

Aviation-Related Impacts on Ultrafine Particle Number Concentrations Outside and Inside Residences near an Airport

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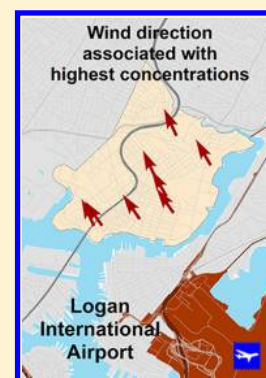
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Supporting Information

ABSTRACT: Jet engine exhaust is a significant source of ultrafine particles and aviation-related emissions can adversely impact air quality over large areas surrounding airports. We investigated outdoor and indoor ultrafine particle number concentrations (PNC) from 16 residences located in two study areas in the greater Boston metropolitan area (MA, USA) for evidence of aviation-related impacts. During winds from the direction of Logan International Airport, that is, impact-sector winds, an increase in outdoor and indoor PNC was clearly evident at all seven residences in the Chelsea study area (~4–5 km from the airport) and three out of nine residences in the Boston study area (~5–6 km from the airport); the median increase during impact-sector winds compared to other winds was 1.7-fold for both outdoor and indoor PNC. Across all residences during impact-sector and other winds, median outdoor PNC were 19 000 and 10 000 particles/cm³, respectively, and median indoor PNC were 7000 and 4000 particles/cm³, respectively. Overall, our results indicate that aviation-related outdoor PNC infiltrate indoors and result in significantly higher indoor PNC. Our study provides compelling evidence for the impact of aviation-related emissions on residential exposures. Further investigation is warranted because these impacts are not expected to be unique to Logan airport.



INTRODUCTION

Aircraft engine exhaust emissions are a significant source of ultrafine particles (UFP; aerodynamic diameter <100 nm) and can cause several-fold increases in ground-level particle number concentrations (PNC) over large areas downwind of airports.^{1–4} The spatial extent and magnitude of the impact varies depending on factors including wind direction and speed, runway use pattern, and flight activity but encompasses large populations in cities where airports are located close to the urban residential areas. For example, in Amsterdam, PNC (a proxy for UFP) were found to be elevated 7 km downwind of Schiphol Airport² while in Los Angeles, PNC were reported to be elevated 18 km downwind of Los Angeles International Airport.^{1,3} Thus, it is important to characterize aviation-related UFP.

Previous studies have shown that UFP can cross biological boundaries (entering the circulatory system) due to their extremely small size.^{5–7} Exposure to UFP is of particular concern because it is associated with inflammation biomarkers, oxidative stress and cardiovascular disease.⁶ Recent exposure assessment studies have started testing airport variables in UFP predictive models,^{8–12} but epidemiological studies that incorporate airports in the exposure assessment are lacking; currently, they primarily focus on traffic-related UFP. To better inform UFP exposure assessment efforts, it is also important to distinguish aviation-related contributions from other urban sources and to characterize them independently. This is

particularly challenging in urban areas with pervasive and dense road networks. Furthermore, studies have shown that residing in the vicinity of airports is significantly associated with hospitalization for cardiovascular disease;^{13,14} however, there the focus has been on association between cardiovascular health effects and increased noise around airports, which can be confounded by UFP. To date, no studies described in the literature investigate the health effects of UFP, or of noise controlling for UFP, around airports.

In a previous study, we found that during winds from the direction of the Logan International Airport (Boston, MA) PNC at two long-term, central monitoring stations located 4 km and 7.5 km downwind of the airport were 2-fold and 1.33-fold higher, respectively, compared to average for all other winds.⁴ In the current study, we investigated residential data sets from wider areas surrounding those two central sites. Our primary objectives were (1) to investigate short-term residential PNC monitoring data for evidence of aviation-related impacts that could be identified despite the influence of other urban sources of UFP, and (2) to analyze the data for evidence of indoor infiltration of aviation-related PNC. To our knowledge,

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this is the first study to report the impact of aviation-related emissions inside residences.

MATERIALS AND METHODS

Logan International Airport and Central and Residential Monitoring Sites. The General Edward Lawrence Logan International Airport is located 1.6 km east of downtown Boston (Figure 1(a)). It has six runways and supports about

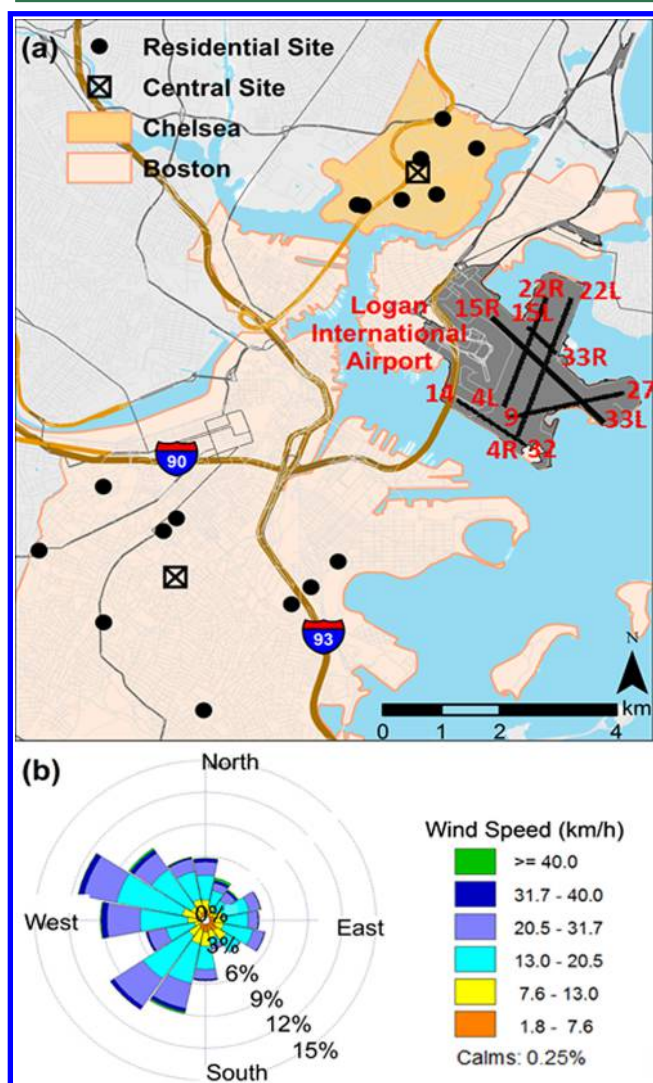


Figure 1. (a) Map of the runways at Logan International Airport and the locations of the central and residential monitoring sites in Chelsea and Boston. Base layers were obtained from mass.gov. (b) Windrose is based on 1 min data for 2014 reported by National Weather Service Automated Surface Station located at the airport.

1000 flights per day. Flight statistics are shown in the Supporting Information (SI) Figure S1. Prevailing winds in the Boston region are westerly (northwest in winter and southwest in summer, combined annual frequency 56%, see Figure 1(b)). The downwind advection of airport-related emissions occurs largely over urban areas located east and northeast of the airport as well as over the ocean during prevailing winds. During easterly winds, several other urban areas are downwind of the airport. We studied two of these areas: Chelsea and Boston.

In Chelsea, outdoor (i.e., ambient) and indoor monitoring was conducted at seven residences that were located 3.7–4.9 km downwind from the airport along 133°–165° azimuth angles measured to the geographic center of the airport (Figure 1(a)). Each residence was monitored for six consecutive weeks between February — December 2014. Ambient monitoring was also conducted continuously at a central site in Chelsea (located on top of a three-story building) during the entire 11-month period (Figure 1(a)). In Boston, monitoring was conducted at nine residences between May 2012 and October 2013. The residences were located 5.0–10.0 km downwind from the airport along 43°–74° azimuth angles measured to the geographic center of the airport. Monitoring was also conducted continuously during this 18-month period at a central site in Boston—the U.S. Environmental Protection Agency Speciation Trends Network site (ID: 25–025–0042). Central sites were selected based on their proximity to the geographic center and representativeness for the study area. Residential sites were selected based on their proximity to highways and major roads (the latter defined as annual average daily traffic >20 000): four sites were <100 m, seven between 100 and 200 m, and five >200 m from highways or major roads. Monitoring schedule, meteorological parameter summary, residence characteristics, and distance to major roadways are shown in SI Tables S1–S6.

During the six-weeks of monitoring at each residence, a HEPA filter (HEPAirX, Air Innovations, Inc., North Syracuse, NY) was operated in the room where the condensation particle counter (CPC) was located for three consecutive weeks followed by three consecutive weeks of sham filtration or vice versa. Only nonsmoking residences were recruited and we found no evidence of smoking in residences. Residences were monitored one or two at a time with limited overlap between monitoring periods. For further details of residential monitoring and filtration, see Simon et al.¹⁵ and Brugge et al.,¹⁶ respectively.

Instruments and Data Acquisition. PNC were monitored using four identical water-based CPCs (model 3783, TSI Inc., Shoreview MN), which recorded 30 s or 1 min average concentrations. The CPCs were annually calibrated at TSI and measured to within $\pm 10\%$ of one another, consistent with manufacturer-stated error. Ambient PNC were monitored continuously at the central-sites. At residences, a solenoid valve connected to the inlet switched the air flow between outdoor and indoor air every 15 min. Thus, residential outdoor and indoor PNC were monitored for 30 min per hour. To ensure that the sampling lines (1-m-long conductive silicon tubing for both indoor and outdoor carrying transport flow of 3 L per minute) were fully flushed, the first and last data points per switch were discarded (7–13% of the total). Any data that were flagged by the instruments (<1% of the total) and hours with <50% data recovery were not included in the analysis.

Flight records for individual aircraft were obtained from the Massachusetts Port Authority (East Boston, MA) and counted to obtain hourly totals for landings, takeoffs and the sum of the two (LTO). Meteorological data (a 2 min running average at 1 min resolution for wind direction and speed) were obtained from the National Weather Service station at the airport and processed through AERMINUTE¹⁷ (a meteorological processor developed by EPA for use in AERMET and AERMOD) to obtain hourly values.

Data and Statistical Analysis. Each PNC data set (residential indoor, residential outdoor, and central-site) was

Table 1. Impact Sector Definitions and Summary of Particle Number Concentration Statistics for Residential Sites

ID	distance to airport (km)	impact sector definition (WD°)	impact sector winds frequency, hours	impact-sector winds hourly PNC statistics			other winds hourly PNC statistics		
				outdoor median	indoor median	indoor minimum	outdoor median	indoor median	indoor minimum
Chelsea Residences									
D1	4.3	111–155	4.7%, 47	36 000	11 100	7600	13 200	4400	3700
D2	4.4	111–154	5%, 50	37 100	14 600	7500	16 200	5100	3500
U1	4.9	142–176	5.3%, 53	14 900	2300	1400	7800	1900	1600
U2	4.0	117–164	11.8%, 119	18 600	2500	1800	10 700	2400	1800
C1	4.2	145–182	5.2%, 50	12 800	3500	2800	8100	2500	1900
C2	4.4	130–171	5.4%, 54	19 700	1900	1300	9700	2200	1700
C3	3.7	124–173	10.8%, 111	26 600	6400	4700	8900	2800	2200
Boston Residences									
D1	6.1	31–59	6.9%, 63	27 800	8400	4300	10 700	5300	4000
U1	5.0	28–61	8.4%, 79	25 100	22 700	17 500	14 700	7400	6100
U2	5.6	30–59	8.2%, 70	19 700	10 900	6900	9700	6100	3700
C1	6.8	53–79	9.6%, 97	9400	3700	2600	8000	2300	1800
C2	7.1	53–78	3%, 30	11 900	7900	6400	10 000	4100	2800
C3	7.8	62–86	9.6%, 94	21 000	7700	5800	14 300	3900	3300
B1	10.0	33–53	3.4%, 34	13 500	4900	4200	10 100	4500	3400
B2	8.8	48–67	6%, 65	8200	4900	3200	7200	4500	3000
B3	9.2	60–78	4%, 39	12 900	15 400	11 600	8100	6300	5100

aggregated separately to calculate hourly medians. Hourly medians were further aggregated by 10°-wide wind-direction sectors, and medians were calculated for each sector. Wind-direction sectors were centered on even 10° and spanned $\pm 5^\circ$. Data were also classified as impact-sector versus other based on the wind direction. Winds that positioned monitoring sites downwind of the airport were called *impact-sector* winds. Impact-sector boundaries (Table 1) correspond to the azimuth angles measured from a monitoring site to the widest distance across the airport complex (SI Figure S2).

For indoor data we also calculated the hourly minimum in addition to hourly medians. Indoor data were also classified by filtration scenario (HEPA or sham). Indoor measurements reflect contributions from both particles generated indoors and particles of outdoor origin that infiltrate indoors. We did not quantify fraction of indoor- versus outdoor-origin particles. Instead, we compared hourly indoor minimums (less likely to be influenced by indoor-generated PNC spikes) with outdoor PNC to determine if higher indoor PNC occurred during impact-sector winds. During periods of elevated outdoor concentrations, indoor concentrations are also expected to be elevated due to air exchange between residences and their surroundings.

Spearman's rank correlation (coefficients reported as r_s) was calculated between PNC and wind speed and PNC and LTO. Inferences based on Spearman's rank correlation were limited to ordinal associations. Correlations were considered significant if p -values were <0.05 . Bootstrapped 95% confidence intervals for the correlation coefficients were also calculated. Further, impact-sector wind data sets at residences were relatively small; they ranged from 30 to 119 h or 3.0–11.8% of the total data. To take the resulting uncertainty into account, we compared distributions of correlation coefficient estimates – generated using bootstrap resampling methods (1×10^4 random samples with replacement) – for impact-sector winds to other winds. Subsamples (1×10^4 random samples without replacement) from other-wind data sets but of size comparable to impact-sector-winds were also compared where appropriate.

RESULTS AND DISCUSSION

We found strong evidence of aviation-related particle infiltration. Outdoor and indoor PNC were statistically significantly higher during impact-sector winds compared to other winds. Wilcoxon rank sum tests indicated that the median of 10°-wide-sector medians from all residences for impact sector winds was higher than other winds for outdoor concentrations (p -value <0.0001 , z -value = -8.1) as well as for indoor concentrations during both sham filtration (p -value <0.0001 , z -value = -5.1) and HEPA filtration (p -value = 0.0037 , z -value = -2.7). Table 1 summarizes indoor and outdoor concentrations.

We present detailed results in the following sections where we have organized our lines of reasoning as follows: first, we demonstrate elevated outdoor PNC during different impact-sector winds in the two study areas (each showing an impact when it was oriented downwind of the airport) including sites upwind and downwind of a highway; second, we discuss correlation of outdoor PNC with wind speed and flight activity, which indicated the aviation-related origin of elevated PNC during impact-sector winds; and third, we report indoor trends at all residences and discuss indoor infiltration of aviation-related, elevated, outdoor PNC for two residences in detail.

Wind Direction and Ambient PNC Patterns at Residences. Higher ambient PNC were observed during winds that positioned the sites downwind of the airport (i.e., impact-sector winds). Impact sector differed by study area and from residence to residence within the study areas. In Chelsea (located NW of the airport) PNC were elevated during SE winds and in Boston (located SW of the airport) PNC were elevated during NE winds (Figure 1). This impact is thus spatially widely distributed in the Boston area.

Chelsea. During impact-sector winds in the Chelsea study area (ESE-S, 111° – 182°), PNC were elevated at the central site and all seven residences. Residences that were upwind of the highway during impact-sector winds are denoted with a U, residences that were downwind of the highway during impact-sector winds are denoted as D, and community sites that are

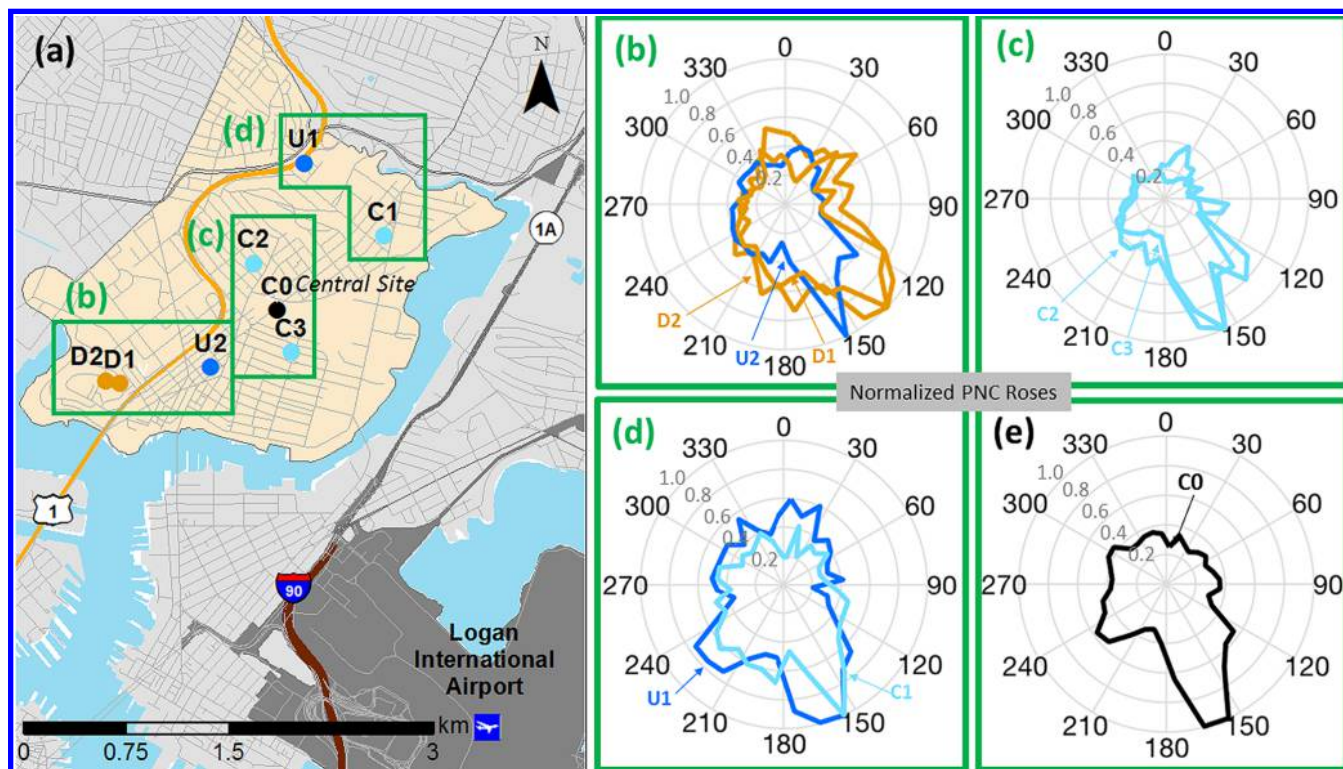


Figure 2. (a) Locations of the central site (C0, black) and seven residences monitored in Chelsea. Residences were classified as upwind (U, dark blue) of the highway during impact-sector winds, downwind of the highway (D, orange) during impact-sector winds and community sites that were not in proximity of the highway (C, light blue). (b)–(e) Normalized (by the maximum) PNC roses are based on hourly medians; concentric circles are increments of 0.2 on a 0–1 scale.

not in proximity of a highway are denoted as C (Figure 2). Median PNC during impact-sector winds were 1.6- to 3.0-fold higher than the medians for all other winds (Table 1). Highest and lowest residential impact-sector medians were 37 000 and 13 000 particles/cm³, respectively, as compared to 16 000 and 8000 particles/cm³ during all other winds.

Impact-sector winds occurred for 4.7–11.8% of the time (annually, ~ 7% in 2014) during the residential monitoring, but their weighted contributions to the monitoring averages were 8–26%. It should be noted that these contributions likely include some input from other sources in impact sectors, such as, traffic. Heatmaps of PNC by wind direction and hour of the day for the central site and all seven residences studied in Chelsea (SI Figure S3 (a) and (c)) indicate PNC peaks coincided with morning and evening vehicular and aviation traffic rush-hours. However, these peaks were highly elevated during impact-sector winds even though traffic impacts are not particularly concentrated in the impact sector; only two of the seven residences (D1 and D2) were downwind of major roadways and highways during impact-sector winds.

Boston. In the Boston study area, a pronounced increase in PNC during impact-sector winds was evident at three sites 5.0–6.1 km downwind of the airport (Figure 3). At residences U1 and U2 (NNE-ESE, 28°–61°), which were both also upwind of Interstate 93 (I-93) (Figure 3(b)), median PNC during impact-sector winds were 25 000 and 20 000 particles/cm³, respectively, as compared to 15 000 and 10 000 particles/cm³ during all other winds. At site D1, which was 6.1 km downwind of the airport and 200 m downwind of I-93 during impact-sector (NE) winds, but impacted by the highway during both NE (31°–59°) and SE (115°–145°) winds, median PNC were greater during NE winds than during SE winds (29 000 vs

19 000 particles/cm³, respectively; means were 29 000 ± 46% vs 21 000 ± 70% particles/cm³, respectively) for similar I-93 traffic volume (hourly traffic flow was 7000 ± 47% during times of NE vs 8000 ± 39% during SE winds).

At the other six sites in Boston, which were 6.8–10.0 km from the airport, increases in PNC during impact-sector winds were not as distinct (Figure 3(c)). Ambient median PNC during impact-sector winds, which likely included considerable contributions from upwind sources including busy roadways and highways in Boston, were 1.1- to 1.6-fold higher at these six residences than the medians for all other winds (Table 1). Heatmaps for PNC by wind direction and time of day for the central site and all residences (SI Figure S3 (b) and (d)) indicate PNC peaks coincided with morning and evening vehicular and aviation traffic rush-hours. The impact-sector PNC were lower in Boston compared to Chelsea.¹⁵

Correlations between PNC and Wind Speed. Because higher wind speeds generally promote greater dispersion and mixing, PNC and wind speed are typically negatively correlated. However, for buoyant aviation emissions plumes, higher wind speeds promote faster ground arrival counterbalancing the increased dilution.¹⁸ Thus, a distinct feature of aviation emissions impacts (unlike road traffic emissions impacts) is a lack of negative correlation between PNC and wind speed.^{4,19,20} We too observed this phenomenon. During impact-sector winds at Chelsea and Boston central-sites, the negative correlation between PNC and wind speed was lacking; correlation coefficients were $r_s = 0.17$ and 0.19 , $n = 435$ and 408 h, respectively, and p -value < 0.001. In contrast, during other winds, the expected negative correlation between PNC and wind speed was observed ($r_s = -0.24$ and -0.05 , $n = 7552$ and $10\,537$ h, respectively, and p -value < 0.001). Similar trends

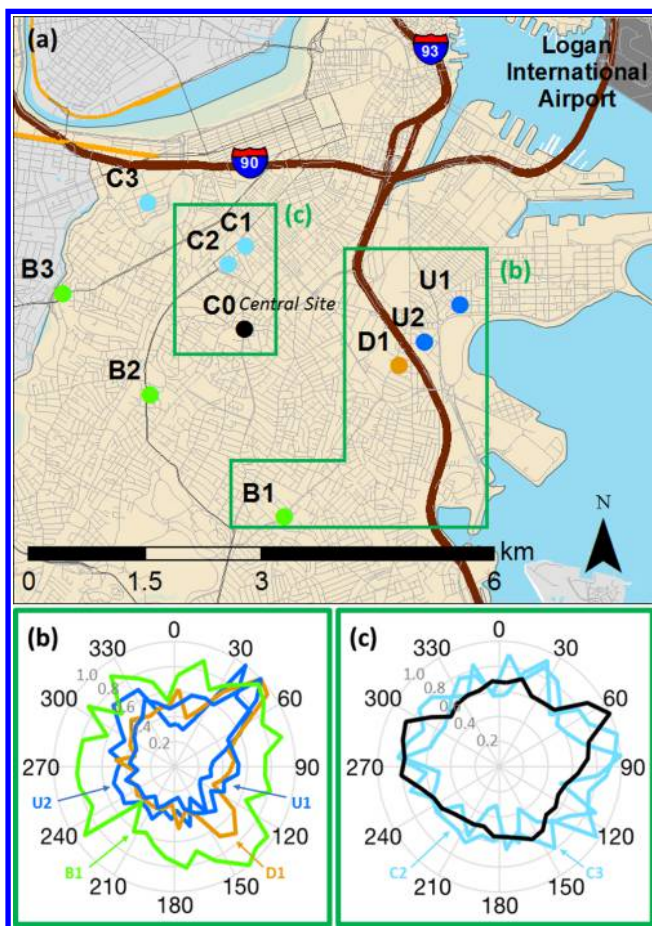


Figure 3. (a) Locations of the central site (C0, black) and nine residences monitored in Boston. Residences were classified as upwind (U, dark blue) of the highway during impact-sector winds, downwind of the highway (D, orange) during impact-sector winds, community sites (C, light blue) and background sites (B, green). (b)–(c) Normalized (by the maximum) PNC roses are based on hourly medians; concentric circles are increments of 0.2 on a 0–1 scale.

were found at the residences in both study areas: correlation between PNC and wind speed was either lacking or even positive during impact-sector winds but it was negative during other winds. Correlation coefficients for residences are shown in Figure 4 where points have been jittered along the categorical *x*-axis to reduce overlap.

Because impact-sector winds were a small fraction of all winds (3–12% of the total data set) we conducted bootstrap resampling of correlation estimates (r_s) and bootstrap subsampling of a similarly small data set from other wind conditions to ensure that the lack of negative correlation was not by chance. The correlation estimates during impact-sector winds were different from the negative estimates obtained for other winds; results are shown in SI Figure S4–S19. The contrast in correlation was most evident in Chelsea and sites upwind of I-93 in Boston. Notable exceptions were sites downwind of both a highway and the airport during impact-sector winds likely because they were dominantly impacted by highway emissions given their proximity to the highways. For example, at site D1 in Boston, we observed no difference in correlation estimates between impact-sector and other winds (SI Figure S11). In comparison, at sites U1 and U2 in Boston, which were upwind of the highway during impact-sector winds but still downwind of the airport, correlation estimates were

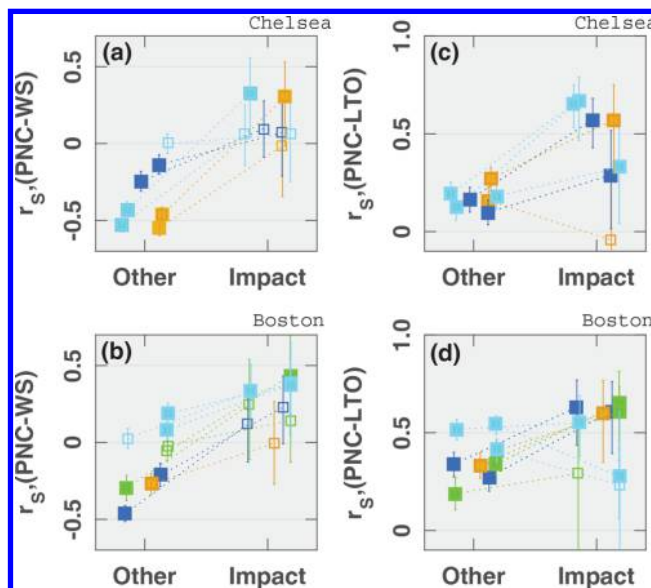


Figure 4. Correlation coefficients between outdoor PNC and wind speed (a, b) and LTO (c, d) for seven Chelsea and nine Boston residences during impact-sector and other winds. Filled squares represent significant correlation (p -value < 0.05) and unfilled squares represent insignificant correlations. X-axis is categorical but points have been jittered to enhance visual clarity by reducing overlap. For description of colors, see captions for Figures 2 and 3.

positive during impact-sector winds and negative during other winds (SI Figure S12–S13).

Correlations between PNC and Flight Activity. PNC at both central sites were previously reported to be positively correlated with aviation activity (measured as LTO, the hourly total landings and takeoffs) after controlling for traffic volume, time of day and week, and meteorological factors (wind speed, temperature, and solar radiation).⁴ Because the central sites both had relatively large data sets (several years of monitoring), we were able to control for these factors; however, the relatively small PNC data sets for residences and the lack of local traffic volume information limited meaningful controls in the current analysis. Also, because the temporal patterns of flight activity and vehicle traffic are similar, some confounding was observed between PNC and LTO irrespective of the wind direction. For example, Pearson’s correlation coefficient for hourly LTO and traffic volume on I-93 in 2012 was 0.85. Nonetheless, Spearman’s correlations and the bootstrap analysis (SI Figure S20–S35) indicate that PNC versus LTO correlation estimates during impact-sector winds were generally higher than during other winds; that is, r_s ranged from 0.29 to 0.67 during impact-sector winds compared to 0.10–0.54 during other winds, but there were exceptions (see discussion in SI).

Indoor Infiltration of PNC during Impact-Sector Winds. Overall Trend at Residences. Infiltration of aviation-related outdoor PNC was evident in the data as higher indoor concentrations during impact-sector winds compared to other winds. The median increase in indoor concentrations during impact-sector winds compared to other winds was 1.7-fold (range: 0.9–3.1-fold). PNC measurements (median and minimums) are summarized in Table 1 for all residences. For trends with respect to wind direction for individual residences see SI Figures S36–S51, which show an increase in indoor medians coincident with impact-sector winds is more apparent for residences in Chelsea and Boston closer to the airport, while

some residences located farthest away (like B1 and B2) showed no trend with respect to wind direction for either outdoor or indoor PNC.

HEPA filtration lowered the indoor concentrations; indoor-to-outdoor PNC ratios were 0.33 ± 0.17 lower during HEPA filtration as compared to sham filtration (see Brugge et al.¹⁶). Figure 5 compares 10° -wide-sector PNC medians for impact-

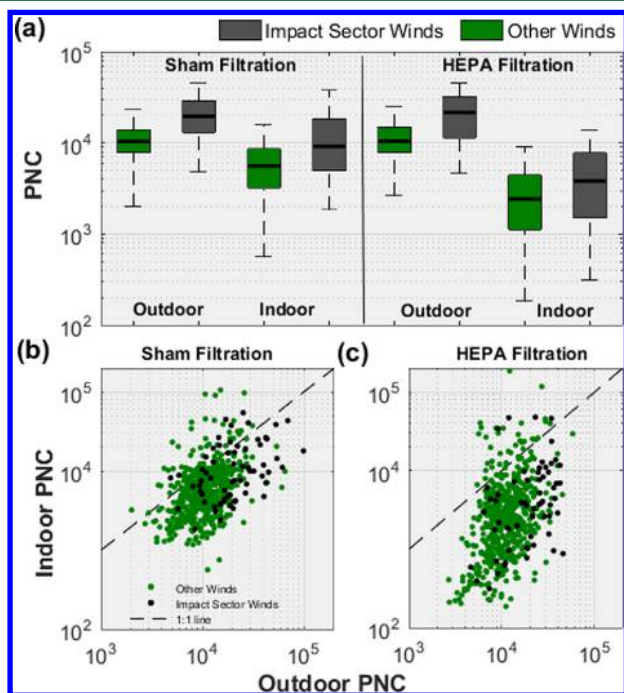


Figure 5. (a) Tukey's boxplots of indoor and outdoor PNC data during sham and HEPA filtration from all 16 homes. The horizontal line inside each box is the median; the boxes extend from the 25th to the 75th percentile and the whiskers extend to $1.5 \times$ interquartile range. In (b) and (c) each point in the scatterplots represents the median of hourly medians classified into 10° -degree-wide wind sectors.

sector and other winds separately for sham and HEPA filtration scenarios in all 16 homes. Because filtration efficiency is not preferential to ambient wind direction, higher concentrations (despite lower indoor-to-outdoor ratios) were still observed during impact-sector winds. Further, this trend was apparent in both the hourly medians and hourly minimums (range: 0.8–2.9-fold) of indoor PNC even though hourly medians are more likely to be skewed by contributions from indoor sources than the hourly minimums (SI Figure S52).

Previous studies have shown that ambient PNC infiltrate indoors via multiple pathways such as forced air ventilation systems, open windows, or cracks in the building envelope.²¹ Infiltration factors vary from 0.03 to $1.0^{21,22}$ in the ultrafine range, the size range for the majority of the aviation-related particulate emissions.³ Infiltration of aviation-related PNC and, resultantly, an increase in indoor PNC and residential exposures can thus be expected in near-airport residences. Our results clearly indicate that to be the case; particles of aviation-related origin infiltrate residences. Two cases are illustrated in detail in the following section.

Illustration of Infiltration at Select Residences. Infiltration of PNC is illustrated for residence C3 in Chelsea in Figure 6 (a). Time series of indoor PNC closely followed the same pattern as outdoor PNC during an 18-h period of consistent

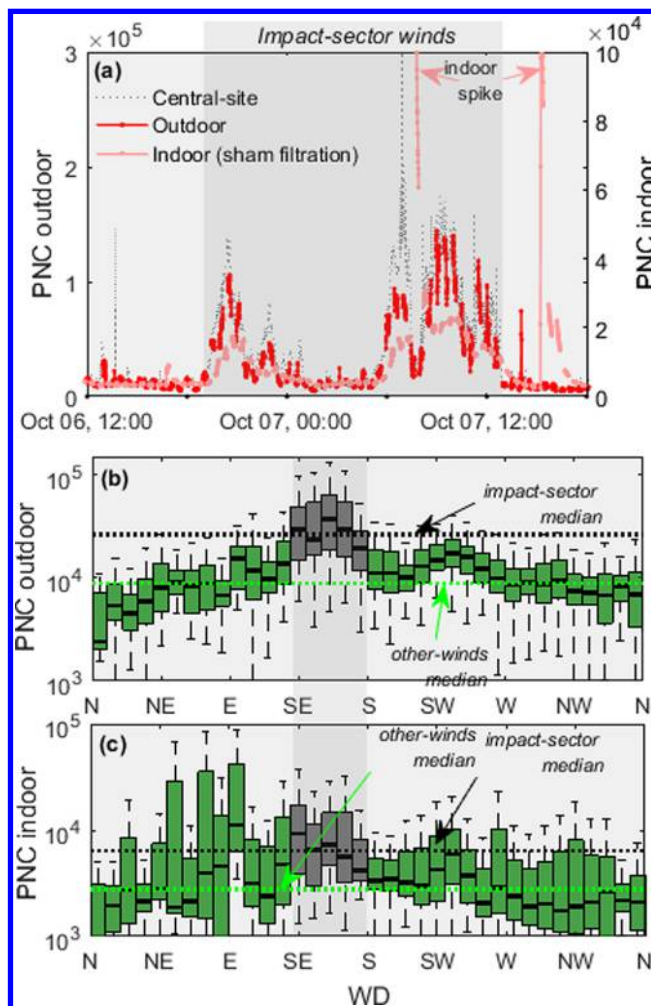


Figure 6. PNC time series for October 6–7, 2014 for site C3 in Chelsea is shown in (a). Impact-sector winds are highlighted in gray. Tukey's boxplots in (b) and (c) show outdoor and indoor PNC. The horizontal line inside each box is the median, the boxes extend from the 25th to the 75th percentile and the whiskers extend to $1.5 \times$ interquartile range.

impact-sector winds (from 1900 h on Oct 6 to 1200 h on Oct 7, 2014). During hours of minimal flight activity (0100–0500 h; LTO = 1.5 h^{-1}), PNC indoors and outdoors at C3 and the central site were all low but increased as flight activity resumed after ~ 0500 h. Residential outdoor PNC was also remarkably highly correlated (Pearson's $r = 0.96$) with the central site located 1 km away indicating the spatial homogeneity of the aviation-related impact over a large area. Further, even though it was past the evening traffic rush-hour period (and thus traffic would have contributed minimally to the observations or for that matter particle formation) when the winds shifted (at ~ 1900 h) to the impact sector, outdoor and central-site concentrations increased to high levels (1 min averages were between 50 000 and 100 000 particles/cm³), which underscores the magnitude of this impact. In comparison, Simon et al.¹⁵ reported mean 1 min on-road PNC from 180 h of mobile monitoring across Chelsea including traffic rush-hours was 32 000 particles/cm³ which was about one third to one half of the observed PNC at C3 during impact-sector winds. Overall, at C3, the median indoor PNC was nearly 3-fold higher for impact-sector winds compared to other winds (8900 versus 2800 particle/cm³) (Figure 6(c), SI Figure S42).

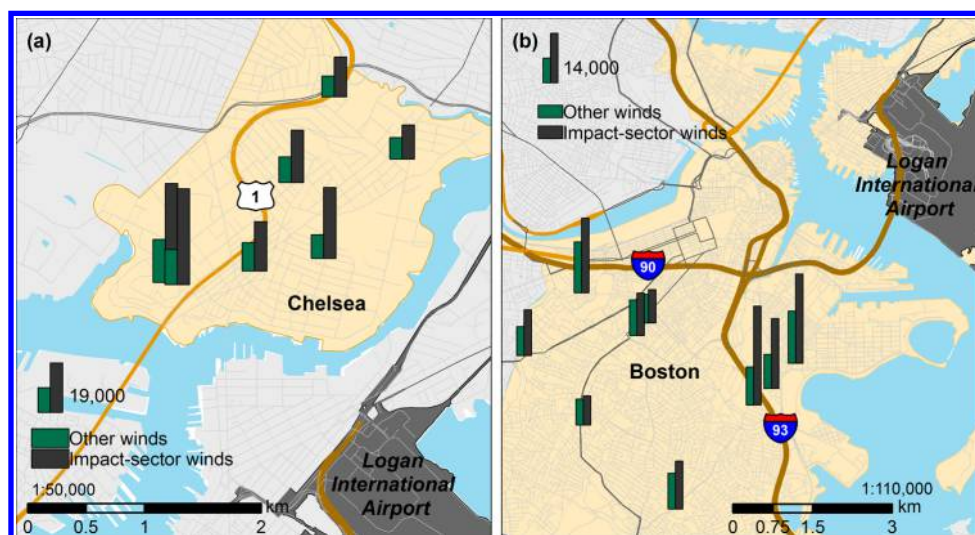


Figure 7. Outdoor PNC at residences during six-week monitoring periods in Chelsea (a) and Boston (b). Median of hourly medians classified as impact-sector and other winds are shown.

Another example of infiltration is shown in Figure S53(a) where a 22-h period of generally consistent impact-sector winds is highlighted (from 1900 h on Nov 6 to 1700 h on Nov 7, 2012) for residence U1 from the Boston study area. U1 is relatively close to I-93 but it is upwind of the highway during impact-sector winds. Outdoor concentrations during impact-sector winds from 1900 h to as late as midnight on Nov 6–7, 2012 were $\sim 40\,000$ particles/cm³ but then decreased to as low as 2000 particles/cm³ during the hours of low flight activity at the airport (LTO decreased from 32 h⁻¹ to 2.8 h⁻¹ during 1900–0000 h to 0000–0500 h). The indoor PNC time series was consistent with the outdoor concentration during these hours. Both outdoor and indoor concentration started increasing again around 0500 h when flight activity resumed at the airport; however, around 0800 h indoor PNC spiked, likely from an indoor particle-generation event that dominated indoor PNC during the following hours despite impact-sector winds. Overall, the median indoor PNC was 2-fold higher for impact-sector winds compared to other winds (15 000 versus 7400 particles/cm³) (Figure S53(c) and Figure S44).

Strength and Limitations. To our knowledge this is the first investigation of the impacts of aviation-related emissions at residences around airports. Our results show an increase in outdoor as well as indoor PNC. These findings point to the need for studies to provide further characterization of these impacts (e.g., measure additional pollutants in a greater number and variety of residences both near and far from airports and under a greater diversity of meteorological conditions and indoor activities).

Our study also had limitations. The foremost is that monitoring was not specifically designed for quantifying the impacts of aviation-related emissions on indoor and outdoor PNC. Data were collected as part of the Boston Puerto Rican Health Study (a study of exposure to urban air pollution and cardiovascular health effects in a Puerto Rican cohort²³), but it allowed for the reported analysis because of the residences' proximity to and distribution around the airport. Ideally, for quantifying the aviation-related impacts and distinguishing them from other outdoor sources (such as traffic) and indoor sources (such as cooking), continuous indoor and outdoor monitoring at several locations in carefully characterized

residences with indoor time-activity records would be necessary. In addition, the study was not designed to characterize the air exchange rates or infiltration factors for ambient particles. As a result, we could not quantify the contribution of indoor- versus outdoor-origin PNC to total indoor observations, or more pertinently the contribution from aviation-related outdoor PNC to indoor observations. Further, the lack of concurrent data from all or even multiple residences precluded spatial analysis. Residence-to-residence differences in outdoor and indoor PNC (Figure 7 and Table 1) were observed. For example, at sites closer to the airport PNC were generally higher than farther away, but at sites immediately downwind of highways, even though they were farther downwind of the airport, PNC were even higher, likely due to impacts from both aviation-related and traffic emissions. Such spatial differences were not investigated. Observed outdoor concentration differences were likely not solely due to the differences in spatial location with respect to the airport or other sources; temporal differences (e.g., meteorological and seasonal factors) likely also contributed significantly, but they could not be controlled for due to lack of concurrent data.

Significance of the Results. Altogether, our results make a compelling case for further investigation of aviation-related air pollution impacts and resulting exposures because these impacts are not expected to be unique to Logan airport. Extrapolating from Correia et al.¹³, we estimate that in the United States ~ 40 million people live near 89 major airports (i.e., within areas with ≥ 45 dB noise levels near airports). Inclusion of aviation-related impacts may also improve predictive models for exposure assessments. Future studies of this impact with concurrently located sites that allow analysis of the spatial gradient and comparison with traffic impacts could be very informative for ultrafine particle epidemiology.

■ ASSOCIATED CONTENT

📄 Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.7b05593.

Information related to flight activity at Logan International Airport (Figure S1), details of monitoring schedule residence characteristics, and summary statistics of the

data (Table S1–S6, Figure S2), heatmaps of PNC by wind direction and time of the day (Figure S3), correlation coefficient estimates from bootstrap subsampling and resampling (Figure S4–S35), additional graphics related to particle number concentration trends with respect to wind direction at monitoring sites (Figure S36–S52) and an example of infiltration (Figure S53) (PDF)

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Notes

The authors declare no competing financial interest.

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