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Particle number concentrations near the Rome-Ciampino city airport

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HIGHLIGHTS

- An extensive campaign of minute-specific PNC implemented in Ciampino Airport, Italy.
- PNC increase by ~20,000 particles/cm^3/minute in the 5 min after take-offs.
- PNC increases are three times larger when prevalent wind from the airport runway.
- Large resident population, with potential health impacts from airport-generated PNC.

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ABSTRACT

Human exposure to ultrafine particles (UFP) has been postulated to be associated with adverse health effects, and there is interest regarding possible measures to reduce primary emissions. One important source of UFP are airport activities, with aircraft take-offs being the most relevant one. We implemented two measurement campaigns of total particle number concentrations (PNC), a proxy for UFP, near a medium-size airport in central Italy. One-minute PNC averages were collected on June 2011 and January 2012 concurrently with 30-min average meteorological data on temperature and wind speed/direction. Data on minute-specific take-offs and landings were obtained by the airport authorities. We applied statistical regression models to relate PNC data to the presence of aircraft activities while adjusting for time trends and meteorology, and estimated the increases in PNC ±15 min before and after take-offs and landings. We repeated the analyses considering prevalent wind direction and by size of the aircraft. We estimated PNC increases of 5400 particles/cm^3/minute during the 15 min before and after take-offs, with a peak of 19,000 particles/cm^3/minute within 5 min after take-offs. Corresponding figures for landings were 1300 and 1000 particles, respectively. The highest PNC estimates were obtained when the prevailing wind came from the runway direction, and led to estimated PNC increases of 60,000 particles/cm^3/minute within 5 min after take-offs. No main differences were noted from the exhaust of different types of aircrafts. The area surrounding Ciampino airport is densely inhabited, raising concerns about the potential adverse effects of long-term and short-term exposure to airport-borne UFP. A close monitoring of airport activities and emissions is mandatory to reduce the public health impact of the airport on the nearby population.

1. Introduction

Atmospheric pollution is one of the main environmental risk factors to human health (Lim et al., 2012). Long-term and short-term health effects from air pollution exposure have been widely documented all over the world, especially among populations living in densely populated urban areas. Epidemiological research during the last two decades has indicated that exposure to air pollution at the levels presently measured in European urban environments is associated with an increase in mortality and with a variety of health conditions, including emergency room visits and hospital admissions for respiratory and cardiovascular diseases. Particulate matter (PM) is the air pollutant most consistently

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associated with adverse health outcomes (Brook et al., 2010; Pope and Dockery, 2006; WHO, 2013).

Typically, particles are classified into three main groups based on their dimension: ultrafine particles (UFP, diameter less than 0.1 μm), accumulation-mode particles (with a diameter in the range 0.1 ÷ 1.0 μm), and coarse-mode particles (diameter larger than 1 μm). UFP contribute very little to the total PM mass, but are very high in number, and can reach several hundred thousand particles per cubic centimeter in urban air, on episodic events (Oberdörster, 2001). Due to their small size and consequent high mobility, UFP easily deposit on the lower respiratory airways and may translocate into the blood stream, if not readily dissolved. Therefore they may affect both the respiratory and the cardiovascular systems (HEI, 2013). However, the epidemiological evidence on the short-term health effects of UFP is inconsistent, mostly because of the lack of routine and standardized measurements of UFP in multiple locations over several years. Similarly, the evidence of the long-term effects of UFP is almost nonexistent due to difficulties in the spatial variability modeling of UFP concentrations (Ostro et al., 2015).

In most European countries, the main source of UFP are tailpipe emissions from motor vehicles (Kumar et al., 2014), though a non-negligible part of UFP is also generated by other non-vehicle exhaust sources such as coal-fired power plants or domestic heating (Kumar et al., 2013; Paasonen et al., 2013). Another relevant source of UFP emissions are aircraft activities. Aircrafts engines emit a large number of particles. Field campaigns demonstrated that particles emissions range between $10^{15} - 10^{17}$ particles kg^{-1} fuel showing a peculiar particle distribution mode, generally unimodal and lognormally distributed. The geometric mean particle diameter falls into the ultrafine particle mode, ranging between 9 and 37 nm. Emissions have shown also large variability depending mainly on engine type, fuel flow and test conditions (Kinsey et al., 2010).

Recently, aircraft activity has been shown to contribute to UFP exposure of people living in proximity of large and busy airports. Prevailing winds play an important role, leading to significant UFP increases in places down-wind of the airport (Keuken et al., 2015). Aircraft landings and takeoffs are associated with elevated peaks in UFP as demonstrated by measurements taken downwind of runways. Moreover, particle size distributions differ substantially between upwind (dominated by particles in the accumulation mode, 90 nm) and downwind locations (dominated by particles in the nucleation mode, 10–15 nm). Airport operations are associated with elevated levels of UFP much further downwind in the neighboring community than would have been predicted by prior studies of UFP from roadway traffic (Hudda et al., 2014; Westerdahl et al., 2008).

Several studies have tried to estimate the contribution of aircraft activities on air pollution by relating time-resolved monitoring data of gaseous pollutants (nitrogen oxides, carbon oxide, ozone, sulphur dioxide) to detailed information on flight activity. Generalized linear models (GLM), stochastic gradient boosting or boosted regression trees models have been applied to large international airports, such as Los Angeles (LAX) and London Heathrow (LHR) (Carslaw et al., 2006; Diez et al., 2012). To our knowledge, only one previous study has investigated the effects of airport operations on particle number concentration (PNC), a proxy for UFP, around small/medium sized airports (Hsu et al., 2012).

We recently conducted a study, the "SERA" project (Study on the Effects of Airport Noise), aimed at monitoring air pollution, noise and the health status of residents of an urban area nearby the G.B. Pastine International Airport (CIA) in Ciampino (Ancona et al., 2010). Frequent PNC spikes were found to be associated primarily with take-offs (Di Menno di Bucchianico et al., 2014).

The objective of this paper is to describe the temporal relationship between flight activities and PNC by use of an alternative statistical approach, the so-called "distributed-lag models" most suited to describe the temporal correlation between "cause" (flight activity) and "effect" (PNC increase). We also aimed at providing different estimates of PNC increases for take-offs and landings considering wind directions and aircraft size. The study was designed to test the following a priori hypotheses: a) take-offs affect PNC levels much more than landings; b) the timing of PNC peaks is crucial, occurring right after take-offs, making the contributions of taxiing, stationing and other phases negligible; c) large aircrafts contribute to PNC increases substantially more than smaller ones do.

2. Materials and methods

2.1. Study area

The Ciampino airport is located in the Ciampino municipality area (37,235 residents at 2011 census), 12 km SE of Rome, Italy (41°47′58″N 12°35′50″E). It is the second airport of Rome and the ninth busiest passenger airport in Italy.

In operation since 1916 as a military airport, it opened to civilian flights in the 30s and was used for decades by heads of State and public authorities on visit to Rome and Italy, with an air traffic volume of around 15,000 flights per year; over the last decade the airport air traffic has risen from about 30,000 in 2000 to about 54,000 in 2010 when low-cost carriers were permitted, which resulted in a sharp increase of airport traffic, reaching 5,802,877 passengers in 2015. It now handles approximately 200 daily flights, equally distributed between departures and arrivals.

Flights into and out of Ciampino airport typically occur from NW (landing) and proceed to SE (take-off), through the only runway available, see Fig. 1. A wide, densely populated conurbation extends from the east side airport fence line. The west side of the airport is mainly rural, while other urban settings are present in the S-SW area. High traffic roadways are located 900-m N (Rome main ring road, about 130,000 vehicles day^{-1}), 200-m W (Via Appia, about 30,000 vehicles day^{-1}) and 200-m S (Via dei Laghi, about 20,000 vehicles day^{-1}) the airport centroid.

2.2. Monitoring site

The measurement site (41°47′12.7″N 12°35′58.7″E) was located 380 m SW of the airport centroid and 240 m from the fence line, see Fig. 1. Because of the prevailing breeze pattern, the site was downwind to planes that took off from 6 a.m. to 12 a.m. No flight operations are allowed between 11.00 p.m. and 6 a.m. Measurements were carried out during the late spring (May 31st – June 13th, 2011) and winter (January 11th – 27th, 2012). However, due to instrument malfunctions, power failures and radar track missing data, the final data set used in this study has been limited to 12 consecutive days (8 during spring and 4 during winter) with 13,021 valid PNC minute-specific records.

A butanol based condensation particle counter (CPC, TSI 3022A) was used to measure PNC at 1-s resolution. Inlet was 3 m from the ground. This type of CPC has a 50% counting efficiency for particles with a diameter (Dp) of 7 nm (Sem, 2002). External air was pumped in the cabin into a stainless steel tube (length = 4.0 m) by an external pump ensuring a Reynolds number < 2000 (laminar flow). The cabin was conditioned at 20–25 °C to dry sample air based on the difference between air temperature and dew point.

During the sampling campaigns, 30-min average meteorological data (air temperature, barometric pressure, humidity, wind speed and direction, precipitation) were collected at the monitoring site

Fig. 1. G.B. Pastine International Airport (CIA) and prevailing winds during the study period.

and compared with data provided from the Ciampino airport meteorological station.

2.3. Airport data

The airport authority provided landing and take-offs (LTO) data, including relevant information for the model development: exact time of each take-off and landing, aircraft model, direction of approach (mainly from NW) and departure (mainly to SE), and radar tracks, see Fig. 2. Aircrafts were grouped into three broad classes (small, large, heavy) based on aircraft weight capability at take-off, according to the Federal Aviation Administration (FAA) Air Traffic Control Policy. During the 12 days selected for this study, there were 634 small, 1271 large and 32 heavy aircrafts landing and taking-off, so large and heavy aircrafts were combined into a single category.

2.4. Statistical analysis

One-minute PNC averages were used as input data in model developing. Minute-specific PNC averages were summarized for the whole period, and at landings and take-offs. Also, polar plots were produced to show PNC values according to prevalent wind speed and directions.

Unconstrained distributed-lag (UDL) and 5-th degree polynomial distributed-lag (PDL) multivariate linear regression models were developed to relate PNC counts to aircraft movements, while considering time trends and meteorology (Almon S, 1965; Schwartz J, 2000). Specifically, the following UDL model has been fitted:

$$
\begin{aligned}
E[PNC_i] \sim\ & \alpha + \sum_{j=1}^{k} \beta_j I(month;day;hour)_{j,i} + \sum_{l=1}^{6} \gamma_l I(dow)_{l,i} \\
& + PS(temperature)_i \\
& + \sum_{m=1}^{8} PS(wind.speed, wind.direction = m)_i \\
& + \sum_{r=-15}^{+15} \delta_r I(take.off)_{i-r} + \sum_{s=-15}^{+15} \vartheta_s I(landing)_{i-s}
\end{aligned}
$$

where:

- $E[PNC_i]$ denotes the expected PNC count on minute i, α is the model intercept;
- *I(month;day;hour)* is a set of k dummy variables identifying strata of month, day and hour, with corresponding β coefficients;
- *I(dow)* is a set of dummy variables identifying strata of days of the week (from Mondays to Saturdays, Sundays being the reference category), with corresponding γ coefficients;
- PS denotes penalized splines, with an effective number of degrees of freedom chosen by minimization of the Generalized Cross-Validation (GCV) function (Wood, 2003). Splines for wind

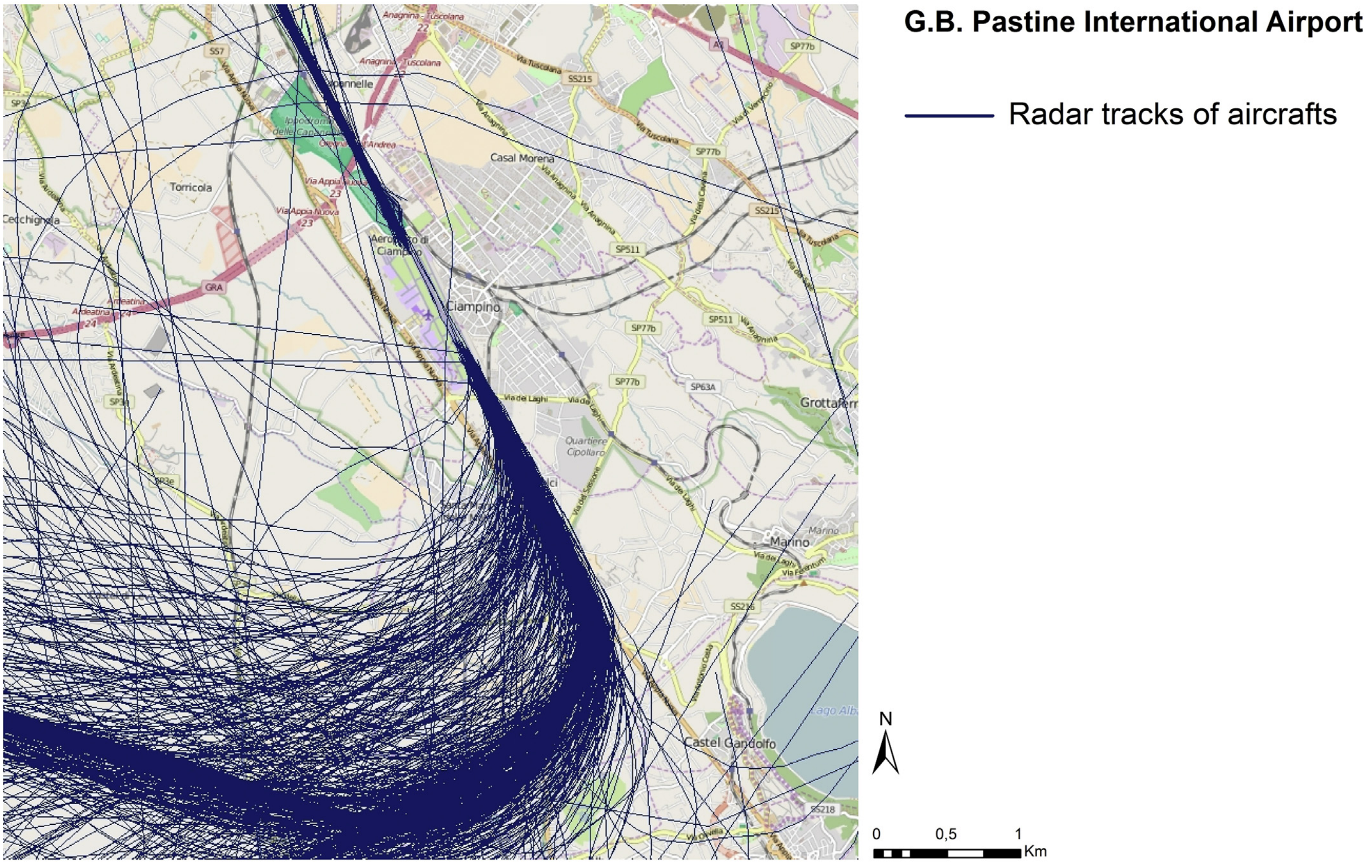

Fig. 2. Radar tracks of aircrafts departing (mainly to SE) and landing (mainly from NW) to Rome-Ciampino airport in May–June 2011.

speed are estimated by eight different wind directions, classified as North (N), North-West (NW), West (W), South-West (SW), South (S), South-East (SE), East (E), and North-East (NE);
– I(take-offs) and I(landings) denote indicator variables for occurrence of a take-off or landing in the ±15 min around i, δ_r and θ_s being their regression coefficients.

The corresponding PDL model was calculated by constraining the coefficients for take-offs and landings terms to follow 5-th degree polynomial shapes.

In previous models, the minute-specific PNC counts were related to take-offs and landings occurring ±15 min around the PNC measurement, while removing the possible confounding effects of other time-dependent factors, such as meteorology, time of the day or day of the week. In particular, we were concerned about the possibility that meteorological factors might cause PNC increases in a non-linear way, independent of aircraft activities. To account for this, we fitted flexible non parametric curves (penalized splines) for the pairwise associations between each meteorological parameter (air temperature, barometric pressure and wind speed) and PNC. Also, we allowed for different relationships between PNC and wind speed by prevailing wind directions.

The same analyses have then been repeated by wind direction (one model for each of the eight directions), and by size of the aircraft (two different models for small and large-heavy aircrafts).

Since the PNC counts are right-skewed because of extremely large outliers, we performed a sensitivity analysis by considering the natural logarithm of PNC and subtracting out its ±60-min moving average (MAV). This approach has been already applied by Diez et al. (2012). The sensitivity model is the following:

$$E[\ln(PNC - MAV)_i] \sim \alpha + \sum_{m=1}^{8} PS(wind.speed, wind.direction = m)_i + \sum_{r=-15}^{+15} \delta_r I(take.off)_{i-r} + \sum_{s=-15}^{+15} \vartheta_s I(landing)_{i-s}$$

This model has the advantage of normalizing the PNC distribution while at the same time removing "by design" potential confounding induced by meteorological factors and time-trend patterns. The drawback of the model lies in its difficult interpretability, since coefficients do not translate directly into predicted increases in PNC counts, as in the main model, but represent increases in the de-trended log(PNC) expected values. The aim of this sensitivity analysis was to check whether a similar lagged relationship between LTO occurrence and PNC values could be detected with the two alternative modeling frameworks.

All graphs and statistical analyses were performed with the R statistical software, version 3.1.3 (R Development Core Team; http://R-project.org).

3. Results

3.1. Description of the study area and PNC counts

Figs. 1 and 2 display the study area and the radar tracks of LTO in Ciampino airport on May–June 2011. The runway was located north of the monitoring site, very close to the residential area of Ciampino, on the east side of the airport. The wind rose shows frequency of counts by wind direction (%) during the study period: as displayed in the polar plot, prevailing winds came from either the SW (22% of the sample minutes) or the N (17%). During the study period, about 32% of the time the monitoring location was downwind of the airport: N (17%), NWW (10%) and NNW (5%).

Minute-specific PNC averages are reported in Table 1, by monitoring campaigns (winter and spring) and according to flight activity (night time (no flight hours), day-time with no flights (no activity), only take-off, only landing or both). It should be noted that the data in Table 1 concerns PNC measurements in the study period during all wind directions, while in Table 3 wind specific PNC data are presented. During both campaigns, mean and median PNC values were higher during take-offs, with or without concurrent landings.

During flight activities there were extremely large peaks in PNC counts on specific minutes, especially during the winter campaign. Fig. 3 shows PNC data in the morning of June 10, 2011 when the monitoring site was down wind of the airport; also indicated are take-offs and landings.

Fig. 3 illustrates that the highest PNC were measured during take-offs, while landing aircrafts resulted in lower PNC peaks down wind of the airport. Furthermore, as illustrated in Fig. 4, PNC values at the monitoring site were highest when the wind direction was from the same direction as the aircraft was taking off.

3.2. Effects of aircraft activity on PNC

This section reports the results of the distributed-lag models, expressed as predicted increases in PNC counts in the ±15 min before and after take-offs and landings. Point estimates are complemented with measures of statistical uncertainty (95% confidence intervals), and are adjusted for time-varying factors such as meteorological parameters, hour and day.

The main results of the UDL (filled circle) and PDL (empty circle) models are reported in Fig. 5. The picture displays predicted PNC increases (y-axis) in the 15 min before/after take-offs (top) and landings (bottom). The largest PNC increases were found in the few minutes around take-offs, with rises >25,000 particles/cm^3 2 min after departures. In contrast, landing episodes were less related to PNC values, with predicted increases within 5000 particles/cm^3 (with the exception of the anomalous excess 12 min after landings).

On average, PNC values increased by around 19,000 particles/

Table 2
The UDL-modelled 5-min average increase in PNC (particles/cm^3) at the monitoring location in a range of 15 min before and after take-off or landing.

Time window (minutes)	Predicted PNC increase (by minute)	95% CI	
Take-offs			
−15 to −11 min	1600	−1400	4600
−10 to −6 min	3400	400	6400
−5 to −1 min	6700	3700	9700
0 to 4 min	18,900	15,900	21,800
5 to 9 min	3200	200	6200
10 to 15 min	−200	−3000	2500
−15 to +15 min	5400	−400	11,200
Landings			
−15 to −11 min	−500	−3300	2300
−10 to −6 min	−1800	−4700	1000
−5 to −1 min	800	−2100	3600
0 to 4 min	1200	−1700	4000
5 to 9 min	1600	−1300	4500
10 to 15 min	5800	3100	8400
−15 to +15 min	1300	−4400	7000

Table 3
Predicted increases in PNC (particles/cm^3) in the 5 min after take-offs, from UDL model: results by wind direction and size of the aircraft.

	Predicted PNC increase (by minute)	95% CI	
Wind direction			
N	59,900	46,900	72,900
NW	15,800	4600	27,000
W	4300	1200	7400
SW	3500	1900	5100
S	19,600	6700	32,400
SE	8200	3400	12,900
E	5500	−2800	13,800
NE	23,700	13,900	33,600
Size of the aircraft			
Small	15,000	1600	28,300
Large-heavy	18,200	6000	30,400

Table 1
Descriptive statistics of PNC (1 min averages, particles/cm^3) during the two monitoring campaigns, grouped by flight hours (5.00a.m.–11.00p.m.) and flight activity (records within 5 min after take-off or landing).

	Total	No flight hours	Flight hours			
			No activity	Activity		
				Only take-off	Only landing	Both
Winter campaign (January 24-27)						
# (minutes)	5300	1600	1600	900	800	500
5th pct.	9700	7500	17,300	18,300	16,400	20,500
25th pct.	18,600	12,400	22,800	26,000	23,300	28,400
median	27,500	15,900	32,900	43,900	35,200	44,200
75th pct.	49,700	21,500	54,000	103,600	55,200	81,900
95th pct.	175,000	33,000	148,800	305,400	167,700	398,100
mean	55,300	18,000	55,400	89,600	65,300	100,800
sd	107,000	13,600	95,000	121,200	135,900	177,200
Spring campaign (June 6-13)						
# (minutes)	10,600	2900	2900	1900	1900	1000
5th pct.	7200	5600	7700	8100	8000	8100
25th pct.	9100	7800	11,100	12,100	11,100	11,600
median	14,400	8900	17,400	18,300	16,200	16,600
75th pct.	23,600	12,400	26,600	27,400	23,900	26,100
95th pct.	46,800	33,100	47,200	60,200	44,300	51,500
mean	23,400	16,800	22,100	36,700	21,200	25,700
sd	83,900	82,200	41,800	136,000	76,500	58,200

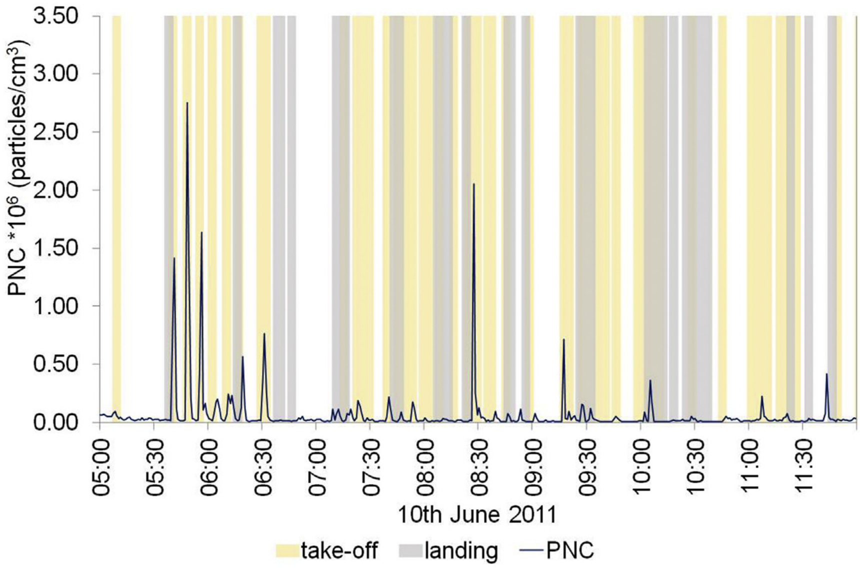

Fig. 3. Time series plot of PNC (1 min averages, particles/cm^3) by aircraft activity measured about 400 m downwind of the airport on June 10, 2011 (prevailing wind was N-NE).

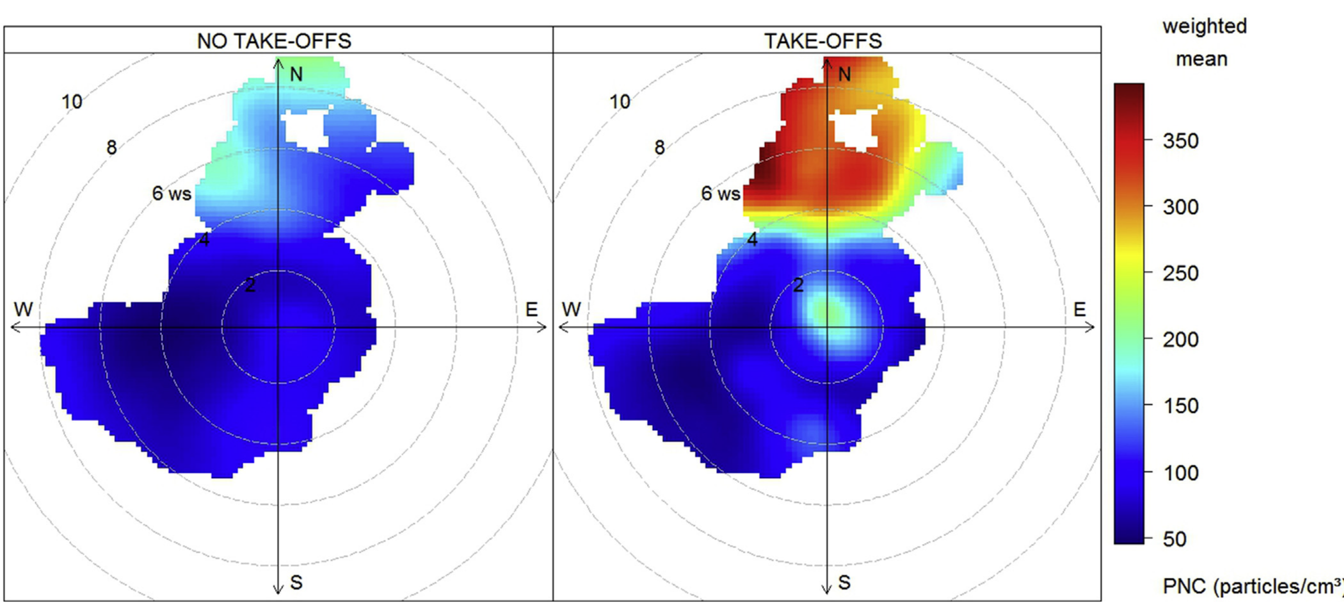

Fig. 4. Bivariate polar plot of PNC (1 min averages, particles/cm^3) weighted mean values (bin mean multiplied by the frequency of occurrence). Left panel: data selected among observations without take-offs in the previous 10 min. Right panel: data selected among observations with at least one take-off in the previous 10 min. In each plot the wind speed increases radially outwards from 0 to 10 m/s.

cm^3/minute in the 5 min during/after take-offs, and only by around 1000 particles/cm^3/minute in the 5 min during/after landings (Table 2). It is important to note that few landings arrived from the south, where the monitor was located. Interestingly, also the minutes before take-offs had an effect on the predicted PNC increases. In particular, in the 5–6 min before take-offs the aircraft is likely to be taxiing toward the runway, thus reaching close proximity to the monitoring site.

Most of the PNC excesses attributable to take-offs were found downwind (wind coming from N, NW and NE), with predicted PNC increasing by ~ 60,000 particles when prevailing winds were from the northern sector (Table 3). Slightly higher contributions from large-heavy aircrafts compared with smaller ones were estimated (Table 3), consistent with our a priori hypothesis.

When we considered de-trended logged PNC averages as the outcome variable, we found a very similar shape of the lagged relationship with LTO activities (Fig. 6), providing further support to the robustness of the approach adopted in the main analysis.

4. Discussion and conclusions

We aimed at quantifying the contribution of aircraft activities to PNC concentrations in a medium-sized airport. Substantial increases of PNC values in the few minutes after take-offs, especially downwind, with small differences between large and small vehicles were estimated. In contrast, landings displayed only a modest contribution to ground-level PNC observations.

This work is part of the SERA project, a study aimed at assessing the health impact of noise and air pollution among people living nearby six Italian airports (Ancona et al., 2014; Ancona and

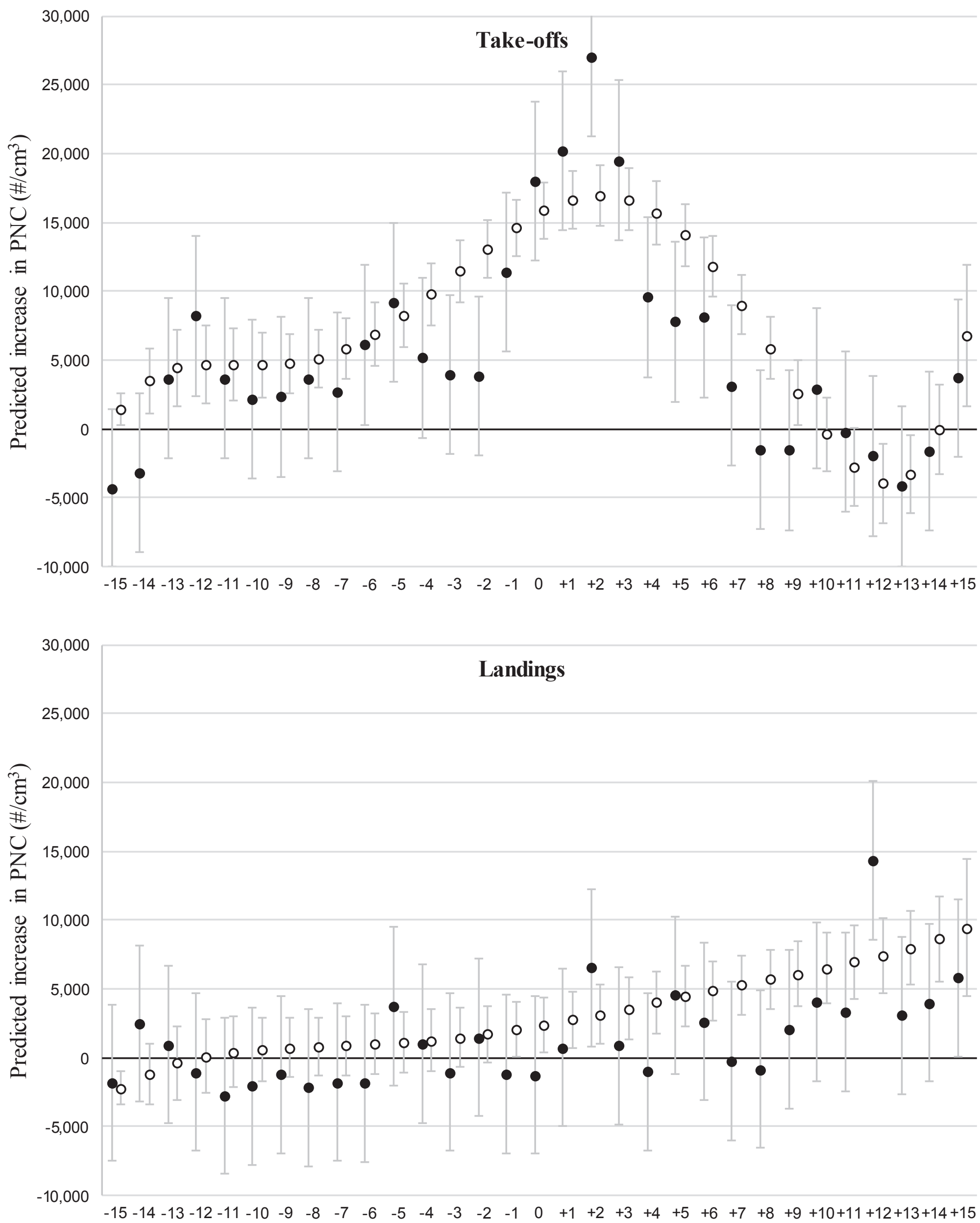

Fig. 5. Results of the UDL [filled symbol] and PDL [empty symbol] models, by minute: predicted increases in PNC counts (particles/cm^3) on minutes before and after take-offs (top panel) and landings (bottom panel).

Forastiere, 2014).

Land use regression models allowed us to describe the spatial distribution of NO_2, benzene, toluene and acrolein concentrations, showing that small-scale spatial gradients were affected by local traffic while only a small fraction of the spatial variability could be attributed to airport related emissions (Gaeta et al., 2016). Moreover, high temporally resolved PNC data combined with radar tracks enabled us to estimate the direct contribution of LTO operations on PNC values in nearby areas, a task otherwise impossible with hourly or daily averaging periods, since airport contributions might be masked in the complex mix of urban activity emissions (Di Menno di Bucchianico et al., 2014). These observations raised the need to design a further study where a more flexible approach, distributed-lag regression models, could provide a qualitative and quantitative estimation of the contribution of aircraft emissions to UFP concentrations near the Ciampino airport.

To date, only a few studies have been carried out applying empirical (statistical) models to isolate and quantify the contribution of aircraft and airport sources to air pollutant concentrations. Continuous black carbon (BC) concentrations were measured at five monitoring sites in proximity to a small regional airport in Warwick, Rhode Island, from July 2005 to August 2006 (Dodson et al., 2009). The authors applied Generalized Additive Models (GAM) to predict 1-min average BC concentrations as a function of wind velocity and direction at each site, plus indicators for aircraft arrivals and departures. The estimated contribution of LTO was in the range of 24%–28% of the BC concentrations at the receptor sites (Dodson et al., 2009). A similar approach was used in another study in the same area based on 1-min average UFP measurements conducted over three one-week periods at four fixed monitoring sites. This study illustrated the complexity of aviation impacts on local air quality and allowed to quantify the marginal contribution

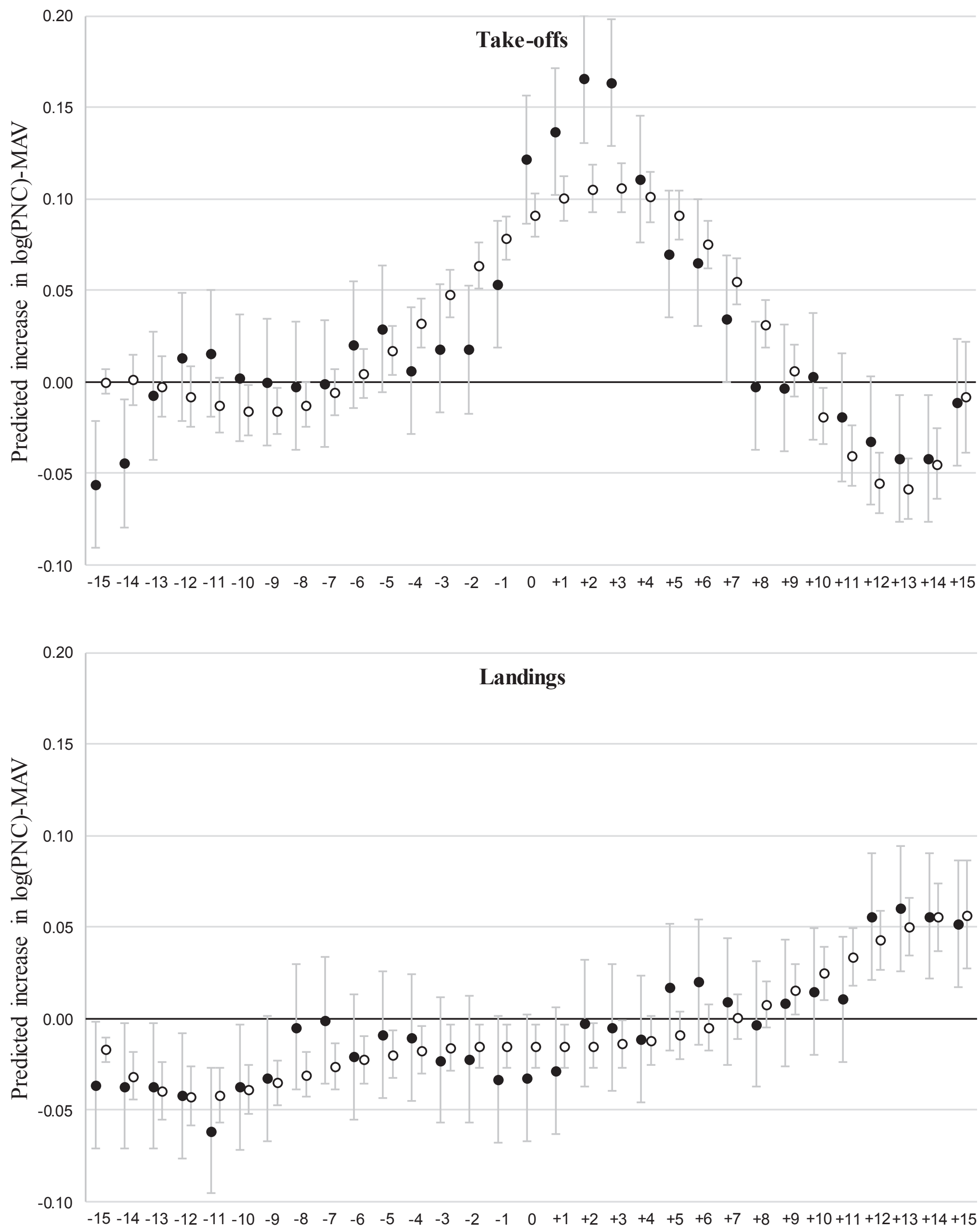

Fig. 6. Results of the UDL [filled symbol] and PDL [empty symbol] models, by minute, from the sensitivity analysis model: predicted increases in log(PNC) − 60-min moving average (MAV), on minutes before and after take-offs (top panel) and landings (bottom panel).

of LTO activity relative to other nearby sources (Hsu et al., 2012).

Using time-resolved multi-pollutant measurements taken near a departure runway at the Los Angeles international airport, single-pollutant and multi-pollutant generalized linear models were built (Diez et al., 2012). The study demonstrated that air pollution impacts from aircraft departures were significant and could be isolated using time-resolved monitoring data, and that combinations of simultaneously measured pollutants could best identify contributions from flight activity.

This study is characterized by several points of novelty compared with the existing literature on the same topic. First, only one previous study investigated the effects of airport operations on PNC around small/medium sized airports. The Ciampino airport is quite an important airport in Central Italy, very close to the metropolitan area of Rome, and the resident population of the Ciampino municipality lives very close to the main highway, making noise and air pollution originated from aircrafts a relevant public health problem. Second, the study is based on one of very few campaigns to collect minute-specific PNC averages on different seasons, coupled with detailed information on LTO, radar tracks, size of the aircrafts, and meteorological parameters. Third, we applied a novel methodology, distributed-lag multivariate regression, to explore the lagged relationship between LTO occurrence and PNC increases. The chosen time-window, ±15 min, was large enough to identify individual contributions of all the aircraft phases, including stationing, taxiing and take-off. The model was robust to adjustment for time trends and meteorological parameters, and was not affected by the skewness of the PNC distribution due to large outliers. Furthermore, the model provided direct estimates of predicted PNC increases (particles/cm^3) by minutes before/after LTO episodes, a result easy to interpret and communicate. Finally, we showed that PNC increases were highest in minutes when the monitoring site was downwind from the runway, providing further support for a likely causal role of Ciampino airport activities on the estimated PNC increases.

On the other hand, several limitations should be acknowledged. First, the campaign was based only on one monitoring station, so we could not estimate spatial contrasts in PNC exposure over a large study area, but only provide measures of intra-day variability at the receptor point. In addition, landings occurred largely from the north, therefore the small impact observed for landings could be underestimated at the sampling point since it was located in the southern side of the airport. In general, the results of this study cannot be used to design epidemiological investigations on the long-term health effects of PNC exposure. Instead, they are well suited to design studies on short-term associations, by relating minute-specific PNC values from airport activities to concurrent measurements of physiological parameters in exposed individuals. Second, we set the study in a medium-size airport with only one runway: while this is a novelty in this field and made the exposure assessment more straightforward, the overall expected impact of the airport on air quality in the surrounding area was low, possibly limiting a priori the power of the study to identify clear and significant contributions. Finally, we only operated monitoring campaigns on two season, winter and late spring, which prevented us from fully capturing the seasonality of the relationship between LTO and predicted PNC increases.

In conclusion, we provided up-to-date evidence of the impact of aircraft activities, especially take-offs, on PNC increases in a monitor nearby. We showed that PNC peaked in the few minutes right after take-offs, especially when the monitor was downwind from the runway. Our study suggests that continuous monitoring of ultrafine particles in a small network around airports, together with advanced statistical modeling, could improve the awareness of airport-related emissions and their contribution to the total air pollution exposure of people living nearby, both at large and medium-sized airports.

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