Spatial and Temporal Patterns of Ambient Ultrafine Particulate Matter (UFP) in Communities along an Arrival Aircraft Pathway

Author: Chloe Kim

Research Advisors: Jonathan Levy, ScD and Kevin Lane, PhD

School: Boston University School of Public Health

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1. Abstract

Communities near airports are exposed to multiple aviation-related air pollutants, including ultrafine particulate matter (UFP). Characterizing UFP contributions from aviation is challenging given spatiotemporal variability and other proximate sources. To address this research gap, UFP was monitored at six locations from April-September 2017 at various distances from a major arrival flight path into Boston Logan International Airport, gathering concurrent flight activity and meteorological data. Descriptive results showed differing UFP concentration distributions as a function of meteorological conditions and runway usage, consistent with a contribution from arrival aircraft. Variable patterns emphasize the importance of regression modeling to ascertain arrival aircraft contributions.

2. Introduction

In recent years, ultrafine particulate matter (particles < 100 nm in aerodynamic diameter, UFP) has received more public and scientific attention for its potential effects on human health.[1,2] Because of their elevated lung deposition efficiency, high particle number, and small size and large surface area, UFPs are suggested to have a higher potency compared to larger particles.[3,4] For example, animal studies have shown significantly greater pulmonary inflammatory potency for UFPs compared to larger particles.[5–7] Epidemiological studies also suggest potential adverse respiratory and cardiovascular health effects from UFP exposures.[6] However, the challenge of accurately assessing population level UFP exposures given its high spatiotemporal variability has made conducting epidemiological studies on the association between UFPs and health outcomes difficult as well.[8]

Aviation activities can impact human health by increasing concentrations of ambient air pollutants.[9] Even though emissions from aircraft have declined due to the advancement of technologies,[10] an accurate understanding of the extent of the impacts of aviation activities is becoming more important as air travel is expected to continuously grow as the fastest growing transport mode over the next 20 years nationally and internationally.[11–13] Air pollution produced by aviation activities has been a concern from the beginning of commercial air travel,[14] as aircraft emit a range of air pollutants such as carbon monoxide, methane, nitrogen oxides, sulfur oxides and particulate matter.[10,14] The switch from a radar-based to a GPS-based system for the nation's air traffic control system has led to increased fuel efficiency, but the resulting flight paths are more concentrated and exposures patterns may have shifted, with the potential for an increase for a subset of the population and a decrease for others. The combination of increased air travel demand and more concentrated flight paths puts some communities living near airports at risk of higher exposure to air pollution, but exposure patterns are uncertain.

Aircraft and motor vehicles produce similar air pollutants such as black carbon, nitrogen oxides and particulate matter (PM), but emission patterns, composition of particles and dispersion characteristics can differ substantially, given the unique plume dynamics of aviation activities, potentially facilitating source attribution. UFP concentrations measured as particle number concentrations (PNC), the focus of this study, can come from direct emissions from aviation and vehicle engine combustion as well as from secondary formation in ambient air.[8,10] UFPs are known to have high temporal and spatial heterogeneity due to its small size and rapid removal processes as shown in monitoring studies near major roadways.[15–17] Monitoring studies near airports also have shown aviation activities as an important source of ambient UFPs.[8,18,19] Similar to major roadways, airports are often located in densely populated areas, creating some potential for co-varying contributions and putting a large number of people at risk of being affected by the associated exposures. However, aircraft's impact on ambient UFP concentrations has been shown to affect a much broader geographic area compared to emissions from motor vehicles.[18] These co-varying contributions of aircraft and motor vehicle emissions to ambient UFPs warrants an independent investigation on aviation's environmental impacts in order to correctly distinguish local contributions of UFPs from aircraft and motor vehicles.

PM emissions from cruising altitudes are considered to have minimal impact on local air quality.[10] However, there have been mixed findings of the impact of aircraft at lower altitudes on ambient air quality, though more recent studies have suggested a larger and more geographically distributed impact downwind from the sources.[7,18,19] Some of these studies have shown the most elevated levels of PNCs under the arrival trajectories.[7,20] For example, one study conducted at Boston Logan International Airport found 1.33-fold and 2-fold higher average PNCs at sites 7.3km and 4km, respectively, downwind from the airport.[18] A study performed at Los Angeles International Airport found large mean PNC increases up to 18km downwind of the airport.[7] They also found that the greatest increase was shown along the landing trajectories.[7] A study done in the Netherlands has also shown increased annual mean PNCs at 7 km downwind of Schiphol airport[8]. A mobile UFP monitoring study also found 3-5 fold increase in median PNCs under the arrival flight paths for Los Angeles International Airport and Atlanta International Airport, in comparison to PNCs in surrounding urban locations with similar road traffic characteristics.[20] On the other hand, some studies found more geographically constrained impacts of aircraft on PNCs, including a study done near T.F. Green Airport in Rhode Island showing a limited influence of both departure and arrival aircraft on PNCs in neighborhoods not close to the airport.[21]

Although these studies have been helpful for hypothesis generation, they have not generally had the necessary real-time spatial and temporal flight activity data to accurately evaluate the contribution of individual aircraft to ground-based PNC. For example, some studies used the counts of landing and take-off (LTO) activities across an hour as the measure of aviation activities and/or examined the effects of aviation activities when monitoring sites were only downwind of the airport rather than considering emissions from aircraft in flight.[8,18] These studies provide insight on air quality patterns near airports and underneath flight paths, but are more limited in their ability to explain the contributions of moving aircraft to ambient PNC. UFP emissions from arrival aircraft can potentially influence exposures at a wide range of locations, given plume characteristics and variable wind patterns, but it is unclear how large or sustained those contributions are, relative to departure aircraft or other combustion sources. An evaluation focusing on arrival aircraft will provide better understanding of an important but highly uncertain question regarding population exposure patterns near airports. Furthermore, by selecting multiple monitoring sites at varying distances from an arrival flight path and the airport, this study can better characterize the plume dynamics of arrival aircraft.

3. Methods

3.A. Study Design

The field campaign was conducted from April to September 2017 in the vicinity of Boston Logan International Airport. Arrival flight path to runway 4R was the main focus of this study, which is the primary runway configuration used when the wind is from the northeast,[22] but also during multiple other meteorological regimes. Six monitoring sites were selected that were at varying distances from the airport and the arrival flight path to runway 4R (see **figure 1 and table 1**), and therefore have potentially varying PNC contributions from aircraft arrivals. Selection criteria for monitoring locations prioritized sites in order to capture the aviation contribution to ambient PNCs apart from other sources. We did so by creating a 200-meter buffer around major roads to avoid large motor vehicle traffic contributions on ambient PNCs at the study sites based upon previously published distribution patterns of traffic-related UFPs.[15] All potential sites were also visited in person and site-by-site determination was made after considering multiple factors including the surrounding environment (e.g. local traffic volume, restaurants, etc.). One of the six sites (Site 6) was 160 meters from a designated major roadway, but was still included as a study site because field observations indicated relatively low traffic volume and preliminary measurements confirmed moderate baseline PNCs.

Figure 1. Map of monitoring sites and flight tracks.

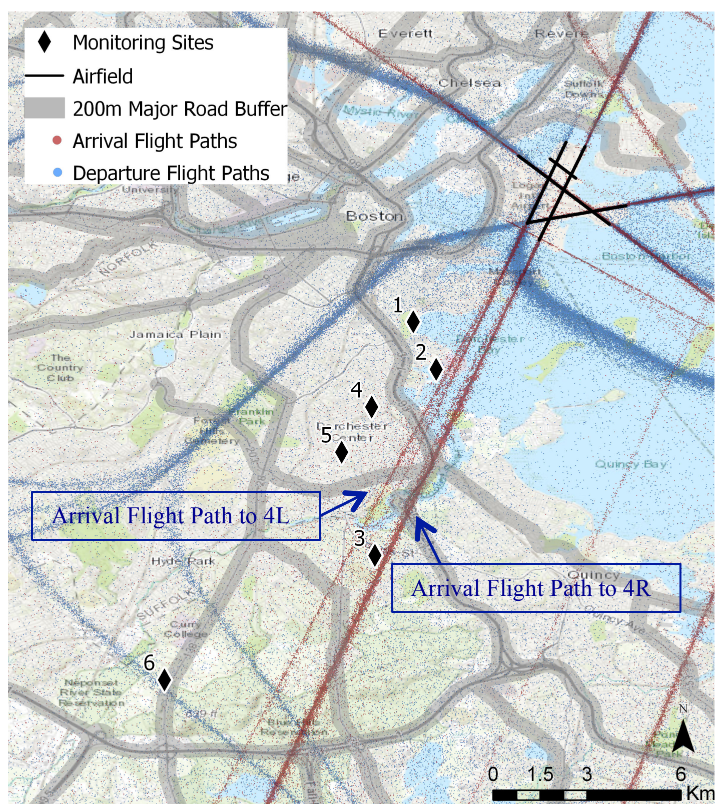


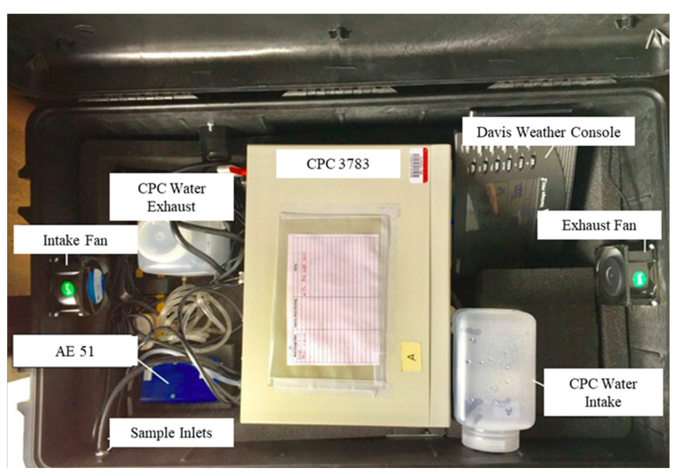
Table 1. Characteristics of each monitoring site.

Site	City	Distance to Flight Path 4R	Distance to Airport	Average Altitudes of Arrival Aircraft	CPC Installation Setup
1	Boston	~ 1 km	~ 3 km	~ 700 ft	Indoor*: second floor office space facing the ocean
2	Boston	< 0.5 km	~ 4 km	~ 1000 ft	Outdoor: shed on a boat dock
3	Milton	< 0.5 km	~ 10 km	~ 1300 ft	Indoor*: second floor classroom
4	Boston	~ 2 km	~ 7 km	~ 1500 ft	Indoor*: first floor restroom facing a small parking area
5	Boston	~ 2 km	~ 9 km	~ 2000 ft	Outdoor: shed in the backyard in residential area
6	Milton	~ 4 km	~ 17 km	~ 2800 ft	Outdoor: greenhouse at a farm

* Indoor setting had the instrument stay inside with the tubing of the instruments placed through the windows to measure ambient concentrations.

Table 1 summarizes the characteristics of different set-ups at the six monitoring sites. Two sites (Sites 2 and 3) were directly underneath the flight path and the other four sites (Sites 1, 4, 5, and 6) were at varying distances to the west of the flight path to runway 4R. Runway 4R was the focus of this study since 4L, the runway that is parallel to 4R, has limited capacity and the number of aircraft landing at 4L (less than 5% of total arrivals) is considerably lower than 4R (22% of total arrivals).[23]

Figure 2. Pelican case containing the CPC, microaethalometer and weather console.



The monitoring strategy was to measure at three sites simultaneously for one week at a time in order to capture as many different spatial and meteorological combinations as possible. We had three condensation particle counters (TSI CPC 3783), three weather station consoles (Davis Vantage Pro 2) and three microaethalometers (AethLabs AE 51) enclosed in weatherproof Pelican cases to allow for flexible field deployment and easy transport among the sites (**figure 2**). The microaethalometers measured black carbon, the results of which are not reported in this manuscript. Multiple pilot tests were conducted to ensure the portable configurations met the temperature requirements of the instruments in both cold and hot weather.

The instruments were deployed either indoors or outdoors depending on what space was available at each site (see **table 1**). The same instrument configuration was used for both indoor and outdoor sites. For indoor deployment, the instrument stayed inside with the tubing of the CPC placed through the windows. For outdoor deployment, the instrument was placed under a roof to prevent any potential damage from water getting into the instrument. The same length of tubes were used at all the sites for consistency, given potential deposition and line loss of UFPs. Pilot testing confirmed that the length of tubing used created minimal losses. The usual weekly schedule was to pick-up, rotate and set up the equipment on Monday and maintain the equipment and download data during mid-week check-in as well as at the end of each week. Co-location testing of the PNC measurements showed there was no significant disagreement among the equipment (correlation coefficient=0.98).

3.B. Data Processing

3.B.a. *UFP Data*

UFP concentration data were collected at 1-second resolution at all monitoring sites. Observations with automatic error flags by the instrument were reviewed and those observations with errors affecting the data quality were removed. We also removed observations with pulse heights lower than 500mV and concentrations lower than 100 particles/cm^3 to eliminate any potentially erroneous observations.

3.B.b. *Flight Activity Data*

The National Offload Program (NOP) data were downloaded for the entire study period. These data came from Terminal Radar Approach Control Facilities (TRACONs) used by air traffic controllers to guide aircraft generally within a 30- to 50-mile radius from airports and up to 10,000 feet. NOP data served the research purposes of this study as the study areas were within the 50-mile and 10,000 feet range of TRACON data and included flight identification number, aircraft type, flight status (arrival, over-flight and departure), aircraft position (latitude, longitude, altitude), and date-time stamp for all arriving and departing aircraft (excluding military aircraft) to and from Logan down to 1-second resolution.

3.B.c. *Meteorological Data*

There were two sets of meteorological data used in this study. This project collected local meteorological data at 1-minute resolution by setting up the weather station (Davis Vantage Pro2) in an open space about 2 meters above the ground right next to the UFP monitoring equipment. This study also used meteorological data collected at the airport by the Automated Surface Observing System when investigating the association between meteorological conditions and runway use.

3.C. Statistical Analysis

Statistical analyses were conducted using R-3.2.3 and Excel, and maps were produced using ArcGIS. We characterized distributions of PNC at each study site to determine baseline PNCs and develop hypotheses about aviation and other source contributions. Given our large sample size, we characterized percentiles from the 0.1st to the 99.9th by study site across the entire study period. In addition, we characterized diurnal PNC concentration patterns using boxplots, which focused on the data between the 5th and 95th percentiles to characterize general trends in the data. Wind roses were generated to display wind speed and wind direction at the study sites during the relevant time period. In addition, we developed time-series plots of one-second resolution PNC concentrations and flight activity over hour-long periods under three different runway configurations and wind conditions, to visually assess the association between individual flights and PNC concentrations.

4. Results and Discussion

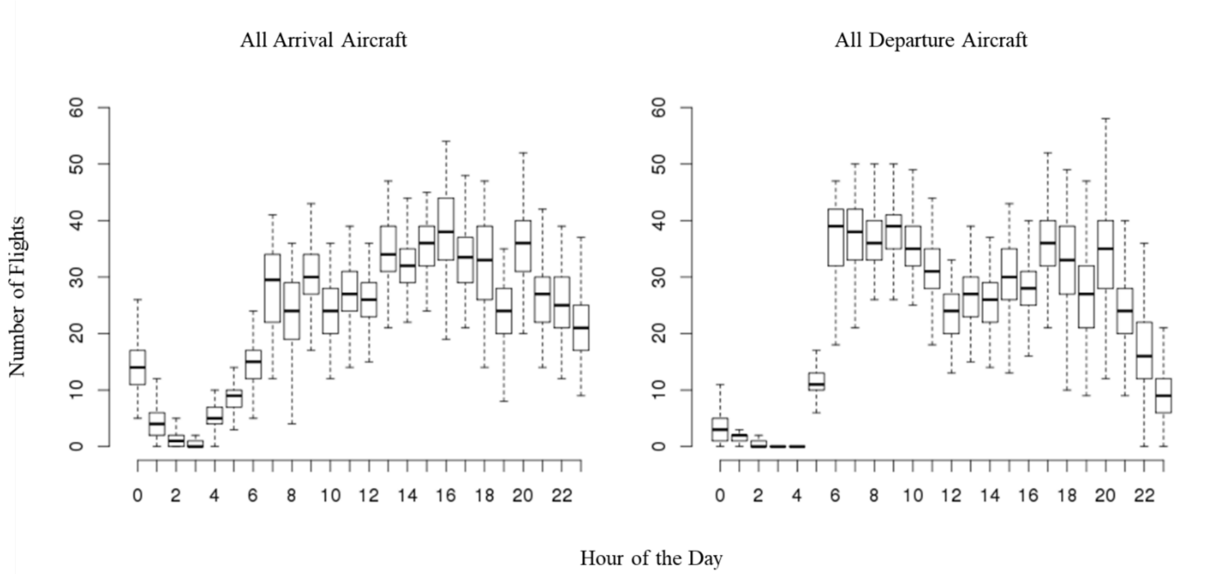
Table 2 displays the sample size and PNC distributions across the six monitoring sites. Sites 4 and 5 had higher medians compared to all other sites, whereas Sites 1 and 2 had higher PNC levels at the 95th – 99.9th percentiles. This would be consistent with a stronger and intermittent aviation contribution at Sites 1 and 2, located closest to the airport. Sites 3 and 6, which were furthest from the airport and not near major roadways, generally had lowest concentrations across all percentiles.

Table 2. Particle number concentration (PNC) distribution in particle number/cm^3 at the six study sites.

	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6
Sample Size (days)	98	94	84	85	92	92
Sample Size (seconds)	7,467,412	7,537,847	6,472,598	6,585,047	6,928,122	7,038,630
0.1st percentile	400	500	800	1,200	900	900
1st percentile	900	1,300	1,200	2,100	1,300	1,200
5th percentile	2,100	2,400	2,000	3,500	2,500	2,000
50th percentile	7,400	7,500	5,700	9,200	7,900	5,800
95th percentile	29,300	27,700	13,300	29,100	21,600	15,400
99th percentile	58,800	57,600	22,100	48,300	33,600	23,700
99.9th percentile	93,800	111,000	37,800	73,600	49,000	45,400

To better interpret the PNC concentration data, we considered diurnal concentration patterns alongside diurnal flight activity patterns and wind roses, noting that NOP data do not allow for accurate runway assignment. As shown in **figure 3**, both arrivals and departures were most active from 7:00 to 20:00, with limited flight activities from 1:00 to 4:00. Most departure activities started at around 6:00 and slowed down around 21:00, while the arrival activities started at around 4:00.

Figure 3. Hourly average number of arrival and departure aircraft at Boston Logan International Airport during the study period of April 2017 – September 2017.



When comparing diurnal PNC concentrations with flight activity patterns, we note that the 4R runway was closed for a portion of our monitoring period. This provided a natural experiment, in which different flight paths were utilized for different periods of monitoring. While disentangling the effects of individual aircraft would ultimately require regression modeling, this natural experiment allows for some preliminary insights to be developed from descriptive figures and statistics. For the purpose of this analysis, we focus on measurements taken in June, when 4R was closed and not operational, and July, when 4R reopened and was operational.

One common pattern shown across Sites 1, 2, 4, and 5 is that PNC levels were elevated at the upper percentiles throughout the day during July but not June, with similar median concentrations, suggesting strong intermittent sources of UFPs (**figure 4**). For Sites 3 and 6, located further from the airport, diurnal concentration patterns were generally similar between June and July (results not shown). The diurnal patterns shown in July are more closely aligned with the diurnal patterns of number of arrival aircraft shown in **figure 3**. These sites do not seem to have been affected by ground-level motor vehicle traffic as no obvious peaks were shown during rush hours.

Figure 4. Diurnal patterns of PNCs (5%, 25%, 50%, 75% and 95% percentiles) at Sites 1, 2, 4 and 5 along with windroses. (a) 4R runway was closed and not operational during the month of June 2017. (b) 4R runway was open and operational during the month of July 2017.

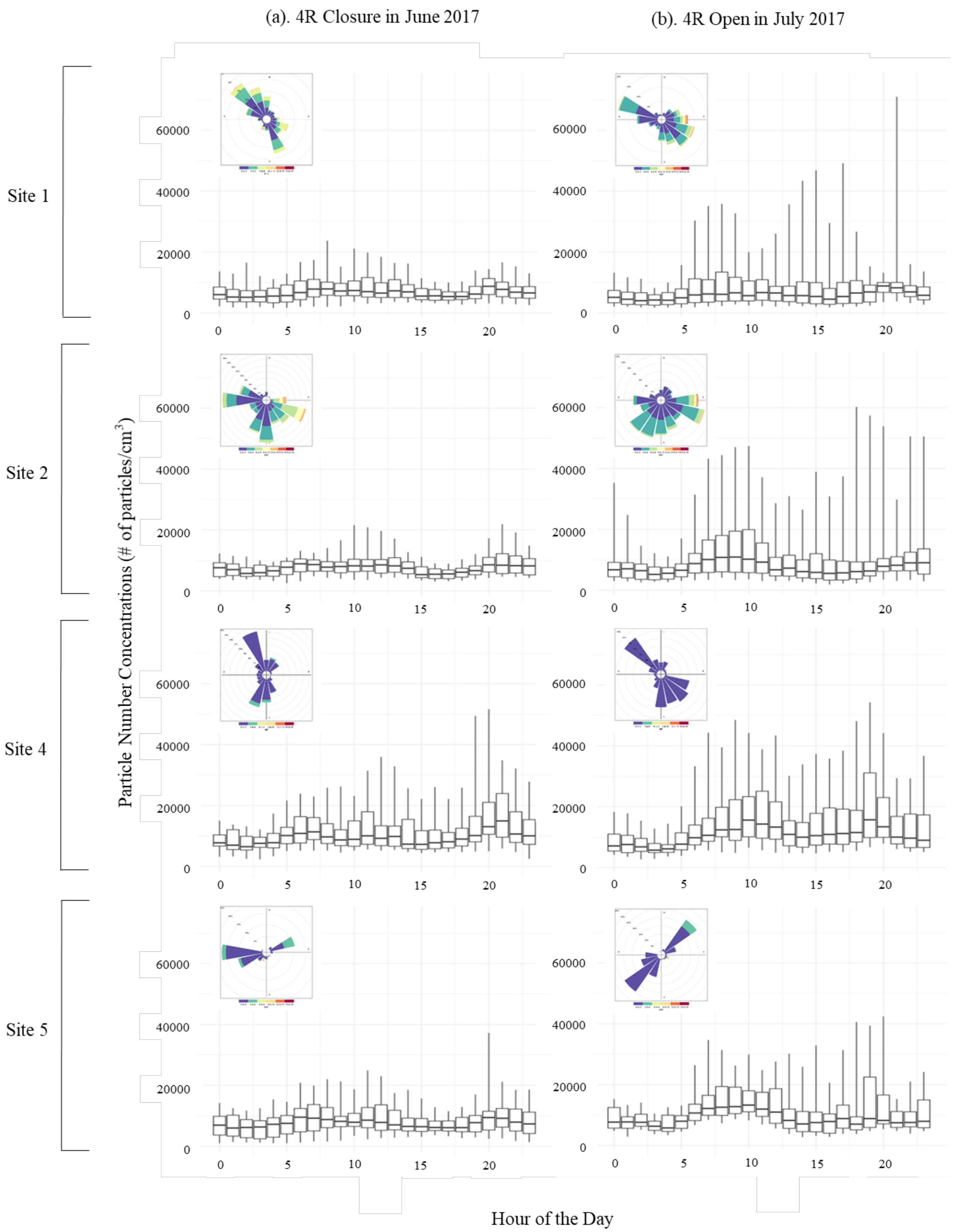
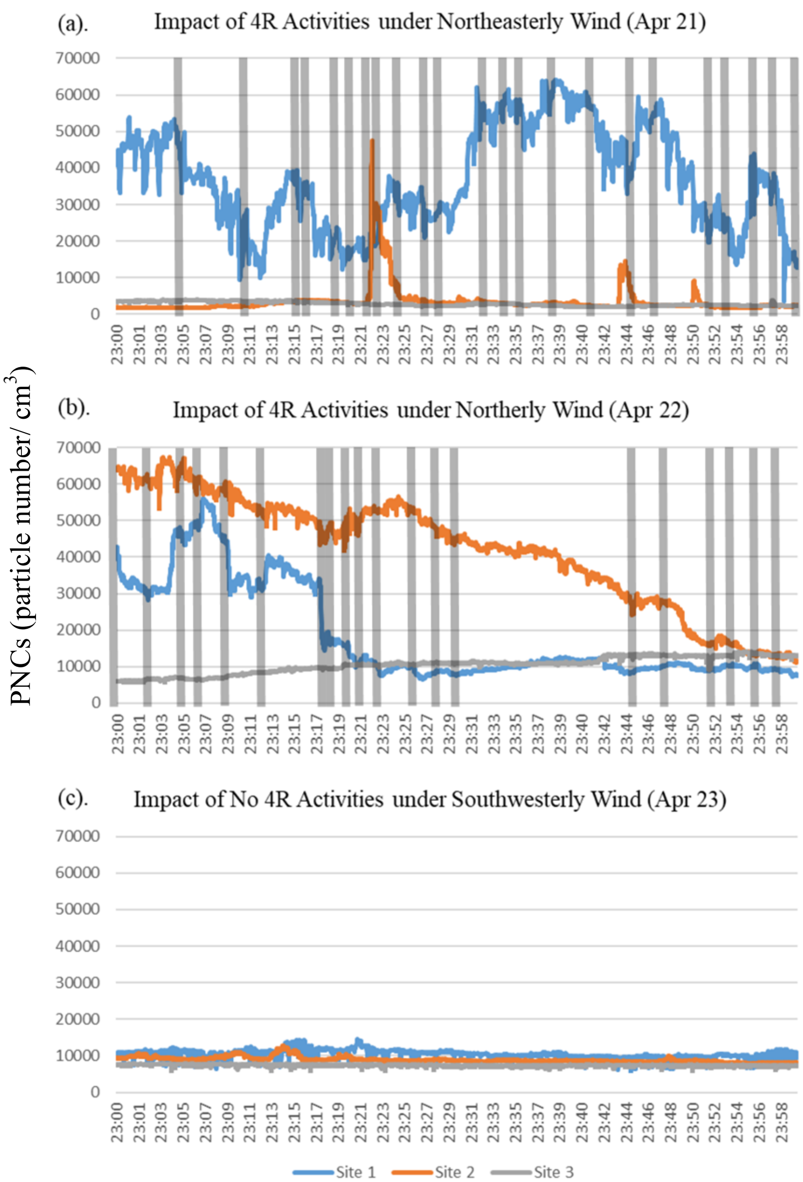


Figure 5. Time series of UFP concentrations on three consecutive days in April at 11 PM under different meteorological conditions and 4R runway use.



That said, UFP concentrations were highly variable throughout the day in a manner that was not clearly consistent with patterns of individual flights. To illustrate this point, **figure 5** displays three time-series of PNCs between 23:00 and 0:00 at three of the study sites (Sites 1, 2 and 3) with arrival aircraft activities marked with grey lines. These times were selected given anticipated flight arrival activity but relatively limited traffic. PNC levels at Site 3 were low under all conditions. **Figure 5 (a)** shows the concentration patterns under northeasterly wind, where the monitoring sites would have been located downwind of the flight track. Site 1 displays elevated concentrations throughout the hour, albeit not perfectly correlated with individual flights. On the other hand, PNCs at Site 2 only displayed intermittent concentration increases above background. Under northerly wind (**figure 5 (b)**), the concentrations were similarly elevated as with northeasterly winds, but without substantive minute-by-minute variability, potentially suggestive of different dispersion characteristics. UFP concentrations measured with southwesterly wind, when no aircraft landed on 4R, were much lower (**figure 5 (c)**) than when 4R was operational.

Figure 5 also illustrates some of the complexities in associating PNCs with flight activity data. Given that both UFP and the flight activity data are at 1-second resolution, it would be theoretically possible to characterize plume dispersion patterns by investigating the relationship between aircraft location and when ground-level PNCs peak. However, the time-lag between aircraft emissions and UFPs reaching the ground at a specific location is dependent on complex interactions among wind direction, wind speed, aircraft location, mixing height and other conditions in the environment.

5. Strengths and Limitations

One of the strengths of this study was the selection of monitoring sites specifically intended for aviation arrival source attribution. Sites were placed at varying distances from the airport and from the arrival pathway and at distances from major roadways, whereas many previous analyses of aviation source contributions were based on opportunistic analyses of data collected for other purposes. In addition, while variable meteorology creates some challenges in analyzing and interpreting PNC data, it also allows for the assessment of the impacts of varying meteorological conditions on aircraft arrival PNC patterns. Also, our real-time flight activity and PNC data allow us to better characterize the real-time spatial and temporal impact of aircraft on PNCs compared to using longer-term averages or the number of aircraft at the airport as the measure of flight activity. Many of the study sites are potentially influenced by 4R arrival aircraft under varying wind conditions, which could not be accurately captured if being downwind from the airport was considered as the only proxy variable for aviation activity. Lastly, the portable instrument configuration allowed for easy short-term data collection at different sites under various site combinations, which could be used for similar research purposes.

One limitation of this study was the varying surrounding environments at the monitoring sites. Even though all the sites needed to be far enough away from major roads to be included in the study, the level of non-aviation UFP contributions was non-zero and varied across sites. However, based on our descriptive analyses, the non-aviation UFP contributions did not preclude us from observing intermittent concentration increases consistent with aviation contributions. In addition, the collected weather data may not accurately represent the meteorological conditions at higher elevations, which may have a more direct impact on aircraft plume dispersion.

We were also limited by the available flight activity data at the time of this analysis. The NOP data have multiple strengths but lack insight about runway utilization and other aircraft detail that are available through the Performance Data Analysis and Reporting System (PDARS) and Automatic Dependent Surveillance-Broadcast (ADS-B). PDARS data allow for gate-to-gate analysis and consist of three different data inputs with quality controlled flight track data,[24] and ADS-B provides satellite surveillance data instead of radar data[25] and can provide more accurate aircraft position information. Future analysis plans will include PDARS, which will improve the accuracy of runway assignment and allow for regression models that would benefit from accurate positioning information.

One-second resolution data are both a strength and limitation of this study. Such finely-resolved temporal data allow us to examine detailed temporal patterns of PNCs, potentially allowing for plume identification and characterization. However, analyses of one-second resolution data are subject to errors, including greater measurement uncertainty, issues with instrument time drift, and challenging lag structures. We plan to explore the sensitivity of our conclusions to averaging time within our regression models.

6. Conclusion

In this study, we collected extensive real-time PNCs across six sites specifically selected for arrival aircraft source attribution. Descriptive statistics suggest a potential intermittent contribution from arrival aircraft at sites in closer proximity to the flight path and airport. Our site selection and availability of dates with varying aircraft activity levels, along with the use of real-time concentration measurements, reduces the possibility of confounding by traffic and other sources. Further, diurnal patterns of PNCs, especially at the upper tails of the distribution, were more suggestive of aircraft activities than traffic sources. Our findings indicate the value and necessity of regression modeling with spatially accurate flight activity data to quantify the contribution of arrival aircraft to measured concentrations. Future analyses will investigate the association between measured concentrations and flight activity data from PDARS, taking account of lags between flight activity and concentration increases and the degree to which this depends on meteorological conditions. The descriptive analyses to date demonstrated that the data structure of this project is suitable for a regression model that can capture the varying impact of arrival aircraft on local PNCs under different meteorological conditions, ultimately providing novel insight regarding the magnitude of aviation sources contributions relative to background concentrations.

7. Acknowledgements

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