $\text{N}_{0.3-10}$ concentrations remain more stable and decrease with the end of the metro service (Fig. 3).

Conversely, the pattern is rather different in Llefia station, where the highest $\text{N}_{0.007-10}$ concentrations were recorded at around 13:00–14:00 h, this peak can also be observed in the rest of stations but not as markedly. Ventilation setups are more advanced in the new stations; the only difference between day (6:00–23:00 h) and night (23:00–6:00 h) settings consists in a lower number of operating fans at platforms during nights. Both at platforms and tunnels, ventilation includes slow extraction of indoor air and slow impulsion of outdoor air.

Thereby, disagreements in the daily evolution of $\text{N}_{0.007-10}$ and $\text{N}_{0.3-10}$ suggest different origins. Hourly trends seem to indicate that UFP could be partly governed by the entrance of particles from outdoor emissions through mechanical ventilation, as increases do not coincide with the beginning of metro operating hours but are more closely related with road traffic rush hours.

According to the results, it should be noted that the nature of the subway environment and the emissions taking place, together with the possible contribution of outdoor sources, do not allow as yet to statistically assure which are the factors controlling all the observed differences in particles concentrations at platforms and to what extent. Nonetheless, those clearer differences between stations allow giving an estimation of potential responsible factors, as for example the favorable effect of the design of the newest platforms of the system, with more advanced ventilation setups.

3.2. Chemical characterization

Martins et al. (2016a) assessed and quantified those chemical components tracing the indoor and the outdoor source affecting the metro system of Barcelona. Accordingly, elements can be assigned to outdoor and metro sources, the latter including emissions generated by the circulation of trains (rail tracks, wheels, brake pads, catenaries [overhead electrical rails], and pantographs [sprung mechanical link between the train and the electric rail]). Authors concluded that the metro source is responsible for more than 50% to the concentration of Al_2O_3 , Ca, Fe, Cr, Mn, Cu, Sr, Ba, Mg, Li, Ti, Co, Zn, and Ce, with a clear dominance of Fe.

The relative contribution of selected inorganic chemical components determined on samples collected by the ELPI is shown in Fig. 4, distinguishing the size ranges 0.007–0.094 (UFP) and 0.953–4.01 μm (coarse particles). The most notable difference is the high relative abundance of Fe in the 0.953–4.01 μm size range compared with UFP, at all the stations. Fe is the most representative tracer of train circulation-related sources, thus it seems to indicate a relative small contribution of these sources to UFP.

On the other hand, the relative contribution of Ca is higher in the ultrafine than in the coarse fraction, except at the newest station of Llefia.

It is important to highlight the significant higher contribution of SO_4^{2-} , P and K to the UFP fraction compared to the coarse. These compounds are typically associated to external sources (Querol et al., 2012; Martins et al., 2016a), what also support the different origins of UFP and coarse particles. Na has also a higher relative contribution in the 0.007–0.094 size range at Joanic, Tetuan and Llefia, while in Santa Coloma a small contribution to both fractions was recorded.

Regarding trace elements, the fraction with the highest contribution varies between stations. A common aspect at all the stations in terms of trace elements is that Cu, Mn and Ba have a higher contribution in the coarser fraction. These compounds have been found to be closely related with wheel and brake abrasion (Mn, Ba), and electric cable wear (Cu).

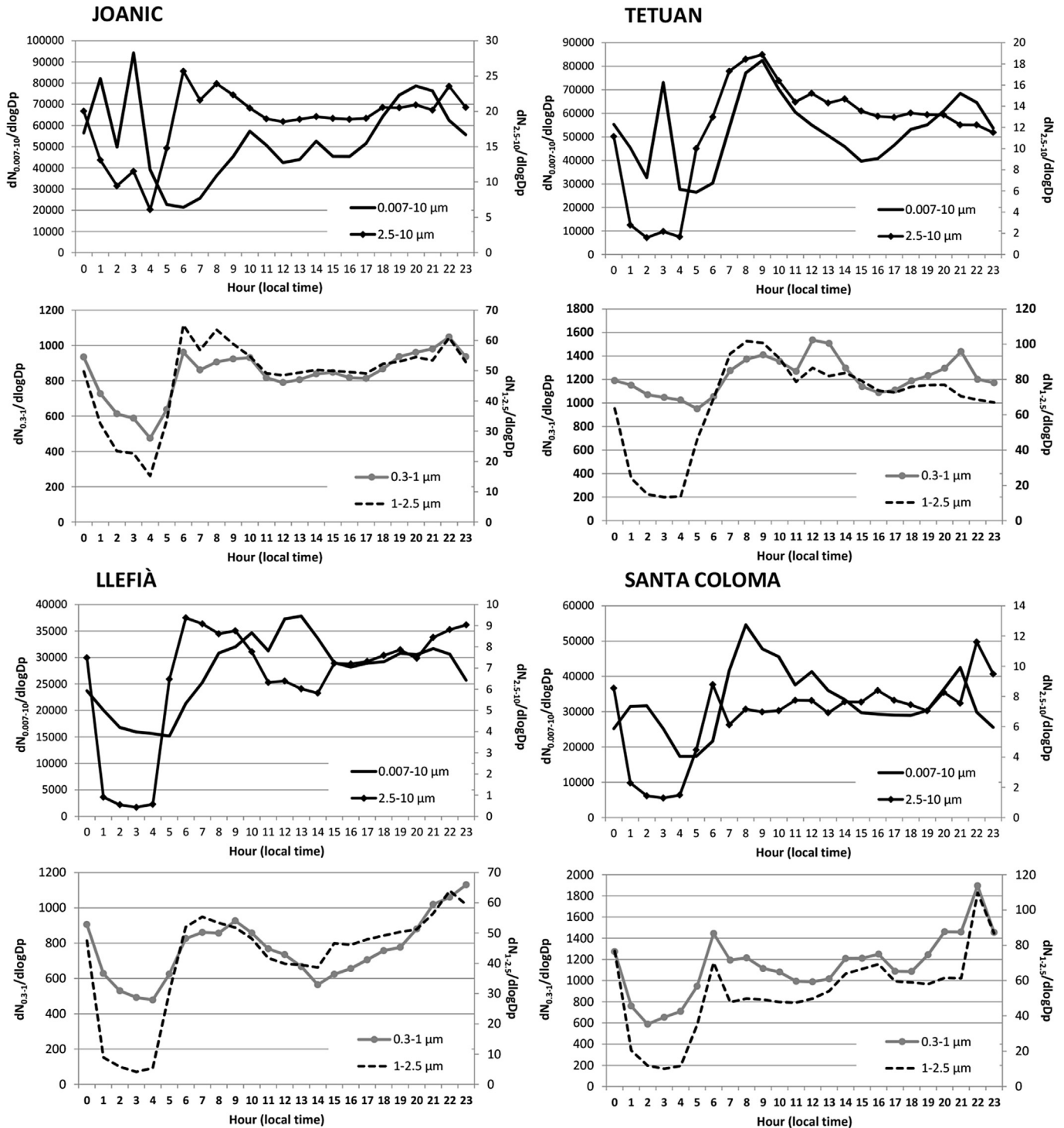


Fig. 3. Mean daily cycle of N concentrations, expressed as $dN/d\log D_p$, for particles in the size ranges 0.007–10 (as reported by ELPI), 0.3–1, 1–2.5, and 2.5–10 μm (as reported by OPS) at Joanica, Tetuan, Llefià and Santa Coloma stations.

3.3. Time variation of N concentrations

Table 5 shows the kernel density plots of $N_{0.007-10}$ and $N_{0.3-10}$ concentrations during weekdays for the colder and the warmer periods and distinguishing between three different periods of the day, based on the train frequency: non-operating hours (0:00–5:00 h), hours with the maximum train frequency (7:00–9:00 h), and hours with a standard train frequency

(10:00–21:00 h). These periods were selected not only based on the train frequency but restricting them so that the ventilation setup was homogeneous within each period at all the stations.

As can be observed, for $N_{0.3-10}$ concentrations, two different types of stations can be identified: (1) those clearly following the expected daily trends, with the highest concentrations coinciding with the maximum train frequency and the lowest at nights, and (2) those with concentrations relatively similar between periods.

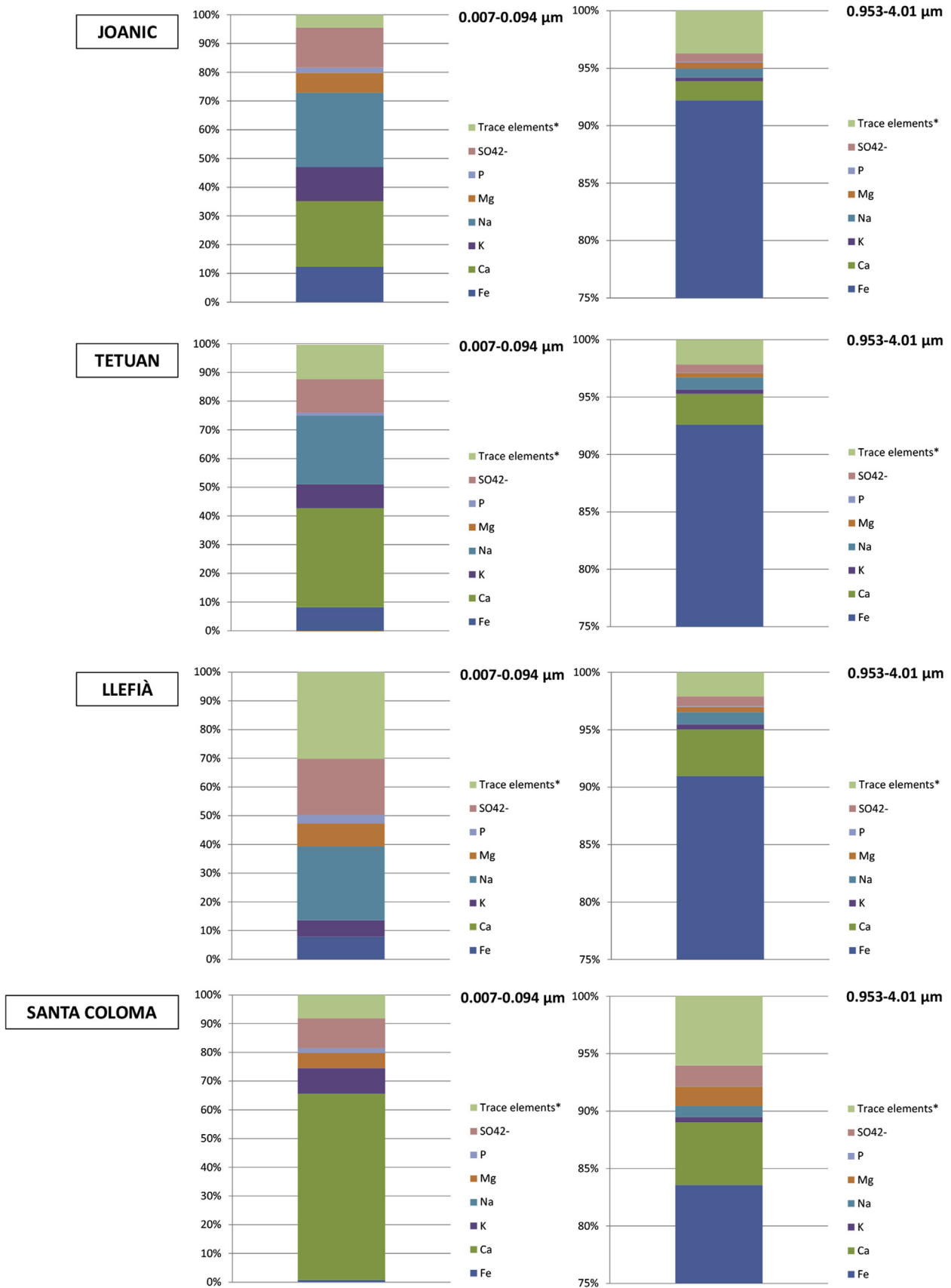
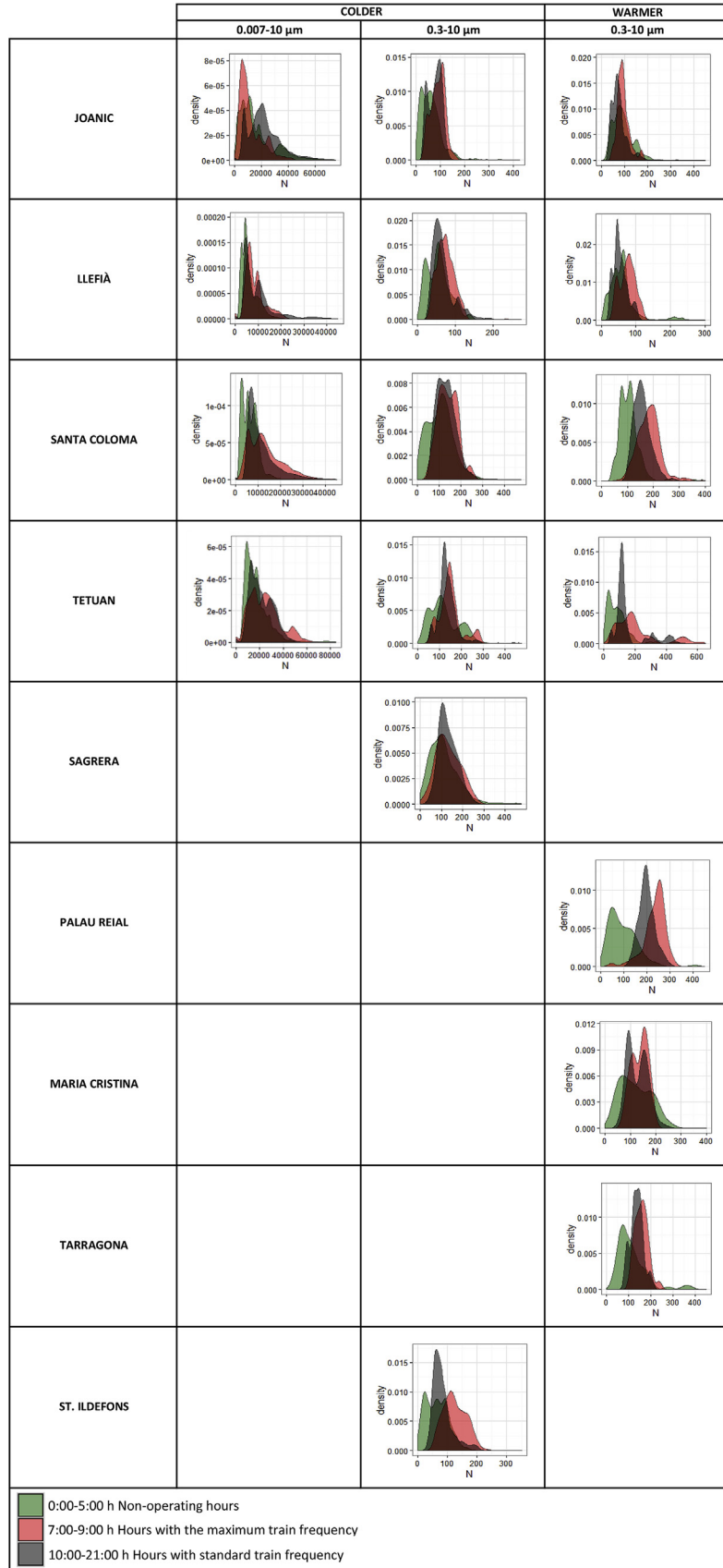


Fig. 4. Relative contribution of the determined chemical components at the four metro platforms during the warmer period for particles in the size ranges 0.007–0.094 and 0.953–4.01 μm *Trace elements include the sum of Li, Sc, Ti, V, Cr, Mn, Co, Ni, Cu, Zn, Ga, Ge, As, Se, Rb, Sr, Y, Zr, Nb, Mo, Cd, Sn, Sb, Cs, Ba, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Pb, Ho, Er, Tm, Yb, Lu, Hf, Ta, W, Tl, Bi, Th, U.

Table 5

Kernel density estimation of 5-min $N_{0.007-10}$ and $N_{0.3-10}$ concentrations for the two different measurement periods, colder and warmer, at all the selected metro stations, and comparing three different periods of the day with differences in the number of trains running. The kernel density function estimates the probability density function of a considered variable (Silverman, 1986). It was used as a known accurate method to study the distribution of a variable (Wand and Jones, 1994).



During the period with the maximum train frequency, $N_{0.3-10}$ concentrations are 2–65% higher on average than at night. This wide range highlights important differences between stations.

When data in a specific station is available for both the warmer and the colder periods, it can be seen that differences between periods are less discernable during the colder period; this is especially true at Santa Coloma and Tetuan stations. Conversely, in Joanic and Llefia, it is not as clear due to the high concentrations recorded at nights during the warmer period. In a number of stations (e.g. Joanic, Llefia and Tarragona during the warmer period), concentrations were found to reach higher values during nights than from 10:00 to 21:00 h or even from 7:00 to 9:00 h, which was related to maintenance/cleaning works carried out during the nights. These works were observed to be responsible for increases in $N_{0.3-10}$ concentrations up to 90%, although these acute events usually lasted less than 30 min.

The station of Palau Reial is the one with the highest $N_{0.3-10}$ concentrations, revealing a poorly-ventilated confined environment, and it is also the one with the clearest differences between periods (Table 5); underlining a significant impact of sources related to train circulation. Very noticeable differences between periods are also observed in Tetuan, where a wide range of concentrations was recorded at 7:00–9:00 h, reaching very high values. An opposite clear example is Sagrera, where concentrations are very similar all day long, which could be related to the design of this station, with two wide accesses located at both ends of the station, allowing for better natural ventilation.

Differences between 7:00–9:00 h and 10:00–21:00 h are generally lower for $N_{0.007-10}$ (dominated by UFP) than for $N_{0.3-10}$, thus the finest particles, which contribute the most to N concentrations, seem to be less affected by the train frequency, as stated in the previous section. In the station of Joanic, $N_{0.007-10}$ concentrations at 10:00–21:00 h were significantly higher than at 7:00–9:00 h, while in the rest of the stations concentrations are very similar. This could be related with the lower depth of Joanic, being more affected by outdoor emissions from a highly road trafficked area.

Variances between stations have not been found to be related to the number of trains operating in each metro line (see Table 2). It is difficult to establish which factors are responsible for this and also to what extent. Nonetheless, the comparison amongst stations seems to indicate that the station design, related to the influence of outdoor emissions, the ventilation set-up efficiency and the occurrence of night activities might be involved.

3.4. Particle number concentrations under specific scenarios

3.4.1. Different ventilation setups

Two different ventilation settings, namely: (A) low extraction of indoor air in the tunnel during operating hours (standard settings in the colder period) and, (B) no ventilation in the tunnel during operating hours, were established to account for differences in air quality conditions at the platforms of Joanic, Santa Coloma and Tetuan (Fig. 5). Ventilation at platforms consisted of impulsion of outdoor air in both cases. Ventilation settings for mode B were tested to assess if the piston effect produced by the movement of the trains was enough to maintain similar air quality conditions than under standard conditions. To avoid time of measurement effects, this analysis was performed accounting for those periods when the ELPI and OPS were simultaneously measuring. Details of the statistical tests used to determine if the differences between ventilation settings at each station and for each size range were significant are reported in the supporting information (Table S2a). Table S2a summarizes the median and the interquartile range (25th–75th percentile) of N concentrations for each station and

ventilation protocol during metro operating hours, as shown in Fig. 5. It also shows the p-value corresponding to the Mann-Whitney-Wilcoxon tests performed under the hypothesis that modifying the standard conditions would result in increased concentrations. Concentrations were higher under mode B than under standard conditions during operating hours at Joanic and Tetuan. This is especially evident at the station of Joanic, highlighting the increase recorded for $N_{0.007-10}$ (>60%). At this station, increases are statistically significant for all size ranges. The increase at both stations lessens as the lower limit of particle size increase, and it is almost negligible in the case of Tetuan for $N_{2.5-10}$, when differences in concentrations between periods are not statistically significant. This seems to indicate that mechanical ventilation in the tunnel during the colder period is not enough to significantly reduce coarse particles at Tetuan, highlighting the need of further measures. Conversely, at Santa Coloma station, concentrations were very similar during both periods, only $N_{0.3-1}$ concentrations seem to suffer a slight increase. It can be concluded that narrow platforms served by single-track tunnels or by two rail tracks separated by a middle wall seem to strongly depend on the mechanical ventilation in the tunnel and the motion of the train is not enough to maintain similar air quality conditions. On the contrary in Santa Coloma with a more spacious double-track tunnels, particles are not as affected when the tunnel ventilation is switched off, which represent an opportunity of energy savings, as previously observed for $PM_{2.5}$ concentrations by Moreno et al. (2014).

3.4.2. Intense maintenance works

Maintenance works are frequent activities carried out at metro stations during night-time, and are likely to affect the air quality of the metro station. They take place from 0:00 to 5:00 h in order to avoid affecting the normal operation of the metro line. The study of how the impact of these works progresses over time is important to characterize the possible effect on the passengers' exposure. The sampling campaign carried out at Sagrera station (L5) was mainly aimed to the assessment of this effect. In this station, intensive renewal works were performed in order to mitigate rail vibrations in the tunnel. These works were performed during 31 nights (44% of measurement days), and they include material transport using diesel vehicles; sleepers' replacement including railway cut and ballast addition and tamping; rail installation; and welding works. All these activities were carried out using gasoline/diesel machinery. $N_{0.3-10}$ concentrations during nights affected by these intense works were by 30–60% higher than at nights under normal conditions. Acute increases (>90%) were observed, but lasted less than 1 h, probably due to an appropriate ventilation at tunnels, mediated by impulsion of outdoor air at nights. Table S2b summarizes the median and the interquartile range (25th–75th percentile) of N concentrations during metro operating hours (5:00–0:00 h) for each size range and distinguishing days following nights affected by works and nights under normal conditions. The Mann-Whitney-Wilcoxon test was selected to account for the significance of the differences in N concentrations between the distinguished days (see Table S2b for information about p-values). During those days following works, median N_{1-10} concentrations were significantly higher (by 15–30%; p-value <0.001) than during days under normal conditions (Figure S3, Table S2b). The highest concentrations were reported during the activities related with material transport and sleepers' replacement, while during new rail installation concentrations were similar to those measured before the beginning of the works period (Table S3).

4. Conclusions

Underground urban rail systems carry more passengers per trip

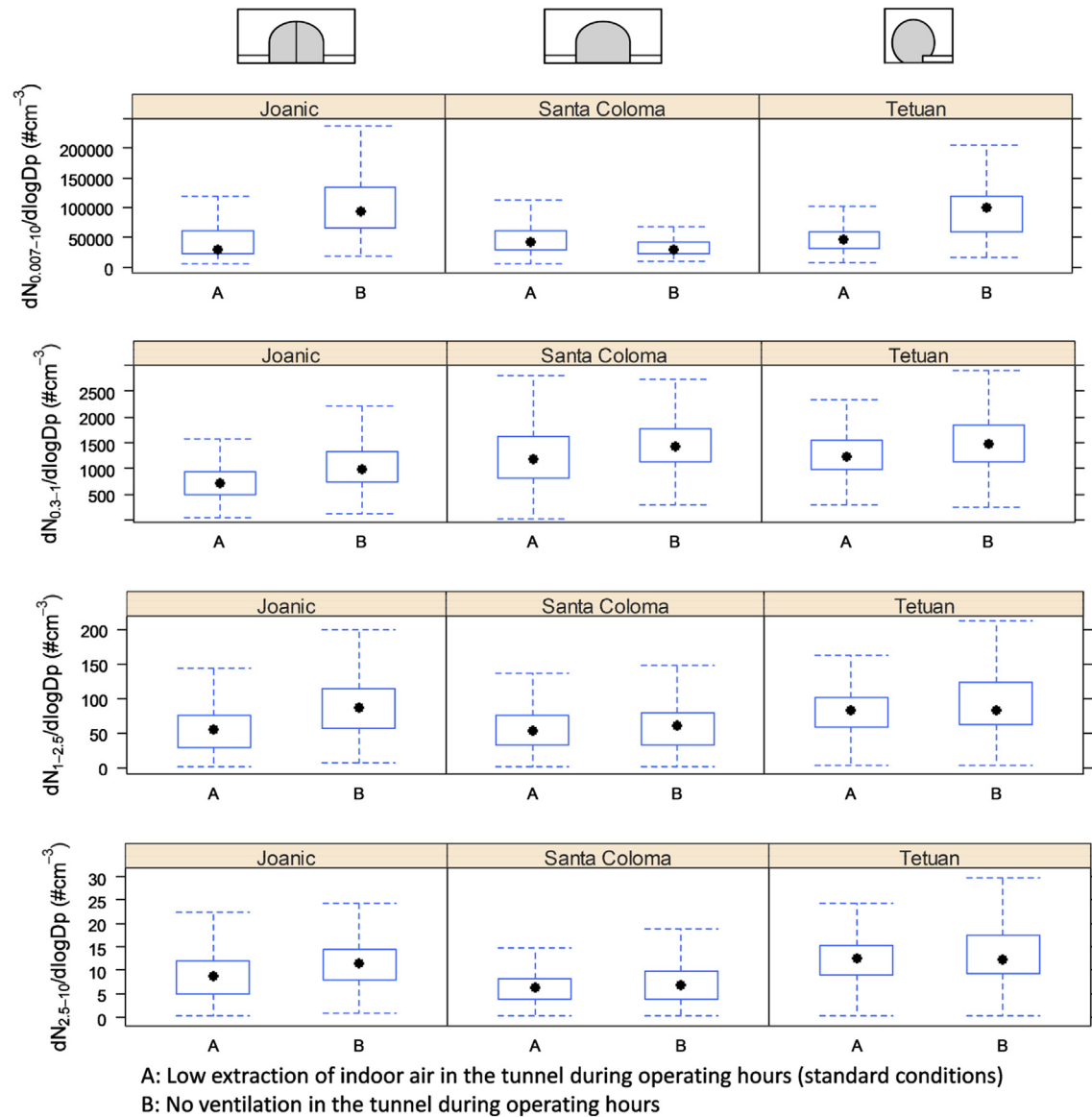


Fig. 5. Box plots of 5-min $dN/d\log D_p$ concentrations for four different size ranges (0.007–0.094, 0.3–1, 1–2.5, 2.5–10 μm), comparing two ventilation settings. The black circle within the box plots shows the median concentrations, while the box bottom and top represent the 25th and 75th percentile, respectively. The whiskers represent the lower and the upper bounds.

in some urban areas than any other commuting mode. Studies have shown that metro air quality can be substantially different than corresponding outdoor ambient air level or other commuting exposure in terms of airborne particles concentration, sizes and chemical composition; even concluding that metro particles have a higher oxidative potential than outdoor ambient particles. In this context, indoor measurements of real-time N concentrations and size distribution were measured at 9 metro station platforms located in the metropolitan area of Barcelona. The main results from this study can be summarized as follows:

- $N_{0.3-10}$ concentrations vary widely among stations, with the higher values being recorded in those stations belonging to the oldest metro lines of the system. The lowest concentrations were recorded at the newest metro station, equipped with PSDs, which may be able to limit the amount of particles introduced to the platform from the tunnel, and, mainly, with an advanced ventilation setup.
- Discrepancies in the daily evolution of N concentrations comprising different sizes suggest that $N_{0.007-10}$ (mainly accounting for UFP) could be partly governed by the entrance of particles from outdoor emissions through mechanical ventilation. Conversely, the evolution of $N_{0.3-10}$ is more closely related with the activities of the metro service.
- The extent to which $N_{0.3-10}$ concentrations are affected by changes in the hourly train frequency varies between stations and between seasonal periods. Factors responsible for these differences have not been totally resolved, although the station design, related to the influence of outdoor emissions, and the ventilation-setup efficiency are likely to be involved.
- The study of N concentrations under specific scenarios reveals that: (1) at old design stations with a spacious double-track tunnel, N concentrations are not significantly affected when the tunnel ventilation is switched off, what could mean important energy savings; (2) during metro operating hours, coarse particles are reduced in a lesser extent than fine particles

by the current mechanical ventilation, particularly at narrow platforms served by single-track tunnels; (3) intense night-time maintenance works at tunnels can increase N concentrations during the following metro operating hours at platforms by up to 30%, specially of N_{1-10} .

This study implicates that the same abatement strategies are not efficient for all particle size ranges at metro stations, highlighting a major challenge. The control of coarse particles during rush hours should be a priority to reduce metro user exposure when compared with ground-level urban concentrations.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at <http://dx.doi.org/10.1016/j.atmosenv.2017.03.002>.

References

- Aarnio, P., Yli-Tuomi, T., Kousa, A., Mäkelä, T., Hirsikko, A., Hämeri, K., Jantunen, M., 2005. The concentrations and composition of and exposure to fine particles (PM_{2.5}) in the Helsinki subway system. *Atmos. Environ.* 39 (28), 5059–5066. <http://dx.doi.org/10.1016/j.atmosenv.2005.05.012>.
- Ajuntament de Barcelona, 2015. Dades bàsiques de mobilitat. Available at: http://ajuntament.barcelona.cat/ecologiaurbana/sites/default/files/DADES-BASIQUESMOBILITAT_2015_Resum.pdf.
- Bachoual, R., Boczkowski, J., Goven, D., Amara, N., Tabet, L., On, D., Leçon-Malas, V., Aubier, M., Lanone, S., 2007. Biological effects of particles from the paris subway system. *Chem. Res. Toxicol.* 20 (10), 1426–1433. <http://dx.doi.org/10.1021/tx700093j>.
- Birenzvege, a., Eversole, J., Seaver, M., Francesconi, S., Valdes, E., Kulaga, H., 2003. Aerosol characteristics in a subway environment. *Aerosol Sci. Technol.* 37 (3), 210–220. <http://dx.doi.org/10.1080/02786820300941>.
- Chan, C.C., Spengler, J.D., Ozkaynak, H., Lefkopoulou, M., 1991. Commuter exposures to VOCs in Boston, Massachusetts. *J. Air Waste Manag. Assoc.* 41, 1594–1600.
- Cheng, Y.H., Liu, C.C., Lin, Y.L., 2009. Levels of ultrafine particles in the taipei rapid transit system. *Transp. Res. Part D Transp. Environ.* 14 (7), 479–486. <http://dx.doi.org/10.1016/j.trd.2009.06.002>.
- Cheng, Y.-H., Yan, J.-W., 2011. Comparisons of particulate matter, CO, and CO₂ levels in underground and ground-level stations in the Taipei mass rapid transit system. *Atmos. Environ.* 45 (28), 4882–4891. <http://dx.doi.org/10.1016/j.atmosenv.2011.06.011>.
- Chien, C.-H., Theodore, A., Wu, C.-Y., Hsu, Y.-M., Birky, B., 2016. Upon correlating diameters measured by optical particle counters and aerodynamic particle sizer. *J. Aerosol Sci.* 101, 77–85. <http://dx.doi.org/10.1016/j.jaerosci.2016.05.011>.
- Colombi, C., Angius, S., Gianelle, V., Lazzarini, M., 2013. Particulate matter concentrations, physical characteristics and elemental composition in the Milan underground transport system. *Atmos. Environ.* 70, 166–178. <http://dx.doi.org/10.1016/j.atmosenv.2013.01.035>.
- Cusack, M., Talbot, N., Ondráček, J., Minguillón, M.C., Martins, V., Klouda, K., Schwarz, J., Ždímal, V., 2015. Variability of aerosols and chemical composition of PM₁₀, PM_{2.5} and PM₁ on a platform of the Prague underground metro. *Atmos. Environ.* 118, 176–183. <http://dx.doi.org/10.1016/j.atmosenv.2015.08.013>.
- Furuya, K., Kudo, Y., Okinaga, K., Yamuki, M., Takahashi, S., Araki, Y., Hisamatsu, Y., 2001. Seasonal variation and their characterization of suspended particulate matter in the air of subway stations. *J. Trace Microprobe Tech.* 19 (4), 469–485. <http://dx.doi.org/10.1081/TMA-100107583>.
- Gustafsson, M., Blomqvist, G., Swietlicki, E., Dahl, A., Gudmundsson, A., 2012. Inhalable railroad particles at ground level and subterranean stations – physical and chemical properties and relation to train traffic. *Transp. Res. Part D Transp. Environ.* 17 (3), 277–285. <http://dx.doi.org/10.1016/j.trd.2011.12.006>.
- Hwang, S.H., Park, J.B., 2014. Comparison of culturable airborne bacteria and related environmental factors at underground subway stations between 2006 and 2013. *Atmos. Environ.* 84, 289–293. <http://dx.doi.org/10.1016/j.atmosenv.2013.11.064>.
- Kang, S., Hwang, H., Park, Y., Kim, H., Ro, C.-U., 2008. Chemical compositions of subway particles in seoul, korea determined by a quantitative single particle analysis. *Environ. Sci. Technol.* 42 (24), 9051–9057. <http://dx.doi.org/10.1021/es802267b>.
- Karlsson, H.L., Holgersson, A., Möller, L., 2008. Mechanisms related to the genotoxicity of particles in the subway and from other sources. *Chem. Res. Toxicol.* 21 (3), 726–731. <http://dx.doi.org/10.1021/tx700356f>.
- Klepczynska-Nyström, A., Larsson, B.-M., Grunewald, J., Pousette, C., Lundin, A., Eklund, A., Svartengren, M., 2012. Health effects of a subway environment in mild asthmatic volunteers. *Respir. Med.* 106 (1), 25–33. <http://dx.doi.org/10.1016/j.rmed.2011.09.008>.
- Kwon, S.B., Namgung, H.G., Jeong, W., Park, D., Eom, J.K., 2016. Transient variation of aerosol size distribution in an underground subway system. *Environ. Monit. Assess.* 188, 361.
- Levy, J.I., Dumyah, T., Spengler, J.D., 2002. Particulate matter and polycyclic aromatic hydrocarbon concentrations in indoor and outdoor microenvironments in Boston, Massachusetts 104–114.
- Ma, C., Matuyama, S., Sera, K., Kim, S., 2012. Physicochem. Prop. Indoor Part. Matter Collect. Subw. Platf. Jpn. 6 (June), 73–82.
- Martins, V., Minguillón, M.C., Moreno, T., Querol, X., de Miguel, E., Capdevila, M., Centelles, S., Lazaridis, M., 2015b. Deposition of aerosol particles from a subway microenvironment in the human respiratory tract. *J. Aerosol Sci.* 90, 103–113. <http://dx.doi.org/10.1016/j.jaerosci.2015.08.008>.
- Martins, V., Moreno, T., Minguillón, M.C., Amato, F., Miguel, E., De Capdevila, M., Querol, X., 2015a. Exposure to airborne particulate matter in the subway system. *Sci. Total Environ.* 511, 711–722. <http://dx.doi.org/10.1016/j.scitotenv.2014.12.013>.
- Martins, V., Moreno, M., Minguillón, M.C., van Drooge, B., Reche, C., Amato, F., de Miguel, E., Capdevila, M., Centelles, S., 2016a. Origin of inorganic and organic components of PM_{2.5} in subway stations of Barcelona, Spain. *Environ. Pollut.* 208, 125–136.
- Martins, V., Moreno, T., Mendes, L., Eleftheriadis, K., Diapouli, E., Alves, C.A., Duarte, M., de Miguel, E., Capdevila, M., Querol, X., Minguillón, M.C., 2016b. Factors controlling air quality in different European subway systems. *Environ. Res.* 146, 35–46. <http://dx.doi.org/10.1016/j.envres.2015.12.007>.
- Mejia, J.F., Morawska, L., Mengersen, K., 2008. Spatial variation in particle number size distributions in a large metropolitan area. *Atmos. Chem. Phys.* 8, 1127–1138.
- Midander, K., Elihn, K., Wallén, A., Belova, L., Karlsson, A.-K.B., Wallinder, I.O., 2012. Characterisation of nano- and micron-sized airborne and collected subway particles, a multi-analytical approach. *Sci. Total Environ.* 427–428, 390–400. <http://dx.doi.org/10.1016/j.scitotenv.2012.04.014>.
- Morawska, L., Thomas, S., Bofinger, N., Wainwright, D., Neale, D., 1998. Comprehensive characterization of aerosols in a subtropical urban atmosphere: particle size distribution and correlation with gaseous pollutants. *Atmos. Environ.* 32, 2467–2478.
- Moreno, T., Martins, V., Querol, X., Jones, T., Bérubé, K., Minguillón, M.C., Amato, F., Capdevila, M., de Miguel, E., Centelles, S., Gibbons, W., 2014. A new look at inhalable metalliferous airborne particles on rail subway platforms. *Sci. Total Environ.* 505C, 367–375. <http://dx.doi.org/10.1016/j.scitotenv.2014.10.013>.
- Moreno, T., Reche, C., Rivas, I., Minguillón, M.C., Martins, V., Vargas, C., Buonanno, G., Parga, J., Pandolfi, M., Brines, M., Ealo, M., Fonseca, A.F., Amato, F., Sosa, G., Capdevila, M., de Miguel, E., Querol, X., Gibbons, W., 2015. Urban air quality comparison for bus, tram, subway and pedestrian commutes in Barcelona. *Environ. Res.* 142, 495–510. <http://dx.doi.org/10.1016/j.envres.2015.07.022>.
- Moreno, T., Kelly, F.J., Dunsnter, C., Oliete, A., Martins, V., Reche, C., Minguillón, M.C., Amato, F., Capdevila, M., de Miguel, E., Querol, X., 2017. Oxidative potential of subway PM_{2.5}. *Atmos. Environ.* 148, 230–328.
- Nieuwenhuijsen, M.J., Gómez-Perales, J.E., Colvile, R.N., 2007. Levels of particulate air pollution, its elemental composition, determinants and health effects in metro systems. *Atmos. Environ.* 41 (37), 7995–8006. <http://dx.doi.org/10.1016/j.atmosenv.2007.08.002>.
- Onat, B., Stakeeva, B., 2013. Personal exposure of commuters in public transport to PM_{2.5} and fine particle counts. *Atmos. Pollut. Res.* 4, 329–335. <http://dx.doi.org/10.5094/APR.2013.037>.
- Pagels, J., Gudmundsson, A., Gustavsson, E., Asking, L., Bohgard, M., 2007. Evaluation of aerodynamic particle sizer and electrical low-pressure impactor for unimodal and bimodal mass-weighted size distributions. *Aerosol Sci. Technol.* 39, 871–887.
- Park, D., Oh, M., Yoon, Y., Park, E., Lee, K., 2012. Source identification of PM₁₀ pollution in subway passenger cabins using positive matrix factorization. *Atmos. Environ.* 49, 180–185. <http://dx.doi.org/10.1016/j.atmosenv.2011.11.064>.
- Price, H.D., Stahlmecke, B., Arthur, R.A., Kaminski, H., Lindermann, J., Däuber, E., Asbach, C., Kuhlbusch, T.A.J., Berube, K.A., Jones, T.P., 2014. Comparison of instruments for particle number size distribution measurements in air quality monitoring. *J. Aerosol Sci.* 76, 48–55.
- Querol, X., Moreno, T., Karanasiou, A., Reche, C., Alastuey, a., Viana, M., Font, O., Gil, J., de Miguel, E., Capdevila, M., 2012. Variability of levels and composition of PM₁₀ and PM_{2.5} in the Barcelona metro system. *Atmos. Chem. Phys.* 12 (11), 5055–5076. <http://dx.doi.org/10.5194/acp-12-5055-2012>.
- Seaton, a, Cherrie, J., Dennekamp, M., Donaldson, K., Hurley, J.F., Tran, C.L., 2005. The London Underground: dust and hazards to health. *Occup. Environ. Med.* 62 (6), 355–362. <http://dx.doi.org/10.1136/oem.2004.014332>.
- Silva, C.B.P.Da, Saldiva, P.H.N., Amato-Lourenço, L.F., Rodrigues-Silva, F., Miraglia, S.G.E.K., 2012. Evaluation of the air quality benefits of the subway system in São Paulo, Brazil. *J. Environ. Manag.* 101, 191–196. <http://dx.doi.org/10.1016/j.jenvman.2012.02.009>.

- Silverman, B.W., 1986. *Density Estimation for Statistics and Data Analysis*. CRC press.
- Steenhof, M., Gosens, I., Strak, M., Godri, K.J., Hoek, G., Cassee, F.R., Mudway, I.S., Kelly, F.J., Harrison, R.M., Lebet, E., Brunekreef, B., Jansen, N.A., Pieters, R.H.H., 2011. In vitro toxicity of particulate matter (PM) collected at different sites in The Netherlands is associated with PM composition, size fraction and oxidative potential—the RAPTES project. *Part. fibre Toxicol.* 8 (1), 26. <http://dx.doi.org/10.1186/1743-8977-8-26>.
- Suárez, L., Mesías, S., Iglesias, V., Silva, C., Cácers, D.D., Ruiz-Rudolph, P., 2014. Personal exposure to particulate matter in commuters using different transport modes (bus, bicycle, car and subway) in an assigned route in downtown Santiago, Chile. *Environ. Sci. Process. Impacts* 16, 1309–1317.
- Triadó-Margarit, X., Veillette, M., Duchaine, C., Talbot, M., Amato, F., Minguillón, M.C., Martins, V., de Miguel, E., Casamayor, E.O., Moreno, T., 2016. Bioaerosol in the Barcelona subway system. *Indoor Air* 1–12.
- Vasconcellos, E.A., 2001. *Urban Transport, Environment and Equity: The Case for Developing Countries*. Earthscan, London.
- Wad, A.H.A.A., 2002. Environmental study in subway metro stations in cairo, Egypt. *J. Occup. Health* 44, 112–118.
- Wand, M.P., Jones, M.C., 1994. *Kernel Smoothing*. Crc Press.