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Aviation Emissions Impact Ambient Ultrafine Particle Concentrations in the Greater Boston Area

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Abstract

Ultrafine particles are emitted at high rates by jet aircraft. To determine the possible impacts of aviation activities on ambient ultrafine particle number concentrations (PNCs), we analyzed PNCs measured from 3 months to 3.67 years at three sites within 7.3 km of Logan International Airport (Boston, MA). At sites 4.0 and 7.3 km from the airport, average PNCs were 2- and 1.33-fold higher, respectively, when winds were from the direction of the airport compared to other directions, indicating that aviation impacts on PNC extend many kilometers downwind of Logan airport. Furthermore, PNCs were positively correlated with flight activity after taking meteorology, time of day and week, and traffic volume into account. Also, when winds were from the direction of the airport, PNCs increased with increasing wind speed, suggesting that buoyant aircraft exhaust plumes were the likely source. Concentrations of other pollutants [CO, black carbon (BC), NO, NO₂, NO_x, SO₂, and fine particulate matter (PM_{2.5})] decreased with increasing wind speed when winds were from the direction of the airport, indicating a different dominant source (likely roadway traffic emissions). Except for oxides of nitrogen, other pollutants were not correlated with flight activity. Our findings point to the need for PNC exposure assessment studies to take aircraft emissions into consideration, particularly in populated areas near airports.

Graphical abstract

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Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.6b01815.

Information related to flight activity at Logan International Airport, details of monitoring sites and instruments, distributions of variables, traffic volume data and fits, additional graphics related to PNC trends at monitoring sites and the effect of wind speed on pollutant concentrations, and correlation coefficient values (PDF)

Notes

The authors declare no competing financial interest.



INTRODUCTION

Exposure to ultrafine particles (UFPs; aerodynamic diameter of <100 nm) is associated with adverse cardiovascular effects, including systemic inflammation biomarkers and ischemic heart disease.^{1–3} Although ambient UFPs can form in the atmosphere through processes such as photochemical formation and condensation of vapors,¹ they primarily derive from anthropogenic combustion sources, such as power generation and transportation activities. In urban areas, roadway traffic emissions are a dominant source of UFPs and have been the focus of exposure assessment and epidemiological studies.¹ Recently, airport-related emissions were shown to also be a significant UFP source;^{4–6} however, their impacts are less well-studied compared to roadway traffic. Distinguishing the contribution of airport-related emissions from traffic emissions can better inform exposure assessment efforts.^{7–9}

Concentrations of UFPs emitted by vehicular traffic are typically highest on or near roadways but decrease rapidly within 200–300 m.¹⁰ In contrast, the impacts from airport-related emissions on UFP concentrations can extend tens of kilometers from airports, encompassing large populated areas.^{4–6} For example, Keuken et al.⁵ reported a 200% increase in UFPs [measured as particle number concentrations (PNCs), a proxy for UFPs] at a site 7 km downwind from Schiphol Airport (Amsterdam, Netherlands) and a 20% increase at a background site 40 km downwind. Using dispersion modeling, Keuken et al.⁵ estimated that aviation activity increased annual PNC exposures by 5000–10 000 particles cm^{-3} at 45 000 addresses. Hudda et al.⁴ reported a 100–900% increase in PNCs over local background that extended 18 km downwind from Los Angeles International Airport (LAX, CA); UFPs < 40 nm constituted 75–90% of the elevated PNCs.⁶

Such impacts are likely not unique to the airports in these studies.^{4–6} At locations with highly variable winds that change direction swiftly, for example, Logan International Airport

in Boston, MA, the busiest airport in New England, the resulting impacts may be intermittent and dispersed over many downwind sectors. Patton et al.^{11,12} found that wind-direction sectors that included the airport as an upwind source were a significant explanatory variable for PNCs in communities located 4–8 km north-northwest (NNW)–south-southwest (SSW) of the airport in Boston. We were motivated to examine newly available PNC data sets, collected as part of two near-roadway health studies in Boston,^{13,14} for evidence of airport-related emission impact on ambient PNCs.

We analyzed PNCs measured continuously at three stationary sites within 7.3 km of the airport. Our objectives were to (1) test the hypothesis that flight activity was associated with PNCs when winds positioned these sites downwind of the airport, (2) analyze the dependence of PNCs upon wind speed to identify if PNCs were higher at higher wind speeds, which would indicate that the impact was likely from aircraft exhaust plumes, and (3) analyze collocated measurements at one site for a suite of pollutants to compare impacts across pollutants.

MATERIALS AND METHODS

Logan International Airport and Monitoring Sites

The General Edward Lawrence Logan International Airport occupies 6.8 km² on the north shore of Boston Harbor, 1.6 km east of downtown Boston (Figure 1a). Daily, about 850 jet and 160 non-jet aircraft operate at the airport. It has six runways: 22R/4L and 22L/4R are parallel and aligned to true north 200°/20°, 27/9 is aligned to 257°/77°, 32/14 is aligned to 306°/126°, and 33R/15L and 33L/15R are parallel and aligned to 315°/135° (Figure 1a). Diurnal trends and flight statistics by runway and wind direction are shown in Figure S1 and Table S1 of the Supporting Information.

During the study period (January 2012–August 2015) winds in the Boston area (Figure 1b) prevailed from west–north–northwest (W–NNW) (270–337.5°) in winter and south–west–southwest (S–WSW) (180–247.5°) in summer (30 and 26% frequency, respectively), consistent with the general pattern in the greater Boston area.¹⁵ During prevailing winds, the majority of flights arrive and depart on runways 22L, 22R, 27/9, and 33L; thus, during these winds, the downwind advection of airport-related emissions occurs largely over the ocean and the communities located northeast of the airport (Figure 1a). During infrequent northeast (NE) (22.5–67.5°) and southeast (SE) (112.5–157.5°) winds (both occurred at 7% frequency), most flights use runways 22L/4R, 22R/4L, and 27/9, causing downwind advection of emissions over Boston and residential communities southwest–northwest (SW–NW) of the airport where our monitoring sites were located.

PNCs were monitored using condensation particle counters (CPCs, model 3783 at Chelsea and Roxbury and model 3775 at Boston Globe; TSI, Inc., Shoreview, MN) at three locations: (1) the roof of a three-story building in Chelsea, 4.0 km northwest of the airport, from January 2014–August 2015, (2) the roof of the two-story Boston Globe parking garage in Dorchester, 6.5 km southwest of the airport, from March–May 2011, and (3) the United States Environmental Protection Agency (U.S. EPA) Speciation Trends Network air quality monitoring site in Roxbury (EPA-STN, ID 25-025-0042), 7.3 km southwest of the airport,

from January 2012–August 2015 (Figure 1a). We refer to these sites as Chelsea, Boston Globe and Roxbury, respectively. Further site and instrument details are provided in Tables S2 and S3 of the Supporting Information. Data quality assurance is also discussed in the Supporting Information. CPCs were calibrated annually at TSI, and side-by-side tests conducted in our laboratory indicate a good agreement ($r^2 = 0.97$; see Figure S2 of the Supporting Information).

Data Processing

Meteorological data, including wind direction and speed, reported as a 2 min running average at 1 min resolution, were obtained from the National Weather Service station at the airport¹⁶ and averaged to obtain hourly values. Wind roses are shown in panels a–c of Figure S3 of the Supporting Information. 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, i.e., LTO. Data for aircraft idling and taxiing times, although likely correlated with LTO, were not available. We classified the hours 0600–2359 as high flight activity hours and 0000–0559 as low flight activity hours. During the study period, the average LTO (± 1 standard deviation) during high and low activity hours were 46.2 ± 10.4 and $5.0 \pm 5.3 \text{ h}^{-1}$, respectively (see Figure S1 of the Supporting Information).

Hourly average black carbon (BC), CO, NO, NO₂, NO_x, ozone, fine particulate matter (PM_{2.5}), and SO₂ concentrations and solar radiation monitored at the Roxbury site were also obtained.¹⁷ These data were combined with hourly average PNCs. Hourly average baseline PNCs, the running fifth percentile over 5 min periods for the PNC time series, was also calculated to exclude short duration (<5 min) spikes, likely resulting from traffic near the monitoring sites, that could skew the averages. Further, hourly average PNCs and baseline PNCs were aggregated by 10° wide wind-direction sectors, and sector averages were calculated.

Statistical Analysis

To test the hypothesis that hourly total flight activity [i.e., LTO (number h⁻¹)] was correlated with PNCs at Chelsea and Roxbury, we used non-parametric Spearman's correlation to avoid specifying a known, parametric relationship between PNCs and variables that might impact airport-related emission concentrations at distant sites. LTO, particle number, other pollutant concentrations (and their log-transformed values), and traffic and meteorological variables were generally non-normally distributed (Figure S4 of the Supporting Information). We present only bivariate correlations for the Boston Globe site as a result of limited monitoring (only 3 months versus 1.67 and 3.67 years at Chelsea and Roxbury). For Chelsea and Roxbury, we report the strength of partial correlation (r_s) and significance (p , considered significant if <0.01) between hourly LTO and PNCs (both hourly average and baseline hourly average), taking meteorological variation, temporal variation (hour of the day and weekday or weekend differentiation), and traffic (hourly traffic volume) into account. Hour of day was treated as a circular variable and resolved into sine and cosine components {sine and cosines of radians $[(2\pi/24) \times \text{hour of day}]$ }. Meteorological variables considered included temperature (°C), wind speed (km h⁻¹), and solar radiation [langley

(Ly)/min, only available at Roxbury]. Wind direction was only used to classify data as impact or non-impact sector. The partial correlations were calculated between LTO and the residuals of PNCs after regression of impact-sector PNCs on the controlled variables (i.e., between LTO and the component of PNCs uncorrelated with controlled variables). This approach helps address the problem of collinearity between flight activity and vehicular traffic volume.

Because measurements for local street traffic were unavailable, we assumed that local traffic patterns were proportional to those measured at the closest traffic monitor on highways (Figure S5 of the Supporting Information).¹⁸ For the Roxbury site, we used concurrent measurements from Interstate-93 (I-93) station 8494, located south of downtown Boston between the site and the airport. For the Chelsea site, the nearest traffic monitoring station was located on highway 1A (station 8087, located north of the airport and northeast of the site), but data were only available for 165 days of the 20 month monitoring period. A cubic spline fit based on hour of the day accounted for 80 and 90% of the variation in traffic volume on highway 1A on weekdays and weekends, respectively (Table S4 of the Supporting Information). Therefore, it was a reasonable proxy for temporal variation in local traffic volume. Additionally, at the Roxbury site, we also used collocated measurements of CO and NO_x as a proxy for traffic congestion in an upwind area. We observed coincident concentration spikes of these pollutants and PNCs when winds were from the direction of busy intersections in the vicinity of the site (southeast and west; panels a–c of Figure S10 of the Supporting Information). PM_{2.5} and ozone were also used as controls to account for factors, such as frontal weather and photochemical formation, that impact PNCs at a regional scale.

RESULTS AND DISCUSSION

Wind Direction and PNC Patterns

At all three monitoring sites, baseline PNC roses and PNC plots for 10° wide sectors, shown in Figure 2 and Figure 3, indicated an emission source in the upwind direction that coincided with the azimuth angle between the sites and the airport. These plots were used to identify impact sectors, i.e., site-specific wind-direction sectors, that were likely impacted by airport-related emissions. Impact-sector widths varied from 20° to 45°. See Table S5 of the Supporting Information for impact-sector boundaries and summary of PNCs.

Impact-sector PNCs were nearly 2-fold higher during high flight activity hours compared to low activity hours. However, high and low flight activity hours are also high and low traffic activity hours, and thus, the difference is indicative of the reduction in general transportation activity. Nonetheless, this difference was accentuated for impact-sector winds compared to other directions (2.1-fold at Chelsea and 1.9-fold at Roxbury compared to 1.4-fold at Chelsea and 1.7-fold at Roxbury for other wind directions; Figure S6 of the Supporting Information). Furthermore, during 0100–0359 h, when flight activity was minimal (average arrivals and departures in 2014 were 1.6 and 0.2 h⁻¹, respectively), PNC averages for impact-sector winds and all other wind directions were comparable. Atmospheric transformation of UFPs (physical and chemical) differ between nighttime and daytime hours, but these effects are expected to be independent of the wind direction.

Chelsea Monitoring Site

PNCs were elevated at the Chelsea site, 4.0 km downwind from the geographic center of the airport, during south-southeast (SSE) winds (impact sector = 135–175°) (Figure 2 and Figure 3). The highest of these elevated concentrations were associated with 145–155° winds, coinciding with a 151° azimuth angle between the site and the airport. The annual (2014) average impact-sector PNC was 2-fold higher than the average for all other wind directions [$35\,000 \pm 75\%$ (average $\pm$ relative standard deviation) compared to $18\,000 \pm 69\%$ particles cm^{-3}]. PNCs were consistently elevated during impact-sector winds across years, seasons, and times of day, except for minimal flight activity hours (panels a–d of Figure S7 of the Supporting Information). The duration of impact-sector winds was mostly a few hours; only 10% of the data was from instances of 6 or more continuous hours of impact-sector winds. During the two longest periods of sustained impact-sector winds (18 h and 26 h), PNCs and LTO were strongly correlated ($r_s > 0.81$; $p < 0.01$; Figure S7e of the Supporting Information). The highest of the daily averages ($>50\,000$ particles cm^{-3}) was observed on the days with the most hours of impact-sector winds (Figure S7f of the Supporting Information). Relatively high PNCs were also observed (2014 average was $22\,000 \pm 53\%$ particles cm^{-3}) during southwesterly winds when highway 1 (2.6×10^4 vehicles/day) and local streets and intersections were upwind of the Chelsea site (Figure 1).

Boston Globe Monitoring Site

PNCs were elevated at the Boston Globe site during northeasterly winds (impact sector = 15–60°). The site was 6.5 km downwind of the airport along a 30° azimuth angle measured from the site to the airport (Figure 2 and Figure 3). The impact-sector average PNC was $25\,000 \pm 118\%$ particles cm^{-3} . Although contributions from traffic emissions on Morrissey Boulevard (4×10^4 vehicles/day, about 100 m upwind of the site during impact-sector winds) cannot be ruled out, our results show that aircraft contributions can be distinguished at this site. The strongest correlations (Spearman's rank correlation) between PNCs and LTO across all 36 10° sectors were observed when wind was from the direction of the airport, i.e., 15–45° (panels b and c of Figure S8 of the Supporting Information). A stronger correlation was observed for sustained impact-sector winds compared to all hours, including short sporadic periods of impact-sector winds. Figure 4 and Figure S8d of the Supporting Information show a 3 day period (May 16–18, 2011) of sustained impact-sector winds when PNCs and LTO were strongly correlated ($r_s = 0.68$; $p < 0.01$). During this period, 97% of the flights landed on runway 4R (aircraft heading = 20°) and 84% departed from runway 9 (aircraft heading = 77°). For all hours of impact-sector winds in May 2011, r_s was 0.62 ($p < 0.01$; $n = 196$ h). In contrast, there was no correlation between PNCs and LTO for winds other than from the impact sector ($r_s = 0.08$; $p > 0.01$; $n = 414$ h). High PNCs during southwest to northwest winds ($44\,000 \pm 88\%$ particles cm^{-3}) are attributable to traffic on I-93 (2×10^5 vehicles/day) located 25 m west of the monitor.

Roxbury Monitoring Site

At the Roxbury site, 7.3 km downwind from the airport, elevated PNCs were observed during east-northeast (ENE) winds (impact sector = 45–65°) (Figure 2 and Figure 3). The highest concentrations were associated with the 50–60° winds, coinciding with a 56°

azimuth angle measured between the site and the airport. The annual (2014) average impact-sector PNC was 1.33-fold higher than the average for all other directions ($28\,000 \pm 54\%$ compared to $21\,000 \pm 65\%$ particles cm^{-3}). PNCs were consistently elevated during impact-sector winds across years, seasons, and times of day, except for minimal flight activity hours (panels a–d of Figures S9 of the Supporting Information). The duration of impact-sector winds was mostly one or a few hours; only 20% of the data was from instances of 6 or more continuous hours of impact-sector winds. During the two longest periods of sustained impact-sector winds (20 and 30 h), PNCs and LTO were strongly correlated ($r_s > 0.79$; $p < 0.01$; Figure S9e of the Supporting Information). Similar to the Chelsea site, daily PNC averages were higher on days with more hours of impact-sector winds (Figure S9f of the Supporting Information). However, unlike the Chelsea site, the highest of the daily averages at Roxbury site ($>50\,000$ particles cm^{-3}) did not coincide with impact-sector winds but with northwest winds in winter (reflecting contributions from traffic-related emissions). The impact-sector average PNC was comparable to the average during westerly winds (Table S5 of the Supporting Information), which orient the site downwind of a bus depot (100 m) and highway 28 (0.75–1 km).

Correlation between PNCs and Flight Activity

PNCs were positively correlated with LTO during impact-sector winds, as indicated by hourly average PNCs plotted versus LTO (colored by ambient temperature) in Figure 5. Figure 6 shows Spearman's partial correlation coefficients between LTO and hourly average particle number and other pollutant concentrations. Controlling for meteorology and temporal variation, the correlation between hourly average PNCs and LTO was positive and significant ($r_s = 0.22$ and $p < 0.01$ for Chelsea, and $r_s = 0.36$ and $p < 0.01$ for Roxbury). Further, at the Roxbury site, controlling for concurrent traffic on I-93 as a proxy for local traffic, meteorology, and temporal variation, the correlation was still positive and significant ($r_s = 0.29$; $p < 0.01$). Likewise, using concurrent NO_x and CO as a proxy for local traffic emissions and controlling for meteorology and temporal variation, the correlation was also positive and significant ($r_s = 0.31$; $p < 0.01$). Additionally, controlling for $\text{PM}_{2.5}$ and ozone as well as traffic on I-93, the correlation was still positive and significant ($r_s = 0.23$; $p < 0.01$). Of the pollutants other than particle number, only oxides of nitrogen were significantly correlated with LTO after taking meteorology, temporal variation, and traffic on I-93 into account ($r_s = 0.09, 0.20$, and 0.18 for NO , NO_2 , and NO_x , respectively; $p < 0.01$). Spearman's correlation coefficient values for hourly average PNCs, hourly average baseline PNCs, hourly median PNCs, and hourly average concentrations of other pollutants are summarized in Table S6 of the Supporting Information.

The impact-sector average BC concentration at the Roxbury site was somewhat higher than in other sectors [median concentration was $0.58\ \mu\text{g}/\text{m}^3$ (interquartile range of 0.39 – $1.0\ \mu\text{g}/\text{m}^3$) compared to $0.49\ \mu\text{g}/\text{m}^3$ (interquartile range of 0.30 – $0.79\ \mu\text{g}/\text{m}^3$); Mann–Whitney U test; $p < 0.01$], and although correlation with flight activity was significant after controlling for meteorology and temporal variation ($r_s = 0.12$; $p < 0.01$), it was not significant after additionally accounting for I-93 traffic ($r_s = 0.08$; $p = 0.023$). Concurrently measured $\text{PM}_{2.5}$ was not significantly correlated with LTO by itself or after controlling for meteorology and temporal variation or traffic.

Effect of the Wind Speed on PNCs

PNCs increased with wind speed for impact-sector winds but decreased with wind speed for winds from other directions (Figure 7). Highest PNCs for winds from other directions were observed during calm to $<10 \text{ km h}^{-1}$ winds. But during impact-sector winds, the highest PNCs were observed during $25\text{--}35 \text{ km h}^{-1}$ winds at Chelsea (Figure 7a) and $30\text{--}50 \text{ km h}^{-1}$ winds at Roxbury (Figure 7b). The increase in PNCs with wind speed was not due to increased flight activity: the average LTO was $41 \pm 29\% \text{ h}^{-1}$ for wind speeds $> 30 \text{ km h}^{-1}$ and $41 \pm 22\% \text{ h}^{-1}$ for wind speeds $< 30 \text{ km h}^{-1}$ in Figure 7d (see Figure S11 of the Supporting Information for LTO values).

Similar findings have been reported previously. Hsu et al.¹⁹ reported maximum PNCs at 25 km h^{-1} winds at sites $\leq 500 \text{ m}$ downwind of LAX, and Yu et al.²⁰ reported high values for SO_2 and NO/NO_x ratios during $25\text{--}35 \text{ km h}^{-1}$ winds at a site 200 m downwind of LAX. Carslaw et al.²¹ reported remarkably stable NO_x concentrations (only a 20% variation, as opposed to decreasing at higher speeds as is the case with roadway traffic emissions) at a site 180 m downwind of Heathrow Airport (London, U.K.) during $10.8\text{--}43.2 \text{ km h}^{-1}$ winds and inferred that the source was buoyant aircraft exhaust plumes. Barrett et al.²² simulated NO_x concentrations for the same site taking flight activity into account and suggested that the relatively fast arrival of buoyant exhaust plumes at higher wind speed counterbalances increased dilution. This explanation is consistent with buoyant-plume theory, which predicts that ground-level concentrations of pollutants downwind of large buoyant-plume sources (e.g., smoke stacks) will increase with wind speed up to a critical value at which maximum concentrations will occur.²³

It is unlikely that other airport-related activities, such as ground support equipment and cargo transfer, and increased vehicular activity in the vicinity of the airport were the dominant source of elevated impact-sector PNCs. The impacts even from highly trafficked highways are widely reported to be limited to a few hundred meters of the roadway^{3,10} and decrease at higher wind speed because dispersion of roadway emissions is proportional to wind speed.²³ However, given that these sources are located upwind in the impact sectors, some contribution, albeit continually waning at higher and higher wind speed, cannot be ruled out.

Higher PNCs were not observed for higher speed impact-sector winds during hours of reduced flight operations, likely because of considerably reduced LTO (i.e., during Hurricane Sandy on 10/28–29/2012 and the nor'easter storm on 02/08–09/2013, highlighted in Figure 7d and Figures S11–S14 of the Supporting Information). For example, coincident with the hours of lower PNCs during impact-sector winds on 10/29/2012, 0000–1459 h (Figure S13 of the Supporting Information), LTO was reduced to an average of 5 h^{-1} before full shutdown in the afternoon (2012 average for this period was 28.5 h^{-1}), while the traffic on I-93 during the same period was only about a third lower than the annual average (4200 compared to 6400 vehicles h^{-1}). Also, the average PNC for hours of no or trace rainfall ($9300 \pm 34\%$) was comparable to that during light–heavy rainfall ($9600 \pm 23\%$) during this period (Figure S14 of the Supporting Information), suggesting that PNC scavenging by rainfall was not significant. Atypical flight operation data from these two extreme weather events were not included in the statistical analysis.

Comparison of Particle Number and Other Pollutants Measured at the Roxbury Site

Pollutant roses for BC, CO, NO, NO₂, NO_x, PM_{2.5}, and SO₂ measured at the Roxbury site (panels a–c of Figure S10 of the Supporting Information) do not indicate elevated concentrations during impact-sector winds. The highest concentrations for all pollutants other than PNCs were observed during SSE winds, when the site was 20 m downwind of the nearest major street. Higher speed winds from impact sector had a diluting effect on concentrations of all pollutants other than particle number. As an example, NO_x concentration dependence upon wind speed is contrasted with PNCs in Figure 8, and other pollutants are shown in Figure S15 of the Supporting Information. The rates of concentration decrease with wind speed were comparable for impact-sector and non-impact-sector winds (Figure S16 of the Supporting Information).

Other pollutant concentrations were least correlated with PNCs during impact-sector winds (Figure S17 of the Supporting Information); i.e., Spearman's correlation coefficients during impact-sector winds were much lower than coefficients during winds that positioned the site downwind of the nearest major roadway (southeast) or highway (west). The difference in pollutant mixture between impact-sector and sectors impacted by local traffic emissions is further evidence that elevated impact-sector PNCs were likely not due to local traffic emissions.

The lack of distinct aircraft-related signals for other pollutants at Roxbury is generally consistent with the findings of previous studies. For example, the contribution from Heathrow emissions to annual average NO_x decreased from 27% at the airport boundary to 15% 2–3 km downwind,²¹ and at sites 0.45–0.65 km downwind from a regional airport in Venice, Italy, NO_x concentrations (although significantly influenced by aircraft emissions) were driven primarily by local traffic emissions.²⁴ However, some impacts farther downwind from airports have also been reported. Dodson et al.²⁵ found that aircraft activity contributed 0.05–0.1 µg/m³ (24–28%) of the total BC measured at five sites 0.16–3.7 km from a regional airport in Warwick, RI. At Hong Kong International Airport, Yu et al.²⁰ detected that aircraft emissions increased SO₂ and CO concentrations 3 km from the airport. Hudda et al.⁴ reported an increase in both BC and NO_x up to 10 km for finer time resolution (1–30 s), mobile monitoring data; however, the flight activity at LAX is nearly twice that at Logan airport, and nearly 95% of it occurs on one set of trajectories. Our results suggest that, for pollutants other than UFPs, the airport-related signal was indistinguishable from the background 7.3 km downwind from the airport. However, it is also possible that the signal was masked in hourly aggregation of the data.

The long spatial range of PNC impacts may also be indicative of secondary particle formation. If organic and sulfur-containing constituents in aircraft-engine exhaust nucleate upon cooling, the net effect of secondary formation may exceed downwind dilution of PNCs, as opposed to the continual downwind dilution of relatively inert pollutants, such as CO or BC. PNCs are known to increase by as much as several orders of magnitude as a result of nucleation between the aircraft exhaust system and up to 30 m downwind.^{26,27} Particles < 30 nm dominate the size distributions for individual aircraft plumes intercepted a few hundred meters from runways²⁸ and up to several kilometers downwind of airports⁵ (particularly under flight trajectories⁶), which suggests that nucleation of fresh combustion

emissions may continue over long downwind distances. Distant impacts are likely a mix of emissions from multiple thrust modes, which our data does not allow us to parse out, but a significant contribution from low-thrust-condition emissions (from idling or even landing) may promote particle formation because these emissions have a relatively high organic carbon content compared to high-thrust emissions (takeoffs), which have a relatively high BC content.^{27,29}

Implications

Our results show that aviation emissions impact ambient PNCs in residential areas up to 7.3 km from Logan airport. At the Roxbury site, impact-sector winds were observed at 3.6% frequency in 2014 and their weighted contribution to the annual average PNC was 4.7%. At Chelsea (4.0 km from the airport), the weighted contribution of impact-sector winds to the annual average PNC was 10%, although such winds were observed at only 5.3% frequency in 2014. The impact is likely to be greater for nearby communities, such as Revere and Winthrop (Figure 1), that are downwind of the airport during SSW winds that occur for as much as a quarter of the time annually.

Finally, our analysis suggests that there is a need to take UFP concentrations into account in epidemiological studies of airport-related health effects, particularly for cardiovascular outcomes in the vicinity of airports. Such studies have tended to focus on the effect of noise^{30,31} and have accounted for particulate mass (PM_{2.5} or PM₁₀); however, particulate mass is a poor proxy for aircraft emissions compared to PNCs.^{32,33} The case for UFPs can be made by calculating particle emission rates. In 2013, flight operations at Logan airport consumed 1.16×10^8 kg of Jet A fuel during taxiing, startup, takeoffs, and ascents up to 900 m³⁴ or about 26% of the city of Boston's estimated fuel consumption by all vehicles in that year.³⁵ However, particle number emission factors for aircraft exceed that of vehicles by an order of magnitude (e.g., Lobo et al.²⁸ reported aircraft emit $0.5\text{--}2.5 \times 10^{17}$ particles/kg of fuel consumed during different thrust modes, and Perkins et al.³⁶ reported vehicles in Boston emit $1.4\text{--}4.9 \times 10^{15}$ particles/kg of fuel consumed). As a result, the magnitudes for total emissions (emission factor $\times$ fuel consumption) from aircraft and vehicular traffic are comparable, suggesting that PNC exposure prediction in Boston (and similar cities) may be improved by incorporating aircraft as a source. Patton et al.^{11,12} found that winds that included the airport as an upwind source accounted for nearly a tenth of the total variation explained by their PNC models for Somerville [7 km downwind of the airport (Figure 1)] and were also a significant explanatory variable for two other residential communities (Dorchester and Malden) in the greater Boston area. Similarly, Weichenthal et al.³⁷ found that distance to Pearson International Airport (Toronto, Ontario, Canada) was an important PNC predictor after accounting for roadways. Inclusion of variables that can further characterize aviation impacts (e.g., active runway direction and distance during prevailing winds) and inclusion of temporal indicators of flight activity may enhance predictive capabilities of models.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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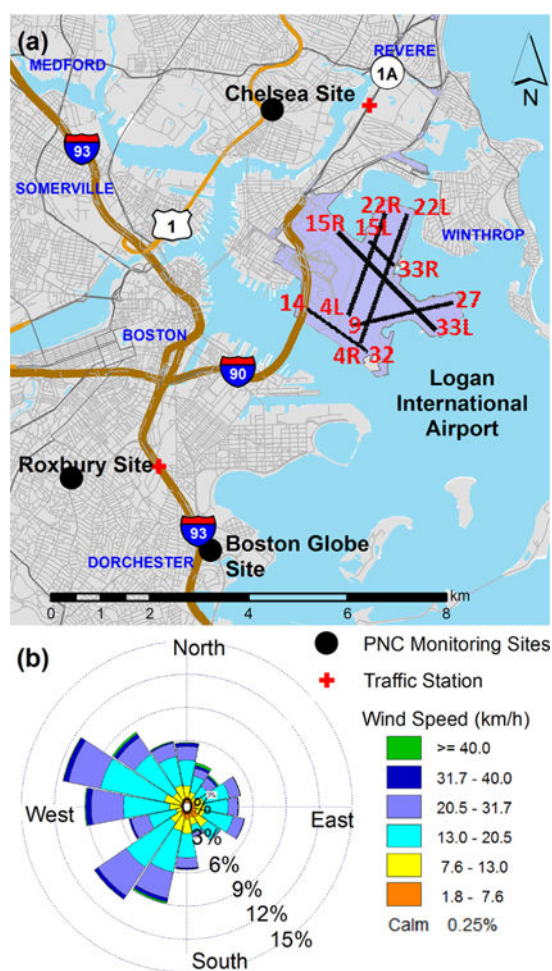


Figure 1.

(a) Map shows runway configuration at Logan International Airport and locations of the three monitoring sites. Base layers for the map were obtained from mass.gov. (b) Wind rose based on 1 min data for 2014 reported by the National Weather Service automated surface station located at the airport.

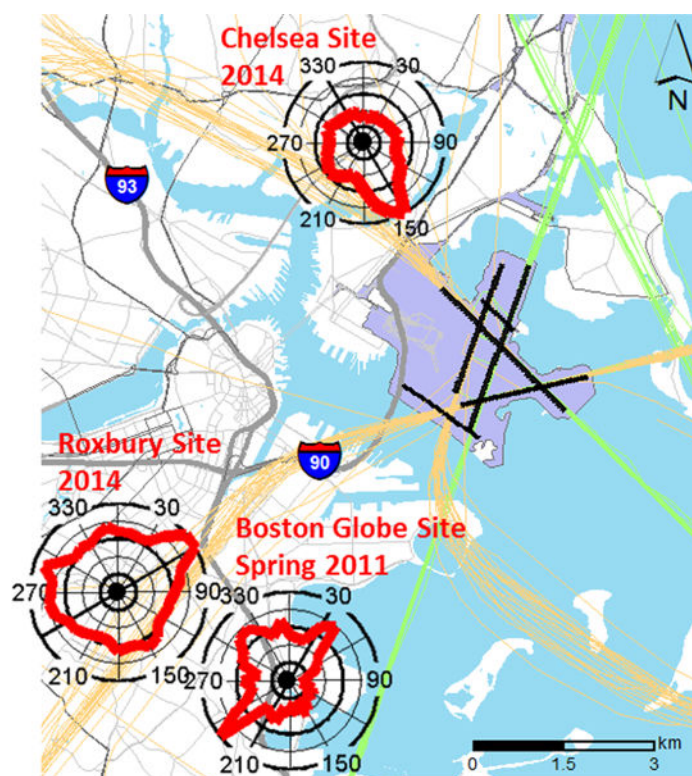


Figure 2. Hourly average baseline PNC roses (normalized to the maximum) for the three monitoring sites. Typical trajectories for frequently used runways for landings are shown in green, and takeoffs are shown in tan. Base layers for the map were obtained from mass.gov.

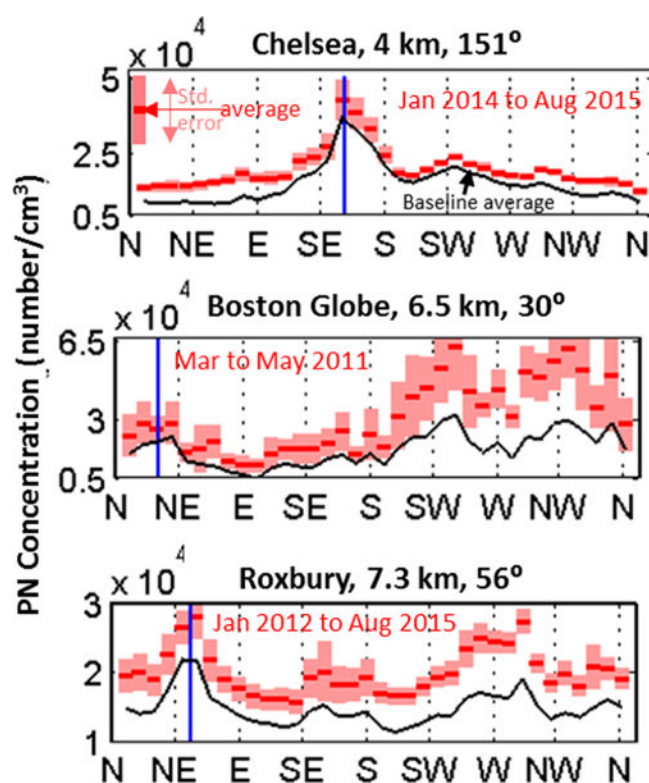


Figure 3.

Hourly average PNC aggregated by 10° wide wind-direction sectors. Sector-average PNCs are plotted as dark red lines, and ± 1 standard error is shaded red. Sector-average baseline PNCs are shown as a black line. The azimuth angle between the site and the airport is indicated by the vertical blue line.

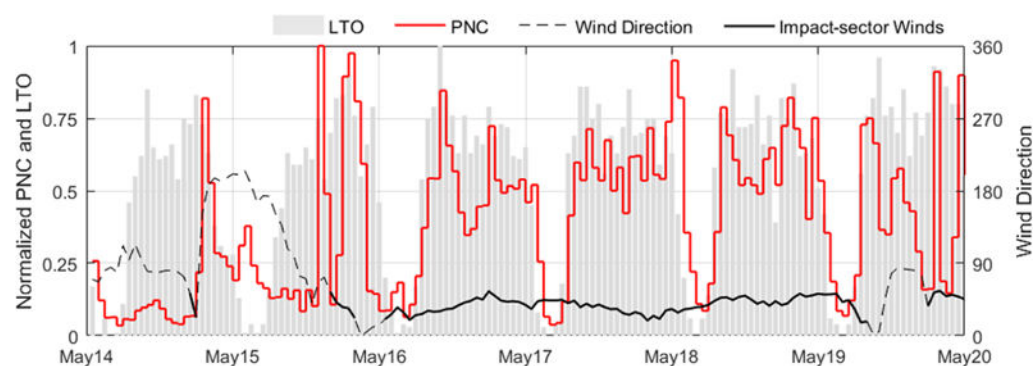


Figure 4.

Time series for wind direction, LTO (flight operations/h), and hourly average PNCs at the Boston Globe site. Impact-sector ($15\text{--}60^\circ$) winds are highlighted as a solid black line, and PNCs and LTO were normalized by the maximum during the week.

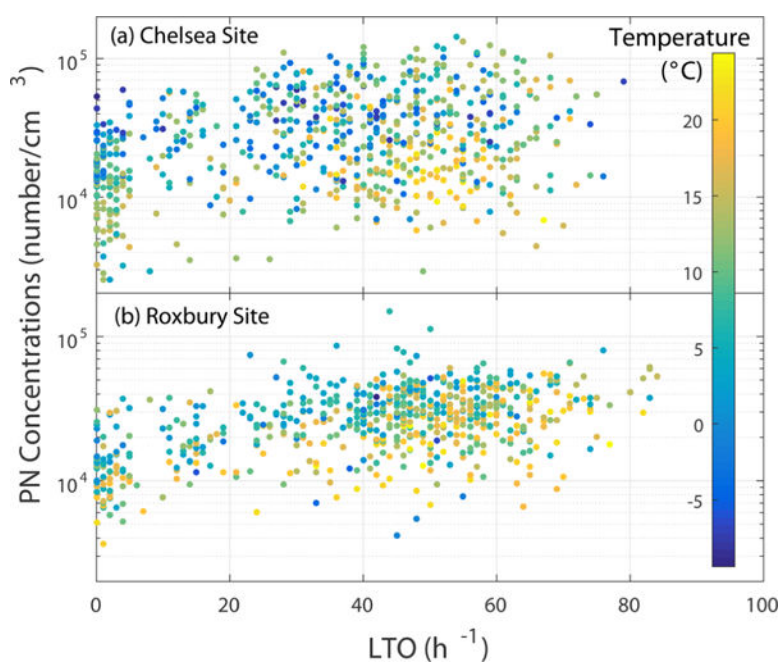


Figure 5.
(a and b) Hourly average PNCs during impact-sector winds plotted against LTO for the Chelsea and Roxbury sites colored by ambient temperature (°C).

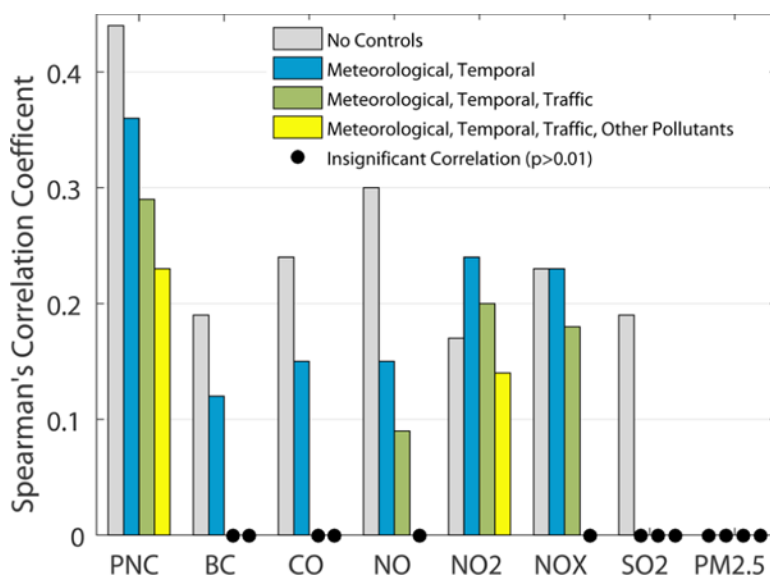


Figure 6.

Spearman's partial correlation coefficients between LTO and hourly average pollutant concentrations at the Roxbury site controlling for different sets of variables (see Table S5 of the Supporting Information). Insignificant correlations ($p > 0.01$) are marked as black dots.

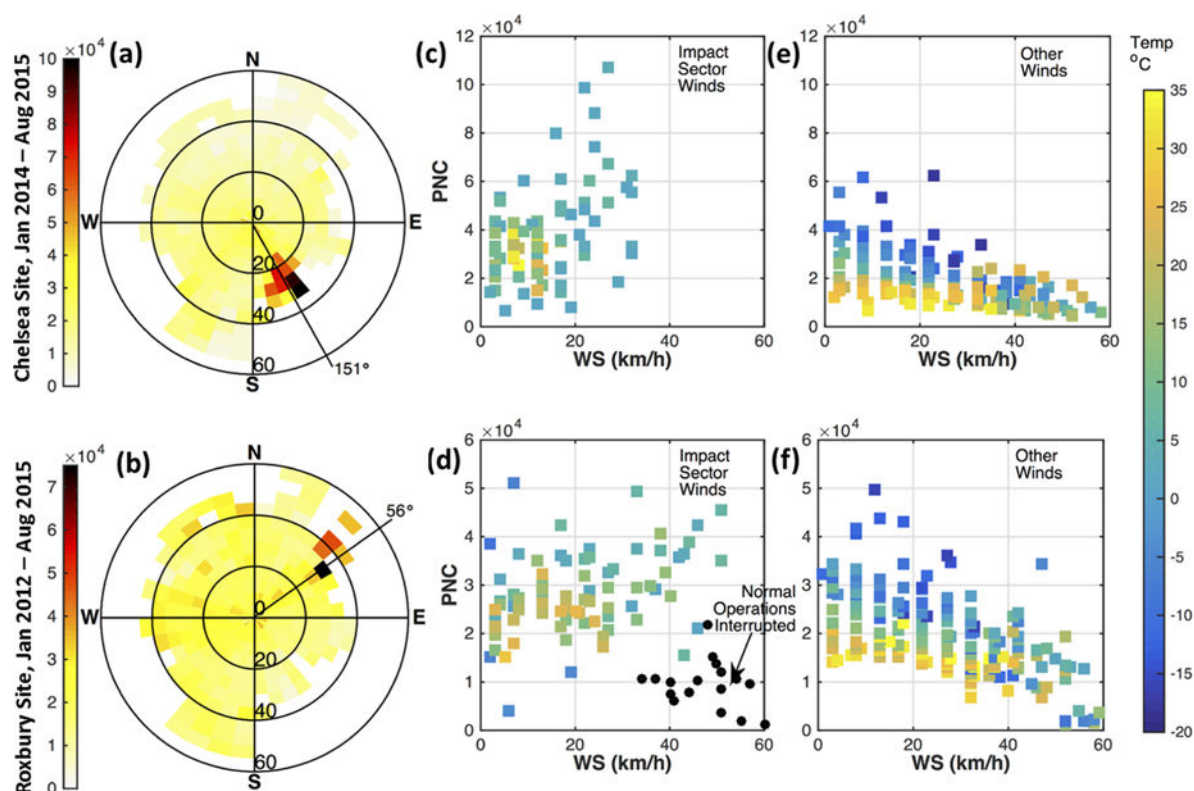


Figure 7.

(a and b) PNC roses. The radial axis represents wind speed (km h^{-1}), and the angular coordinate represents wind direction. The azimuth angle of the airport from the sites is marked. (c–f) PNC dependence upon wind speed for impact-sector winds and all other directions. For visual clarity, hourly average PNCs were aggregated in 3.6 km h^{-1} (1 m s^{-1}) and 5°C bins, and bin averages are plotted against wind speed. (d) Hours (not bin averages) corresponding to times when normal flight operations were interrupted by two extreme weather events are marked with black dots (also see Figures S11–S14 of the Supporting Information).

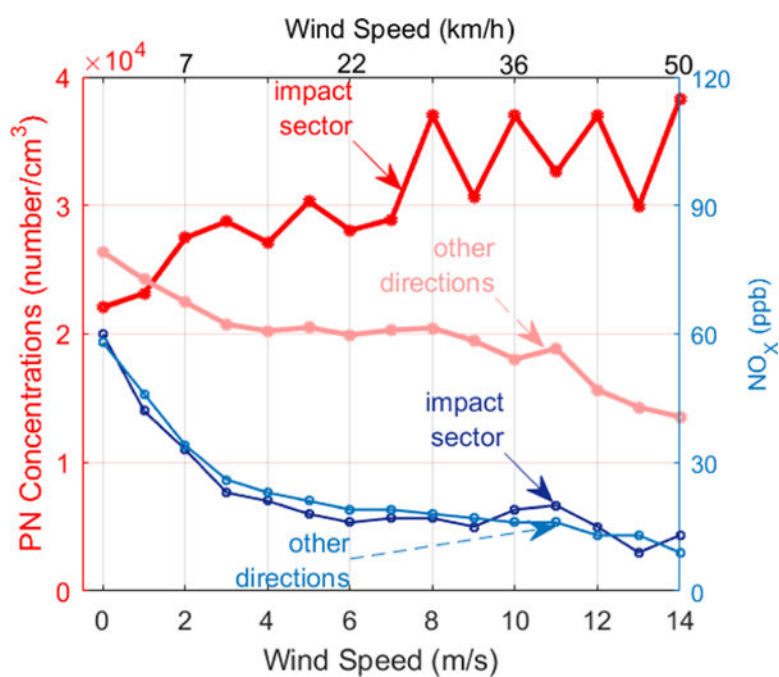


Figure 8.

Wind speed dependence of PNCs and NO_x concentrations at the Roxbury site. See Figures S15 and S16 of the Supporting Information for other pollutants.