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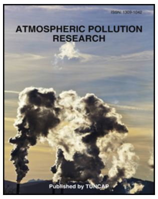

Monitoring of ultrafine particles in the surrounding urban area of a civilian airport

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ABSTRACT

Airports have been identified as a significant source of ultrafine particulate matter (UFP, particulate matter with diameter less than 0.1 μm), which may induce or aggravate pulmonary or cardio-respiratory health conditions, if prolonged exposure to high concentrations of UFP occur. Thus, assessing its impacts is vital to estimate UFP contribution to air quality degradation within the city and the degree of population exposure. However, there is lack of information regarding UFP concentrations in the vicinity of airports. This work aims to study the influence of air traffic and ground activities of Lisbon Airport (LA), in the surrounding urban area, focusing on the UFP concentrations. An UFP monitoring campaign was carried out in 2017 and 2018, for a 19 non-consecutive days period. The monitoring network was designed to include several sampling sites in the vicinity of LA and a set of sites further away of the LA, under the landing or take-off path. Based on the information collected, correlation analysis between air traffic activity and UFP concentrations was conducted. The results show the occurrence of high UFP concentrations in LA vicinity. Considering 10-min means, the particle counting increased 18–26-fold at locations near the airport, downwind, and 4-fold at locations up to 1 km distance to LA. Adverse orographic conditions leads to UFP punctual and average high concentrations. Results show that particle number increases with the number of flights and decreases with the distance to LA.

1. Introduction

The past 20 years have seen European airports evolve from mere infrastructure providers into businesses, directly contributing to the employment of people and also to the nearest cities' development (ACI, 2016). During the past decades, air traffic registered a significant global increase, which is expected to continue over the coming decades. Data from the International Airports Council shows that, in Europe, between 1990 and 2014, there was an 80% increase in the number of flights, and it is estimated that this figure will increase by about 50% over the next 20 years. Furthermore, an increase in aircraft age and travelled distance is also expected (ACI, 2016). These factors together contribute significantly to the worsening of the impacts associated with air traffic, namely local air quality, noise levels and greenhouse gas emissions. Air quality is particularly affected by the large quantities of particulate matter (PM) emitted by airplanes, with consequent implications on air quality, as some studies have showed (e.g. Morawska et al., 2009). PM is one of the most harmful pollutants to human health (ACI, 2016; EEA, 2016) leading to health impacts on populations, living close to airports, and workers (Cattani et al., 2014). Several studies identify airports as a significant source of several pollutants, such as: fine particles, with an aerodynamic diameter less than 2.5 μm ($PM_{2.5}$) and ultrafine particles (with an aerodynamic diameter less than 0.1 μm, UFP), nitrogen dioxide (NO_2) and volatile organic compounds (VOC). They also reveal significant increases in UFP concentrations in the vicinity of several airports (Westerdahl et al., 2008; Zhu et al., 2009; Hsu et al., 2013, 2014; Hudda et al., 2014; Keuken et al., 2015; Stafoggia et al., 2016). Unlike the health effects of $PM_{2.5}$ and PM_{10} (IARC, 2014; Buonanno et al., 2015; Ebisu et al., 2016; César et al., 2016; Grana et al., 2017), the conclusions regarding the effects of UFP are limited because they are not regularly measured (Lanzinger et al., 2016). Nevertheless, results from previous studies suggest that prolonged exposure to high concentrations of UFP may be responsible for reduced lung function and/or aggravation of respiratory diseases, such as asthma or chronic obstructive pulmonary disease (Carosino et al., 2015; Terzano et al., 2010; Stanek et al., 2011; Slezakova et al., 2012; Ferreira et al., 2013). Although clinical studies related to UFP exposure are still not enough for unequivocal conclusions regarding its toxicity, they make clear that its effects should not be neglected (Gomes et al., 2012). In this context, together with airport locations close to urban and suburban areas,

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special attention should be devoted to human health in those areas. Some of these studies were conducted close to the main European airports, namely trying to distinguish the range of average UFP concentrations in those European cities (Kumar et al., 2014; Hofman et al., 2016).

Regarding Lisbon, several studies have been carried out to evaluate air quality in the area of Lisbon and its surroundings (Russo et al., 2014a,b; FCT-NOVA, 2017; Monjardino et al., 2018). Also, several interventions have been carried out in areas considered critical to contribute to air quality improvement (Ferreira et al., 2015; Monteiro et al., 2015). However, there is a lack of studies performed to assess UFP levels. One of the main reported contributors to air pollution in Lisbon is road traffic (Russo and Soares, 2013), which is characterized by the emission of toxic particles and gases. However, another emission source which is far less addressed in those studies is the activity of the aviation industry (Ren et al., 2018; Stacey, 2019). In Portugal there are no detailed studies on the impact of airports on air quality on its surroundings, regarding particulate matter concentrations in general, and UFP in particular, or other atmospheric pollutants. One way to overcome this gap is to assess air concentrations of UFP based on UFP measures collected within airport's vicinity. Therefore, this study intends to fill the referred information gap, assessing the air traffic in LA activities effect on UFP concentrations, which assumes special relevance due to LA's location: within the city centre, surrounded by residential, business, services and recreational areas, schools, sport complexes, hospitals and companies, among others. Furthermore, given the lack of studies in airport-related UFP concentrations in the immediate airport's vicinity, it also aims to assess the airport-related UFP concentrations in the immediate LA vicinity.

Another gap on assessing air quality on airports is that, in the aviation sector, total emissions are given by the sum of the emissions occurred at distinct phases, namely on taxi out and ground idle, take-off, climb, cruise, descent, final approach, landing and taxi in and ground idle (ICAO, 2011). Landing operating phases includes both (1) the approach (bellow 915 m, duration of 4 min and thrust setting to 30%) and (2) the landing, taxi and ground idle (duration of 7 min and thrust setting to 7%). Conversely, take-off operating phases include (1) taxi and ground idle to take-off (duration of 19 min and thrust setting to 7%), (2) take-off (ground to 450 m, duration of 0.7 min and thrust setting to 100%) and (3) climbing (from 450 to 915 m, duration of 2.2 min and thrust setting to 85%) (ICAO, 2011). Moreover, the landing and take-off cycle (LTO) includes all activities near the airport, which occur bellow 914 m. Relevant direct air quality impacts, at local and regional levels, result from emissions during LTO cycles. Above this altitude aircraft engine emissions also have an impact on air quality, but they have a distinct nature and spatial scale of influence. Besides the evident LTO activities, there are others, such as, passenger and luggage transport, aircrafts maintenance and fuel supply, auxiliary power operations and engines start up, also responsible for UFP emissions.

Therefore, this study intends to fill the above mentioned information gap, assessing the air traffic in LA activities effect on UFP concentrations, which assumes special relevance due to LA's location: within the city centre, surrounded by residential, business, services and recreational areas, schools, sport complexes, hospitals and companies, among others. Furthermore, given the lack of studies in airport-related UFP concentrations in the immediate airport's vicinity, it also aims to assess the airport-related UFP concentrations in the immediate LA vicinity. This study also proposes to assess when and how much air traffic in LA affects UFP concentrations taking into consideration the flights' durations (short/medium or long-haul) and the LTO cycle. A thorough analysis on UFP emissions on the vicinity of the LA will improve the ability and capability of alert system for air quality in Lisbon.

This approach can easily be applied to other airports. We start in Sec.2 by briefly describing the study area, the data used and the proposed approach. In Sec.3 the results are discussed, and Sec.4 concludes the paper.

2. Background and methods

The UFP input into the human body is mainly processed through three ways: respiratory, dermal and ingestion (Albuquerque et al., 2012). Because of their small size, they rapidly reach the bloodstream and spread through all organs (WHO, 2013). Compared to fine particles, and because of their smaller size, they have a much higher specific surface area, which can be associated with increased reactivity and toxicity (Sioutas et al., 2005; Ezz et al., 2015). Ultrafine particles can also cross the cell membranes and damage intracellular proteins, organelles and DNA (Peters et al., 1997; Penttinen et al., 2001; Semmler et al., 2004; Geiser et al., 2005; Carosino et al., 2015). Consequently, clinical studies related to UFP exposure emphasize that its effects should not be neglected (Gomes et al., 2012), as prolonged exposure to high concentrations of UFP may be responsible for reduced lung function and/or aggravation of respiratory diseases, such as asthma or chronic obstructive pulmonary disease (Carosino et al., 2015; Terzano et al., 2010; Stanek et al., 2011; Slezakova et al., 2012; Ferreira et al., 2013; Habre et al., 2018). Moreover, the economic costs associated with treating these health problems could be considerably reduced by decreasing the atmospheric concentration of UFP and other pollutants (Shah et al., 2013; Holland, 2014).

Aiming to assess the area of influence of air traffic activities on urban and suburban air quality, a monitoring campaign was designed by choosing several sampling sites in the vicinity of LA and a set of sites further away of the LA, under the landing or take-off path (Fig. 1). The unique characteristics of LA, within the city and surrounded by many intense traffic roads, difficult the unequivocal association between UFP and the corresponding particle number concentration (PNC) measurements far from LA, especially regarding the take-off path. Measurements were limited due to geographical conditions, access restrictions to LA boundary and vicinity, equipment performance and variable meteorological conditions. Moreover, other factors that might play a role, such as engine type Masiol and Harrison, 2014; Ren et al., 2016), were not evaluated.

The Lisbon Airport (LA) is the Portuguese larger and busiest airport, with an increasing number of flights (66% between 2008 and 2016) and passengers (97% between 2008 and 2017) (Lisbon Airport, 2017). According to the most recent data, the LA registered in 2016 approximately 183000 flights and it is close to reach its full capacity (185000 flights/year). Currently, LA has only one runway in activity. It is aligned approximately SSW-NNE. Once the predominant winds are from North, most of the landings and take-offs take place from South to North (runway 03). For South wind conditions, landings and take-offs use the same runway, but in opposite direction (runway 21). As shown in Fig. 1a), LA (dashed contour) is located within the city, surrounded by housing, commercial, offices and school complexes. Sampling locations, indicated by numbers, are shown in Fig. 1b). The thin black arrow indicates the only runway and main direction of landing and take-offs; the dashed black line indicates the landing and take-off path and the thick blue arrow on top left, indicates de predominant wind direction (https://pt.windfinder.com/windstatistics/lisboa). The locations close to the airport allow an assessment of the effect of all operations at the airport (landings, take-offs, movement of aircrafts and other vehicles within facilities); the most remote locations are intended to assess the effect of the aircraft approaching or after the take-off. Locations 1 and 2, close to a major road (as sampling sites 3 to 5) but more distant to the airport and out of the predominant wind range, indicate the UFP concentrations expected out of the airport activities influence.

2.1. Monitoring campaigns

Three campaigns were carried between July 2017 and May 2018, covering three different seasons and different sampling periods

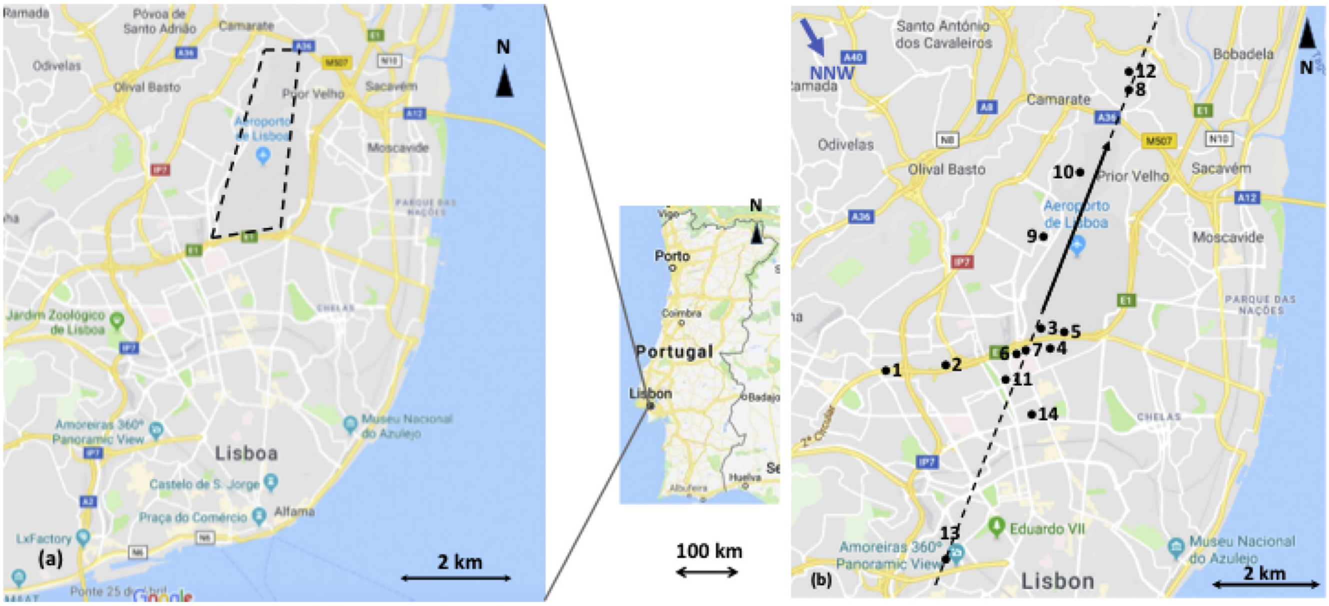


Fig. 1. (a) Airport location (dashed contour) on map. (b) Representation of LA and sampling sites. The thin arrow indicates the main runway and direction of landings and take-offs, the dashed line shows the landing and take-off route, and the thick arrow, on top left, indicates de predominant wind direction. (Maps source: https://www.google.pt/maps, last accessed on April 2018).

(Table 1). The first UFP monitoring campaign was carried out in the summer (4-days monitoring period, in July 2017), the second in the fall (11-days, from October to December 2017) and the third in the spring (4-days, from March to May 2018), complying approximately 75 h of suitable measurements.

When located next to intense traffic roads, the sampling periods were chosen in order to minimize the road traffic influence (weekends and holidays, or dawn). Measurements were carried out with one particle counter equipment. Except for sites 13 and 14, measurements were carried out on the street, where the monitoring equipment was handled by an expert. In sites 13 and 14 (residences) the monitoring equipment was left on a balcony. Each sampling site was properly geo-referenced.

All take-offs and landings during the sampling periods were identified on Flightradar24 (https://www.flightradar24.com/data/airports/lis/), as well as the model and age of the aircraft and destination distance type (short/medium or long-haul).

2.2. Sampling equipment

The ultrafine particles concentrations were measured with the

Table 1
Sampling date and period for each site and the corresponding height of the Mixing Layer (ML), wind speed (v) and direction, temperature (T), relative humidity (RH) and measured minimum (Min), mean and maximum (Max) PNC values.

Site	Date	Period	Distance	ML	Wind		T	RH	PNC [pt.cm^{-3}]		
		[Time UTC]	[m]	[m]	v [km.h^{-1}]	Direction	[°C]	[%]	Min	Mean	Max
Sites located far from the influence of LA[a]											
1	11/07/17	14:49–19:04	2836	617	6	NNW	28	29	3010	14 073	118 000
2	13/07/17	13:29–17:49	1895	400	6	NNW	33	32	1400	15 776	277 000
Sites located in the landing direction and/or under the influence of LA activities[a]											
3	18/07/17	14:05–18:01	314	1000	4	NW	23	61	932	15 516	194 000
4	20/07/17	14:00–18:02	349	1083	7	NNW	22	44	2460	45 865	226 000
5	01/10/17	05:44–08:29	337	0	14	NNW	18	82	750	33 065	342 000
5	05/10/17	06:08–08:08	337	0	5	NNW	14	87	5440	52 676	227 000
6	22/10/17	10:35–10:52	610	724	15	NNW	19	43	2630	92 381	469 000
7	29/10/17	10:05–11:52	497	288	16	NNE	20	35	9860	56 861	343 000
11	19/11/17	10:28–11:58	1197	185	9	NNE	17	48	12 000	58 744	227 000
13	08/12/17	16:05–00:00	4886	0	7	NW	14	91	3910	14 630	120 000
13	09/12/17	00:00–04:58	4886	0	9	NW	12	86	1160	3635	29 900
14	31/03/18	22:10–00:00	1548	0	7	SW	12	78	3370	5066	8470
14	01/04/18	00:00–07:52	1548	0	5	SW-SE	10	84	2720	6680	13 200
14	30/05/18	23:10–00:00	1548	0	14	NW	15	84	2170	4718	28 300
14	31/05/18	00:00–11:43	1548	0–2336	8	NW	16	80	805	4164	23 200
Sites located in the take-off direction[b]											
8	11/11/17	10:32–12:22	821	414	7	NNE	22	46	9090	21 122	325 000
12	25/11/17	09:42–12:03	1272	734	7	NNE	16	89	9480	15 168	243 000
Sites located laterally to the runway[c]											
9	15/11/17	09:51–11:39	692	110	9	NNE	17	41	7750	34 952	172 000
10	18/11/17	09:51–12:06	872	178	6	NNE	19	44	6090	25 041	325 000

[a] The distance is indicated relative to the start of the runway, in a straight line.
[b] The distance is indicated relative to the end of the runway, in a straight line.
[c] The distance is indicated relative to the centre of the runway, in a straight line.

Table 2
P-Trak® technical characteristics (adapted from P Trak®, 2013).

Concentration range	0 to 5 × 10^5 pt cm^{-3}
Particle size range	0.02–1 μm
Operation temperature range	0 to 38 °C
Sample flow rate	100 cm^3/min

particle counter "*P-Trak® Ultrafine Particle Counter, 8525*". The P-Trak® is a portable measuring device which detects and counts, each second, particles with less than 1 μm diameter present in a cubic centimetre volume of air, using an optical method for this purpose. Therefore, the PNC is expressed in number of particles by cubic centimetre (pt.cm^{-3}). The particles captured by the inlet stream are mixed with alcohol vapour (isopropyl). Alcohol is used to grow microscopic particles in the air into larger droplets that are easier to detect and count. This mixture passes through a condenser promoting the condensation of the alcohol on the particle's surface, creating a droplet with enough size to diffuse visible light. Droplets then pass through a laser beam, and a light detector counts the number of light flashes produced, each one corresponding to a particle. Before sampling, it is mandatory to verify that the counter is operating normally. For this purpose, it is used an HEPA zero filter (P-Trak®, 2013) which is attached to the counter that should register zero in a few seconds. Further specifications can be found in Table 2.

Although P-Trak® measures particles less than 1 μm size, and UFP are defined as particles with a diameter less than 0.1 μm, interference will be minimal since, unlike mass concentrations, the concentration of number of particles consists mainly of particles smaller than 0.1 μm (Kumar et al., 2011). Further details about the sampling equipment may be found in P Trak®, 2013.

2.3. Meteorological data

The meteorological conditions during sampling were collected from Portuguese Institute for Sea and Atmosphere. (http://www.ipma.pt/en/otempo/obs.superficie/). The height of the Mixing Layer (ML) was also compiled from atmospheric soundings, at 12:00 UTC over Lisbon (http://weather.uwyo.edu/upperair/sounding.html), for the sampling period (Table 1). Wind data was obtained from IPMA weather station with a 10-min time resolution.

2.4. Data analysis

The sampling dates were chosen based on wind intensity and direction daily forecast, in order to be downwind (or close to downwind) to the airport and/or aircraft plume during each sampling. Furthermore, during sampling the wind speed and direction were permanently both on-site and on IPMA's website checked. Whenever the wind conditions were not satisfactory, the sampling was cancelled. So, regardless the site, measurements were not ever done upwind which allows for a more robust analysis. Once wind direction is highly variable, and similarly to what was done by Hudda et al. (2016), for each site, PNC *versus* 10° wind direction ranges were plotted to find the wind direction responsible for the highest concentrations. These wind directions were called "impact wind direction" (IWD).

A linear regression considering all sampled data, aggregated regardless of the location of the monitoring site, was performed using the Least Squares Method to access correlations between 10-min PNC averages and number of flights, and meteorological parameters, namely wind speed and mixing layer height. In regression between number of flights and PNC, 10-min periods were chosen. During that period both the maximum number of landings and take-offs was 6, whereas the maximum number of flights (landings plus take-offs) was 10. Then, PNC averages during all 10 min without flights, all 10 min with 1 flight, and so on, until the maximum number of flights registered during 10 min were calculated. Finally, we plotted these data and found the correlations between the number of flights and PNC. Regression was performed with a 95% confidence level. Single factor ANOVA was performed among all sites and among sites with similar characteristics with a 95% confidence level.

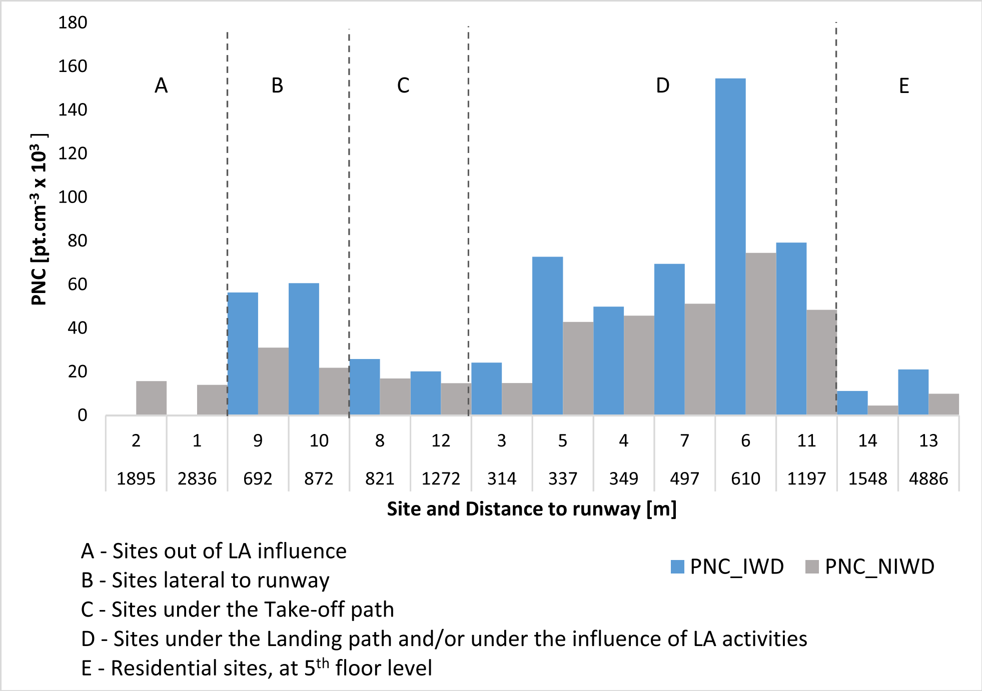


Fig. 2. 10-min PNC averages obtained under impact wind direction (blue) and non-impact wind direction (grey). Sites are ordered by distance to runway and type of location. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3. Results and discussion

3.1. Statistical analysis

The measurements taken at each sampling site (minimum, average and maximum PNC), the respective average meteorological parameters (mixing layer height (ML), wind intensity (v), temperature (T) and relative humidity (RH)) and distance to runway are summarized in Table 1.

Generically, the highest PNC values (average, median, standard deviation and maximum) were found at sampling sites 4, 5, 7 and 11, in LA vicinity, up to 1200 m. Fig. 2 presents the 10-min PNC averages under impact wind direction and other directions (NIWD). Results show that downwind average PNC ranges from 3.3×10^4 pt. cm^{-3} to 5.9×10^4 pt. cm^{-3}, and the peaks range from 2.3×10^5 pt. cm^{-3} to 3.4×10^5 pt. cm^{-3}. Measurements in non-impact wind conditions or further away to LA have lower standard deviation and PNC values (Fig. 2). Sampling sites located laterally to LA main runway (sites 9 and 10) present higher average PNC values than sampling sites located under the take-off path (sites 8 and 12): 2.5×10^4 pt. cm^{-3} to 3.5×10^4 pt. cm^{-3}, and 1.5×10^4 pt. cm^{-3} to 2.1×10^4 pt. cm^{-3}, respectively. Still, both locations present high peak PNC values, range from 1.7×10^5 pt. cm^{-3} to 3.3×10^5 pt. cm^{-3}.

The obtained results for IWD are presented in Table 3. Generally, there are no relevant differences between impact wind direction and other directions values. These results show that most of the time, and regardless the site, measurements were made downwind. The highest differences occur in sites lateral to runway and site 6. Therefore, results may be slightly sub-estimated.

These results are in agreement with the results by Hudda et al. (2014) which analysed UFP emissions in the Los Angeles International Airport, which reach the same level of the ones from the entire city road network. According to this study, the highest UFP concentrations were found aligned downwind to the aircraft's trajectories. In this direction, at 8 km distance from the airport, concentrations over 7.5×10^4 pt. cm^{-3}, were registered. Still regarding Los Angeles airport, Riley et al. (2016), found a 3–5-fold increase in UFP concentrations in transects under the landing approach path. An increase from 1.4×10^4 pt. cm^{-3} (non-downwind conditions) to 4.2×10^4 pt. cm^{-3} (downwind conditions) at 40 km distance from the Schiphol airport (Netherlands) was also observed (Keuken et al., 2015). Additionally, a 2×10^4 pt. cm^{-3}. min^{-1} UFP concentration increase within 5 min after take-offs in Ciampino airport (Rome, Italy) was reported, being incremented by three when measurements were taken under downwind conditions (Stafoggia et al., 2016). Psanis et al. (2017) concluded that UFP concentrations increase by two orders of magnitude during take-offs in a small airport of the Aegean Sea Insular Region. Ren et al. (2016) found UFP emissions during one take-off to be the twice of the UFP emissions from all gasoline passenger vehicles in Tianjin. This study was carried out up to 400 m way from Tianjin International Airport in China for particles from 10 nm to 1 μm. Authors found UFP to be the main aircraft particles emissions. It is also highlighted the lack of studies in the immediate airport vicinity (up to 400 m away) and within the airport (Ren et al., 2018).

Table 3
Impact wind directions (IWD, in °) by site.

Site	IWD (°)	Site	IWD (°)
3	351–360	9	71–80
4	351–360	10	91–100
5 (Flights)[a]	321–330	11	51–60
5 (Iddling)[a]	11–20	12	101–110
6	1–10	13	311–320
7	61–70	14	311–320
8	21–30		

[a] Please see Fig. 6.

Table 4a
Single factor ANOVA among all sites.

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Sites	199145	13	15319	64,4	5,1E-92	1,7
Within Sites	101856	428	238			
Total	301001	441				

Table 4b
Single factor ANOVA among sites with similar characteristics.

Sites	Location	p-value
1 and 2	Out of LA influence	0.42
9 and 10	Lateral to LA	0.15
8 and 12	Take-off path	0.09
13 and 14	Residences	< 0.01
4, 5, 7 and 11	Landing path and/or under LA influence	0.30

Single factor ANOVA among sites presented in Table 4a clearly presents statistically significant differences in the means among all sites (p-value much lower than 0.01). This result shows that at least one site presents a different mean value. However, when applied to sites with identical location, ANOVA outputs indicate that means are statistically identical. Table 4b resumes the obtained p-values. Residential sites present statistically different means. However, it should be noticed that they are about 5 km distance from each other. When site 6 is added to "Landing path and/or under LA influence" group, ANOVA returns a p-value much lower than 0.01. This result highlights the particular aircraft plume dispersion conditions. This site is located close to LA (610 m from runway 03) in a terrain depression in comparison to the LA baseline. This particular orography affects the aircraft plume dispersion leading to higher PNC than the values measured in site 7, closer to LA (500 m from runway 03), but a few meters higher than site 6.

Results from regression analysis between PNC and the number of flights show significant correlation coefficients (r) between PNC and the total number of flights, as well as, between PNC and the number of landings and take-offs (Fig. 3). Results show higher positive correlations between PNC and the number of flights ($r = 0.90$, $p = 0.01$). Comparing the obtained results for take-offs and landings (please see Data Analysis for details), take-offs have a significant and higher positive correlation value ($r = 0.86$, $p = 0.01$) than landings, although also statistically significant ($r = 0.78$, $p = 0.04$). During landings aircraft engine power is approximately set to 30% while it operates at 100% power during take-off, with consequent higher emissions (ICAO, 2011). The obtained results from regression analysis between PNC and mixing layer height were insignificant. On the other hand, correlations between PNC and wind intensity (Fig. 3d) shows a moderate positive statistically significant correlation ($r = 0.57$, $p < 0.01$).

Obtained results are in agreement with previous studies (Keuken et al., 2015; Campagna et al., 2016; Riley et al., 2016; Stafoggia et al., 2016; Psanis et al., 2017) that found significant positive correlation values between PNC and total number of flights. Additionally, the stronger relationship between PNC and take-offs highlights that take-offs have stronger impact on PNC, also in accordance with previous studies (e.g. Stafoggia et al., 2016 and Ren et al., 2016). Also, the moderate positive correlation between PNC and wind intensity is in accordance with previous studies. Generally, higher wind speed promotes greater dispersion and mixing, and PNC and wind speed are negatively correlated. However, for buoyant aircraft plumes, higher wind speeds promote faster ground arrival which counterbalance the dispersion (Hudda et al., 2018).

The range of 10-min PNC average by site is plotted in Fig. 4 (1st quartile, average (x), median (−), 3rd quartile and outliers (dots). Sites are ordered by typology of location and increase distance to LA. The

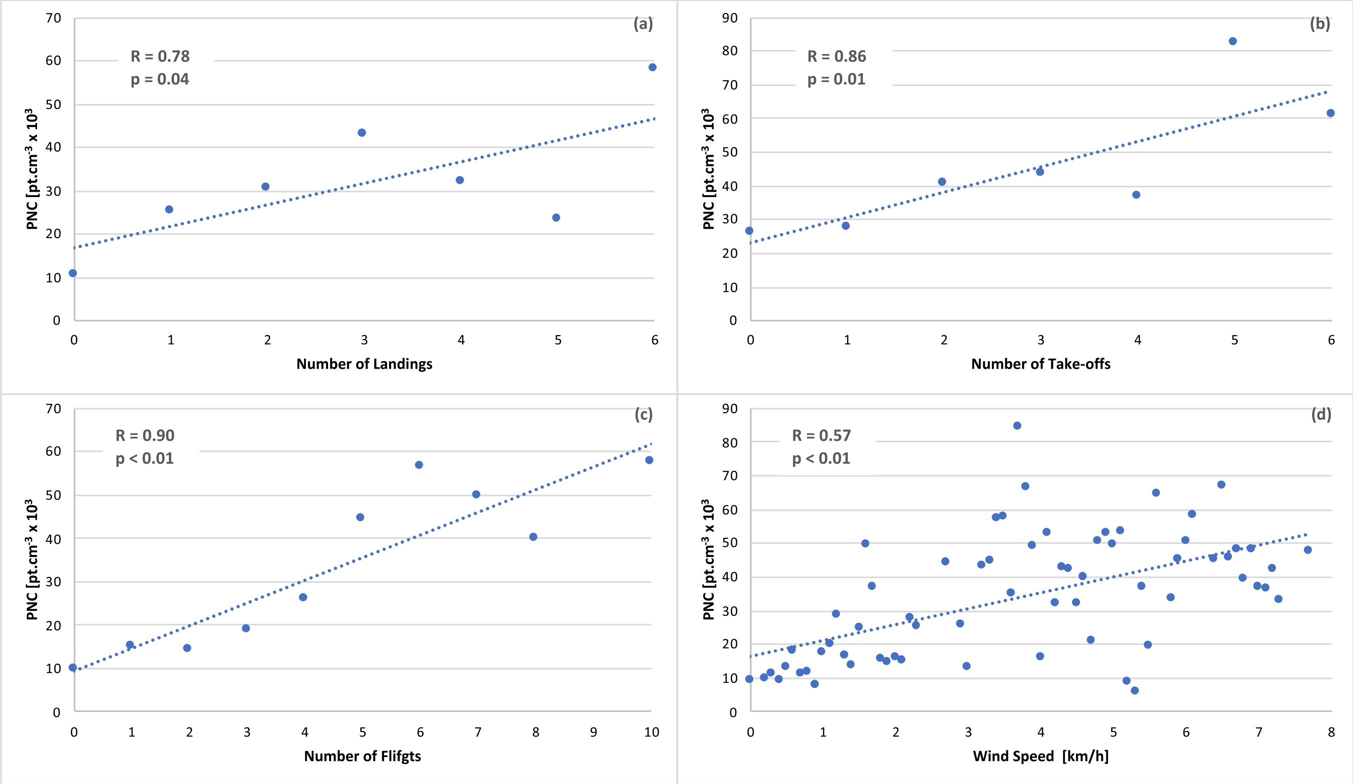


Fig. 3. Overall statistical outputs for regression analysis with 95% confidence level between PNC 10-min averages and the number of flights occurred during that time (a) number of landings; (b) number of take-offs; (c) number of flights (landings plus arrivals) and (d) wind intensity.

whiskers extend up from the top of the box to the largest data element that is less than or equal to 1.5 times the interquartile range (IQR) and down from the bottom of the box to the smallest data element that is larger than 1.5 times the IQR). Higher dispersion values were obtained for site 5 and 6, even though with higher mean, median, quartiles and extreme values over site 6. Therefore, the highest values and range dispersion are downwind located close to the airport (Fig. 4, bottom panel). Lower dispersion values were obtained for sites 12 and 14 with mean, median and quartiles very similar and lower than 20 pt. cm^{-3} x 10^3. The lowest PNC were obtained during non-downwind conditions (sites 1, 2, 3, 8, 12 and 14) or further away to LA (site 13). Comparing sites far from intensive road traffic influence (sites 9, 10 and 11) to sites close to intensive road traffic influence (sites 1 and 2), higher PNC was found on sites far from intensive traffic road, downwind to LA.

Sites closer to LA present the higher PNC, except for residential sites (13 and 14). Although site 14 is much closer to LA then site 13, PNC are lower in site 14 which might be explained by the reduced power of aircraft engine when it flies near this site. All the sites in group D are close to each other. The major difference among them is the surroundings (e.g. terrain depression which is the case of site 6). Therefore, besides proximity to LA, ventilation also plays an important role in PNC.

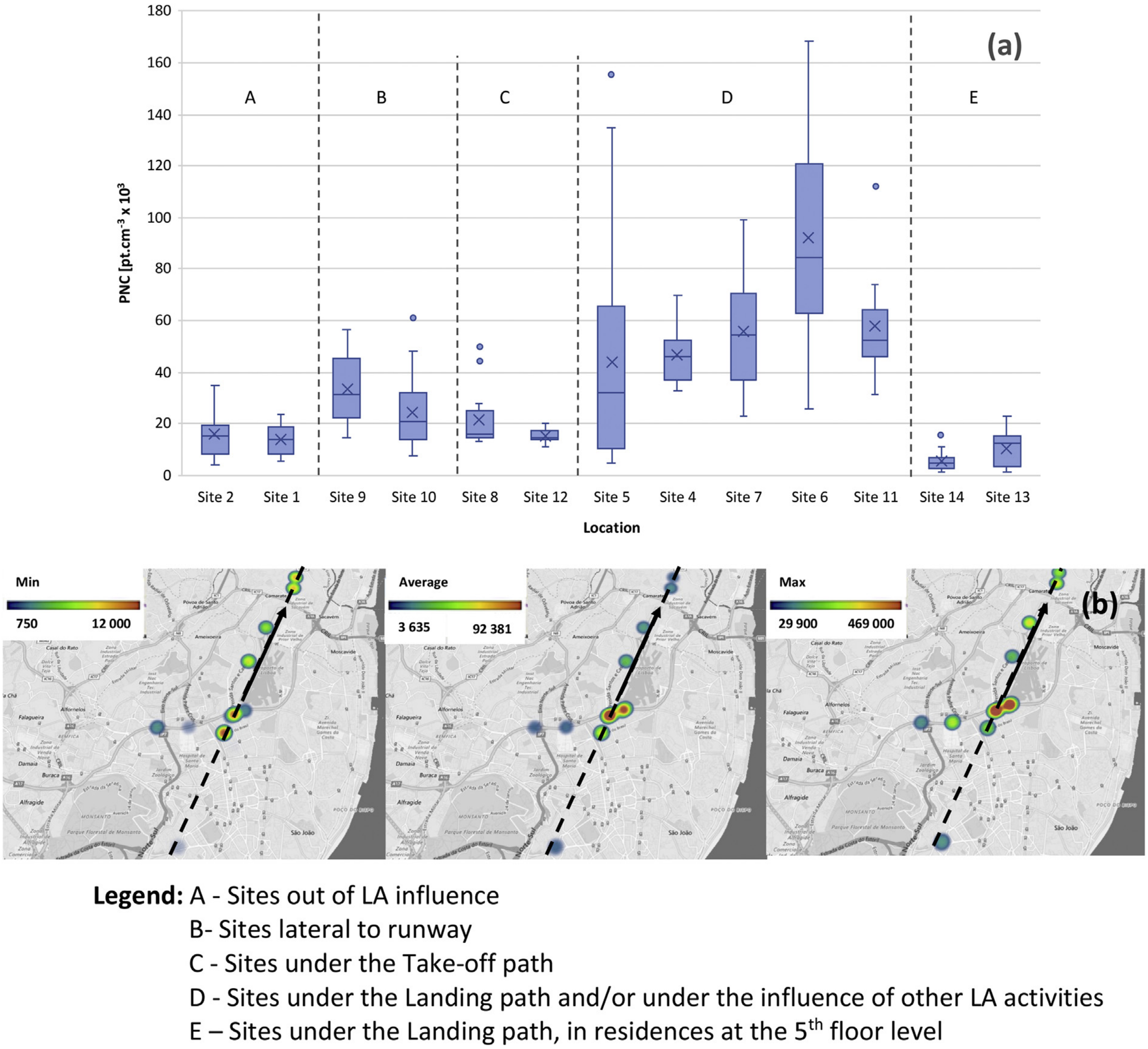
This result highlights that air traffic contributes to elevated PNC downwind to airport, as previously concluded by several studies (e.g. Keuken et al., 2015, Shirmohammadi et al., 2017).

3.2. *Influence of wind and mixing layer's height on PNC*

Fig. 5 illustrates the concentrations measured at five sites (4, 5, 6, 7 and 11) close to the landing route, near the LA (a) for different wind intensities and for different ML height (b). These particular sites were chosen for comparison because of their characteristics in the vicinity of LA and close to the same flight path (landing). The highest PNC values were obtained for higher wind intensity (higher than 14 km h^{-1}); relation between PNC and mixing layer height is unclear. These results show that, close to LA, both wind speed and direction affect PNC values, which is in accordance to the results obtained by Ren et al. (2016) and emphasize that higher wind speeds lead to higher PNC peaks by promoting faster ground arrival of the plumes emitted by aircrafts, counterbalancing the dispersion (Hudda et al., 2018).

The highest PNC maximum and average values were obtained in site 6, 610 m away from the start of the runway, in a straight line. These results can be explained by the terrain depression in comparison to the LA baseline. This adverse orographic conditions to aircraft plume dispersion associated with the high turbulence generated by landings, when the aircraft altitude is very low (75 m above the ground), lead to a PNC increase by 7-fold, compared to the values obtained without landings.

Results for sampling site 5 allow a comparison of PNC values between absence and during LTO cycles. The maximum value was recorded for the higher wind speed, which can be explained by instant plume transport, in accordance to correlation found between PNC and wind speed. In the vicinity of LA the lowest recorded value was obtained in sampling site 5 after a period of approximately 3 h without landings or take-offs. With the beginning and intensification of air traffic, during morning period, these concentrations increase about 10 times compared to those observed after the short period without aircraft movement. The results obtained at sampling site 5, illustrated in Fig. 6, show that the number of LTO cycles and aircraft movement in the airport, particularly when they are holding for take-off, cause a significant PNC increase. These results show an increase of PNC when the aircraft passes near the monitoring site, similarly to what Hsu et al.



Legend: A - Sites out of LA influence
B- Sites lateral to runway
C - Sites under the Take-off path
D - Sites under the Landing path and/or under the influence of other LA activities
E – Sites under the Landing path, in residences at the 5th floor level

Fig. 4. (a) Boxplot of 10-min PNC mean distribution by site ordered by location and increase distance to LA (please see sites spatial distribution in Fig. 1b). Boxes delineate median, upper and lower quartiles, with the whiskers extending up from the top of the box to the largest data element that is less than or equal to 1.5 times the interquartile range (IQR) and down from the bottom of the box to the smallest data element that is larger than 1.5 times the IQR. Dots represent outliers, i.e. values beyond the ends of the whiskers (b) PNC geographical distribution: minimum, average and maximum (PNC expressed in pt. cm^{-3}).

(2012) and Masiol et al. (2016) had also concluded.

Regarding the aircraft's type (long-haul flights *versus* low/medium-haul flights), associated with large and small aircrafts, respectively, data showed no differences on PNC (Fig. 6), in accordance with conclusions reached by Staffogia et al. (2016).

Results show that PNC increases with most of the flight occurrences, but not all, particularly for the sampling points located across the take-off route. Nevertheless, we would like to highlight that the PNC measurements are carried out at a fixed point on the ground, whereas an aircraft moves quickly and has a 3-dimensional movement and the wind suffers constant variations of intensity and direction. For these reasons, it was not always possible to establish a direct relationship between the LTO cycles and the obtained measurements, as showed by Campagna et al. (2016).

Fig. 7 represents the mean of 10-min PNC averages by 10° ranges of wind direction and the number of LTO cycles occurred during those wind direction ranges, at sampling site 5. This site is located at approximately 350 m east to the beginning of the runway, close to the airport fence, and also near to the taxiing lane used by aircrafts to access the main runway. The impact wind direction for landings and take-offs is 320 to 329° (Fig. 7a) is consistent with the site relative position to the beginning of the runway (black thin arrow), as indicated by the small dashed red line (Fig. 7b). The impact wind direction for taxiing is 10 to 19° (Fig. 7a) is also consistent with site relative position to taxing lane (blue large dashed line) as illustrated by the orange dot line (Fig. 7b). Aircrafts idling to take-off contribute to relevant PNC increase. However, the most significative increase is registered with take-offs and landings.

For distinct and complementary purposes, results obtained at a 5 km distance from LA, at a 5th floor level, and under thermic inversion conditions from the ground, are presented in Fig. 8. The PNC is given in 10-min average and the bars represent the number of landings occurred during each 10-min period. These results clearly show that PNC values during landing period are higher than 10 pt. cm^{-3} x 10^3, with peaks of 20 pt. cm^{-3} x 10^3. When the landings stop, these values fall down to 5 pt. cm^{-3} x 10^3 and later to 2 pt. cm^{-3} x 10^3. Thus, it is possible to conclude that, even for distances 5 km far from the LA, the impact of airplanes' landing is noticeable on PNC registries. Moreover, is only when landings stop is that PNC starts to lower.

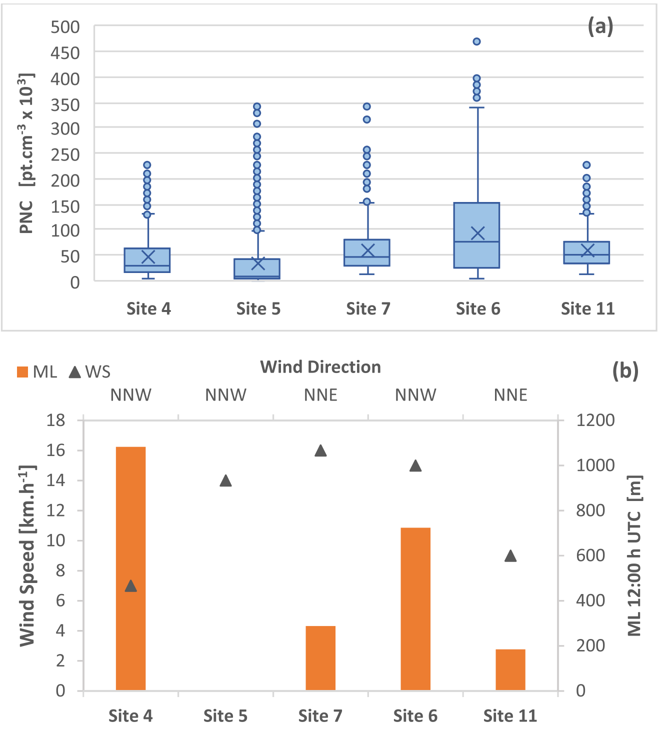


Fig. 5. PNC concentrations at five sites located in LA landing route vicinity, ordered by increasing distance to the runway (a), and corresponding wind speed and ML height (b).

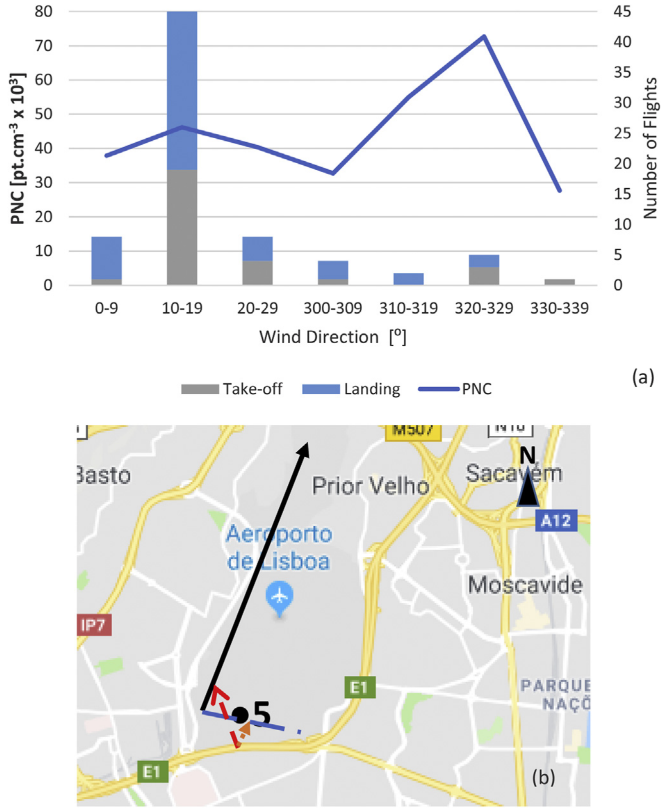


Fig. 7. (a) 10-min UFP average concentration, number of flights and wind direction, in LA vicinity (site 5) (b) Geographical detail of sampling site: relative position to the beginning of the runway (small dashed red arrow) and to aircrafts idling to take-off (pointed orange arrow). The runway is represented by the black arrow and idling path by the large dashed blue line. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

4. Conclusions

The present work aimed to fulfil the lack of PNC studies in Lisbon and assess the impact of air traffic in the vicinity of the LA to PNC. Several sampling sites were chosen in the vicinity of the airport. Sites further away of the LA were chosen to assess the area of influence of air traffic activities on urban and sub-urban air quality.

Our results indicate that the particle count increases with the number of flights and decreases with the distance to the runway and the altitude of aircrafts relative to the sampling site. Peak values of particle number count also increase with wind speed. Results show high positive correlations between PNC values and the number of flights (r = 0.90) and that air traffic contributes to elevated PNC values downwind to the airport, especially for take-offs. Close to the LA south boundary (sites 3 and 5, approximately 300 m west and east to runway, respectively) PNC 10-min averages increased by 18–26-fold, compared to the PNC 10-min averages recorded without LTO cycles. Still in the vicinity of LA but further away, until 1200 m, the PNC increase is around 4-fold. A particular case is site 6. This site is located close to LA (610 m) in a terrain depression in comparison to the LA baseline. This particular orography affects the aircraft plume dispersion leading to PNC increases by 7-fold, almost twice the increase found in site 7, closer to LA (500 m), but a few meters higher than site 6. Even at the furthest point of LA on the landing route (site 13), at a 5th floor, far from the direct influence of road traffic and under thermal inversion conditions, the influence of aircraft traffic was reflected on the increase of the 10-min PNC average, by a 16-fold, compared to the period without flights.

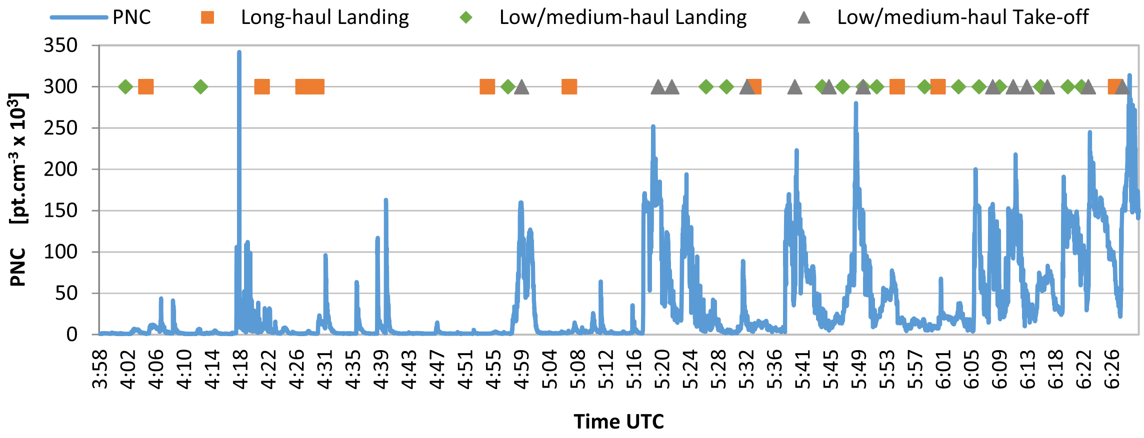


Fig. 6. UFP concentration at sampling site 5 (LA vicinity) and LTO cycles differentiated by long-haul flights and low/medium-haul flights.

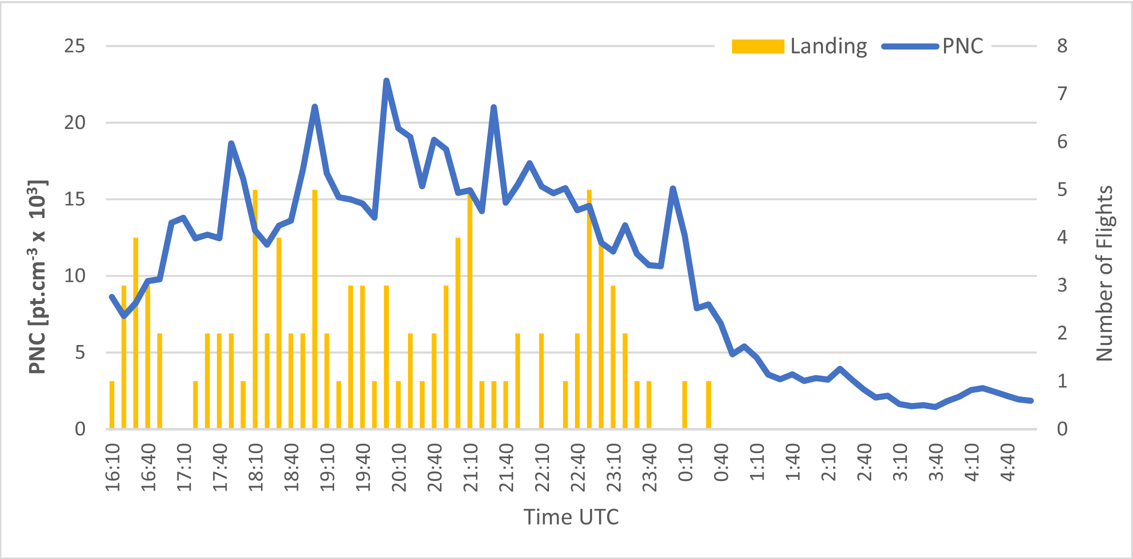


Fig. 8. UFP concentration at sampling site 13 (landing path, far from LA), wind direction and number of landings during a 10-min period.

Regarding the aircraft's type (long-haul flights *versus* low/medium-haul flights), associated with large and small aircrafts, respectively, data showed no differences on PNC.

These results highlight that people working or living nearby (up to approximately 1.5 km) the Lisbon Airport are exposed to high PNC values. Also, people working in the airport are expected to be exposed to even higher PNC levels for 8-h periods, 5 days per week. Additionally, passengers spend considerable periods in terminals, although for shorter periods. Nevertheless, their UFP exposure were compared to be equivalent to approximately 11-h of exposure to regular urban environment (Ren et al., 2018). Furthermore, the number of flights is expected to continue increasing over the next years, leading to an increase in UFP emissions. Technical protection measures should be considered in order to improve indoor air quality in terminals. Furthermore, future airports construction should take in account these results and implement technical measures to mitigate their effect on workers, passengers and nearby population.

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