

Supporting Information for

Aviation emissions impact ambient ultrafine particle concentrations in the greater Boston area

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Number of Figures: 17

Information Related to Flight Activity at Logan International Airport

Diurnal Flight Activity Patterns

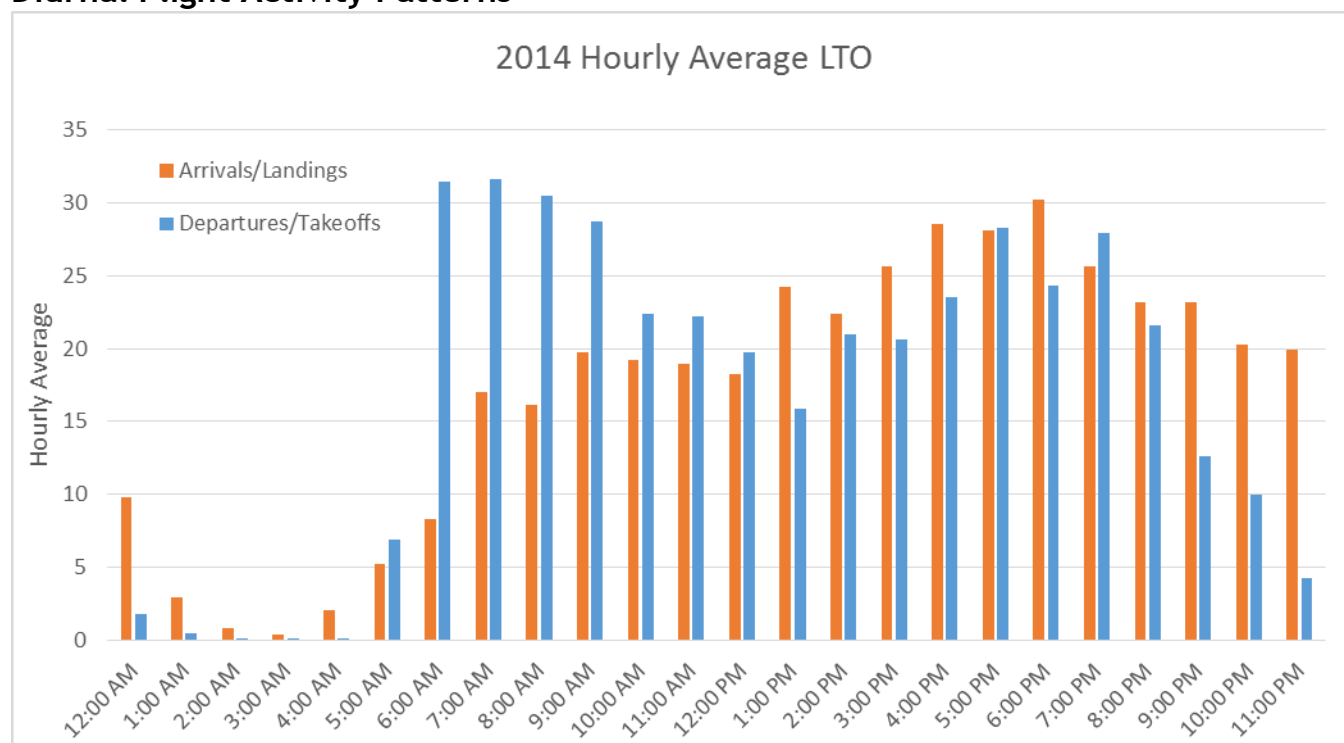


Figure S1: Annual (2014) average of hourly totals for landings and takeoffs through the day

Based on flight activity patterns, we classified the hours 0600-2359 as high and the hours 0000-0559 as low flight activity hours (see Figure S1). During the study period (Jan 2012-Aug 2015), the average LTO during high and low activity hours were $46.2 \pm 10.4 \text{ h}^{-1}$ and $5.0 \pm 5.3 \text{ h}^{-1}$, respectively. Arrivals and departures during these periods were $22.8 \pm 4.4 \text{ h}^{-1}$ and $23.4 \pm 8.0 \text{ h}^{-1}$, and $3.4 \pm 3.4 \text{ h}^{-1}$ and $1.7 \pm 2.8 \text{ h}^{-1}$, respectively. Traffic activity has a similar diurnal pattern but the difference between high and low activity was less: i.e., traffic during low activity period was about a quarter to a third of that in high activity period. The average hourly volume on I-93 and I-90, two major interstate highways in the area, during high and low activity periods were $8300 \pm 1700 \text{ h}^{-1}$ and $5600 \pm 1400 \text{ h}^{-1}$, and $2300 \pm 1700 \text{ h}^{-1}$ and $1300 \pm 800 \text{ h}^{-1}$, respectively.

Flight Statistics by Runway

Table S1: Arrivals and Departure fractions on runways for 8 wind direction sectors

Runway	Aircraft Heading	% of Arrivals by runway during Wind Direction*								% of Total Arrivals January 2012-August 2015
		N	NE	E	SE	S	SW	W	NW	
22R	200	0%	0%	0%	0%	0%	0%	0%	0%	0%
04L	20	10%	12%	19%	16%	1%	0%	1%	4%	7%
22L	200	2%	2%	4%	17%	53%	50%	18%	3%	21%
04R	20	66%	81%	71%	50%	5%	2%	2%	15%	29%
27	257	7%	1%	1%	10%	36%	42%	51%	31%	27%
9	77	0%	0%	0%	0%	0%	0%	0%	0%	0%
32	306	1%	0%	0%	0%	0%	0%	3%	5%	1%
14	126	0%	0%	0%	0%	0%	0%	0%	0%	0%
33R	315	0%	0%	0%	0%	0%	0%	0%	1%	0%
15L	135	0%	0%	0%	0%	0%	0%	0%	0%	0%
33L	315	14%	3%	1%	3%	3%	5%	24%	42%	14%
15R	135	0%	1%	4%	4%	1%	0%	0%	0%	1%
Runway	Aircraft Heading	% of Departures by runway during Wind Direction*								% of Total Departures January 2012-August 2015
		N	NE	E	SE	S	SW	W	NW	
22R	200	2%	2%	3%	19%	63%	66%	39%	7%	28%
04L	20	3%	4%	5%	3%	0%	0%	0%	1%	2%
22L	200	4%	4%	4%	10%	22%	20%	8%	2%	9%
04R	20	12%	10%	8%	7%	3%	2%	1%	5%	5%
27	257	7%	2%	0%	2%	1%	2%	18%	32%	10%
9	77	61%	76%	76%	55%	5%	1%	2%	13%	29%
32	306	0%	0%	0%	0%	0%	0%	0%	0%	0%
14	126	0%	0%	0%	0%	0%	0%	0%	0%	0%
33R	315	2%	2%	2%	1%	0%	0%	0%	1%	1%
15L	135	0%	0%	0%	0%	1%	1%	1%	0%	0%
33L	315	7%	1%	0%	1%	0%	2%	21%	32%	10%
15R	135	2%	1%	1%	1%	4%	5%	10%	8%	5%

*Wind direction data was available for 98.8% of the flight activity during January 2012-August 2015.

Details of Monitoring Sites and Instruments

Table S2: Details of monitoring sites and instruments used

	Chelsea	Boston Globe	Roxbury
CPC Model ¹	Model 3783	Model 3775	Model 3783
CPC d50, Accuracy	7nm, ±10%	4nm, ±10% for <50000 and ±20% for >50000	7nm, ±10%
CPC detectable maximum concentration	10 ⁶ particles/cm ³	50000, 10 ⁷ particles/cm ³	10 ⁶ particles/cm ³
Monitoring Period	Jan 2014-Aug 2015	Mar-May 2011	Jan 2012-Aug 2015
Location Coordinates	42.396, -71.033	42.315, -71.049	42.329, -71.083
Distance, Azimuth Angle to Logan ²	4 km, 151°	6.5 km, 30°	7.3 km, 56°
Impact Sectors	130-175°	15-60°	45-65°
Annual Occurrence of Impact Sector Winds in 2014	5.3%	7.5%	3.60%
¹ See http://www.tsi.com/uploadedFiles/_Site_Root/Products/Literature/Application_Notes/CPC-002-appnote.pdf for a summary of TSI CPC models.			
² Straight line distance from the airport to sites are reported from the coordinates 42.362965 N, 71.006424 W (located centrally at the airport).			

Table S3: Monitoring Instrumentation and Equipment used at Dudley Square, Roxbury EPA-STN Site

PM2.5 AQI & Speciation Mass	BAM-1020 W/PM2.5 SCC-Beta Attenuation
Black carbon PM2.5 STP	Magee Scientific AE22ER Aethalometer-Optical absorption
Carbon monoxide	Gas Filter Correlation Teledyne API 300 EU
Nitric oxide (NO), Nitrogen dioxide (NO₂), Oxides of nitrogen (NO_x)	Chemiluminescence Teledyne API 200 EU/501
Sulfur dioxide	Ultraviolet Fluorescence API 100 EU
Solar radiation	Met One Pyranometer Model 50.5

CPCs were housed in locked, weatherproof, and temperature and humidity controlled boxes and conductive silicon tubing was used for sampling line. Sites were serviced weekly for data retrieval, and instrument time was reset to the National Institute of Standards and Technology official time (time.gov) during visits. During data processing all instrument-flagged data was reviewed and removed from the analysis. CPC were annually calibrated at factory. More than one machine and instrument model was used but side-by-side tests conducted in laboratory indicate good agreement (See Figure S2 below). Also, since not all data was concurrent we have refrained from spatial or site-to-site comparisons (that were also beyond the scope of this study).

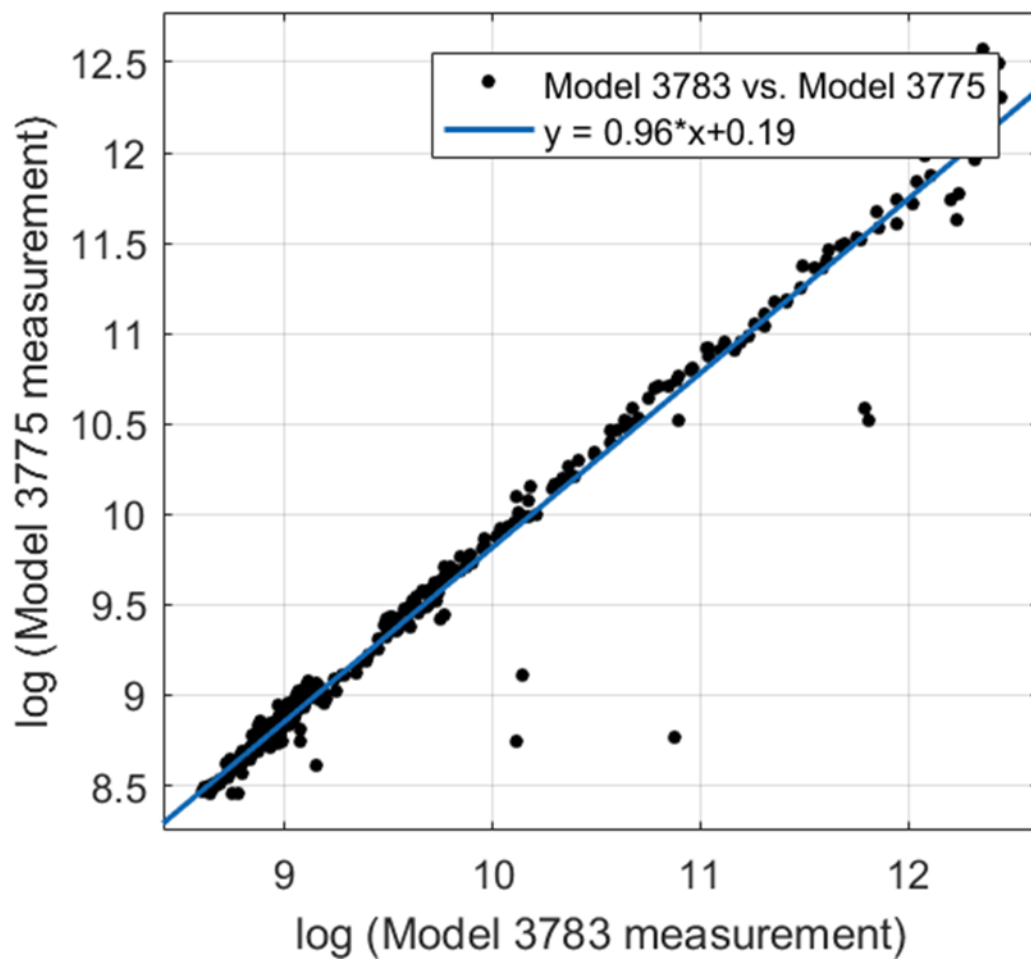


Figure S2: Comparison of laboratory measurements conducted with TSI CPC Models 3775 and 3783

Linear model:

$$\text{Model 3775} = p1 * \text{Model3783} + p2$$

Coefficients (with 95% confidence bounds):

$$p1 = 0.9624 \text{ (0.9447, 0.9801)}$$

$$p2 = 0.194 \text{ (0.0224, 0.3656)}$$

Goodness of fit:

SSE: 9.787

R-square: 0.9721

Adjusted R-square: 0.9721

RMSE: 0.1727

Rose diagrams for wind during monitoring periods at three sites

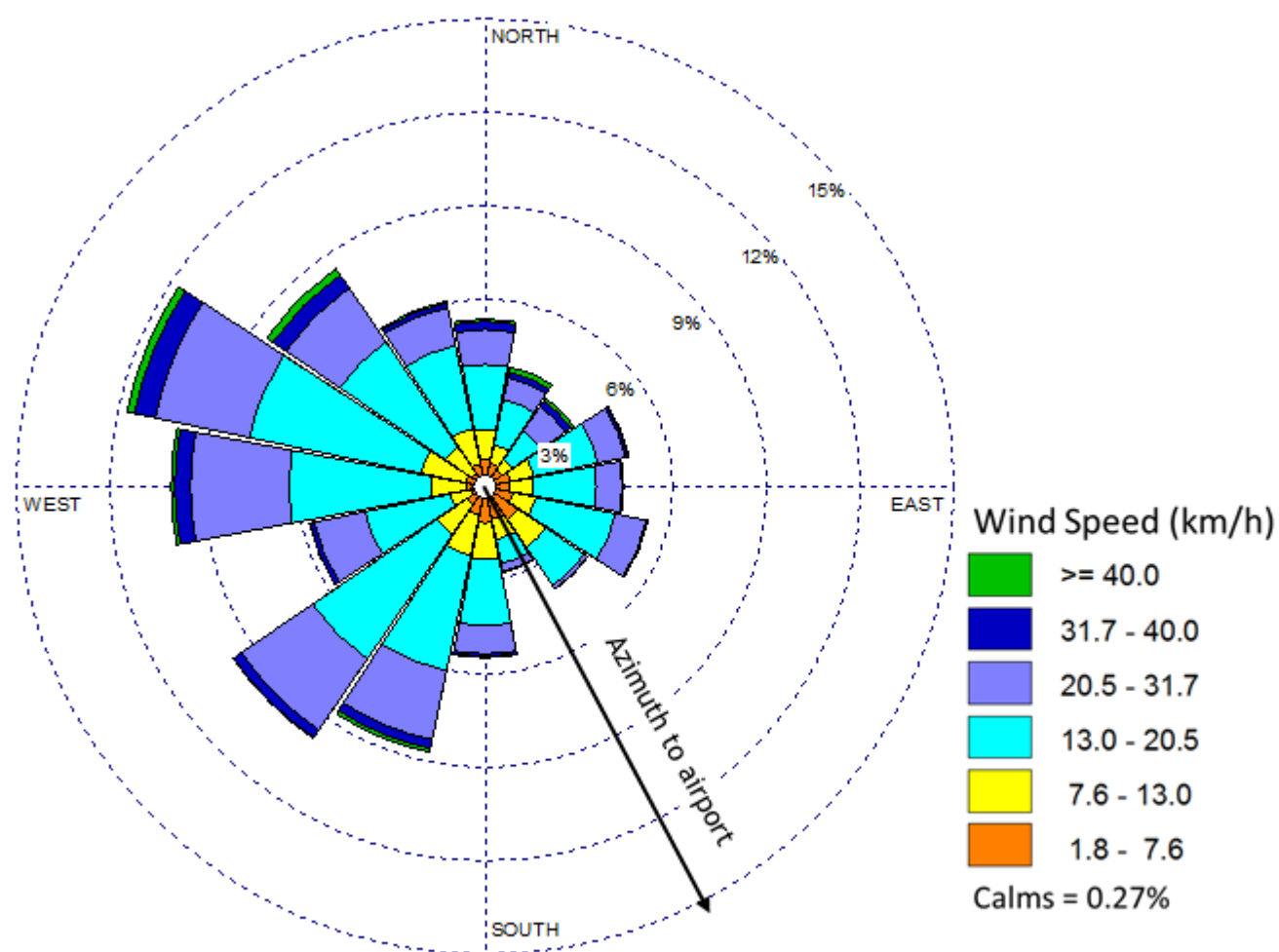


Figure S3 (a): Rose diagram for Jan 2014 - Aug 2015, i.e., the monitoring period for Chelsea site. Rose is based on 1-minute data reported by National Weather Service Automated Surface Station located at the airport.

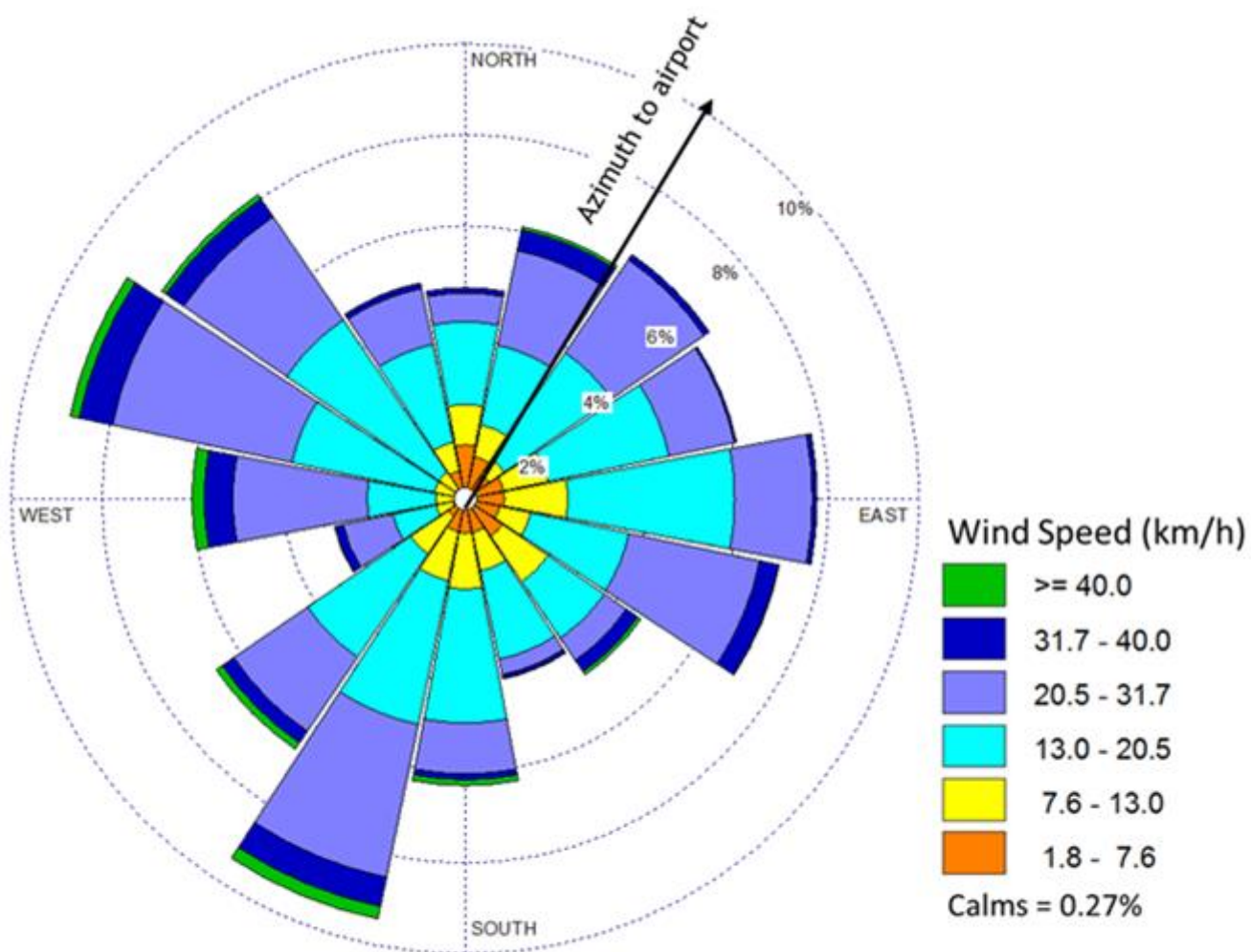


Figure S3 (b): Rose diagram for Mar 2011 - May 2011, i.e., the monitoring period for Boston Globe site. Rose is based on 1-minute data reported by National Weather Service Automated Surface Station located at the airport.

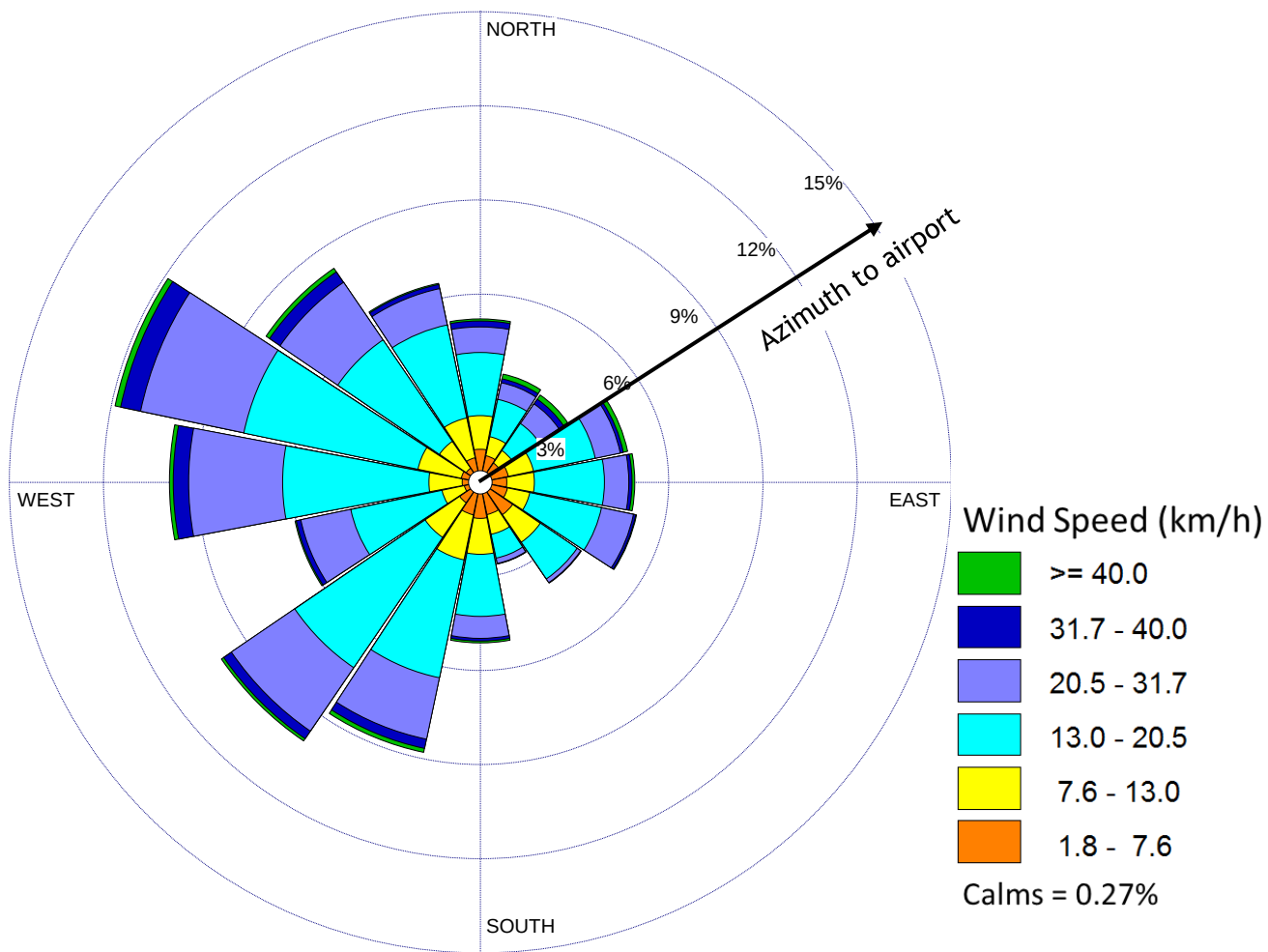


Figure S3 (c): Rose diagram for Jan 2012 - Aug 2015, i.e., the monitoring period for Roxbury site. Rose is based on 1-minute data reported by National Weather Service Automated Surface Station located at the airport.

Distribution of Particle Number and Other Pollutant Concentrations, and LTO

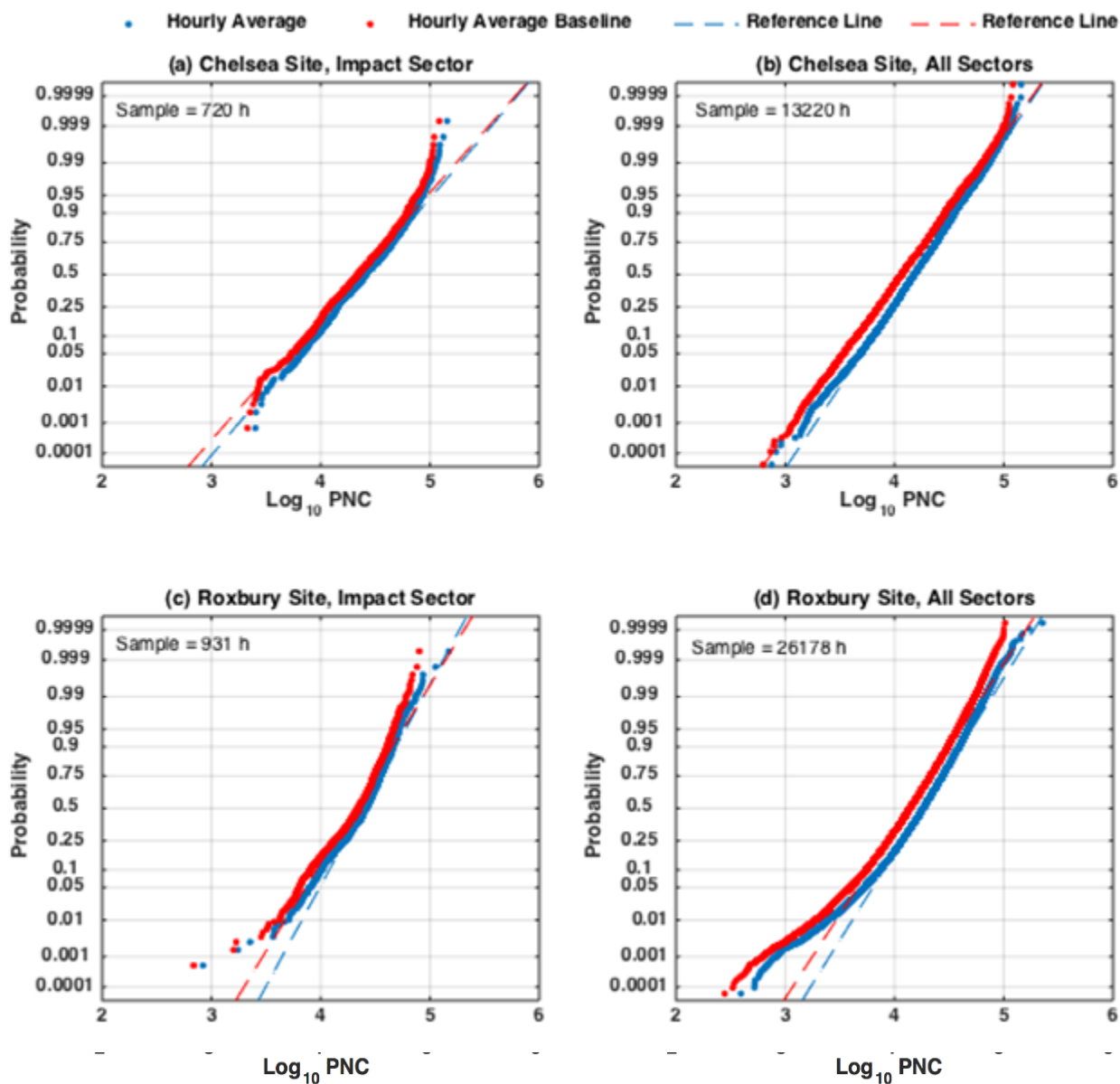


Figure S4 (a)-(d): Distribution of log transformed PN concentrations at Chelsea and Roxbury sites during impact sector winds and the entire dataset. Reference lines for normal distributions are shown.

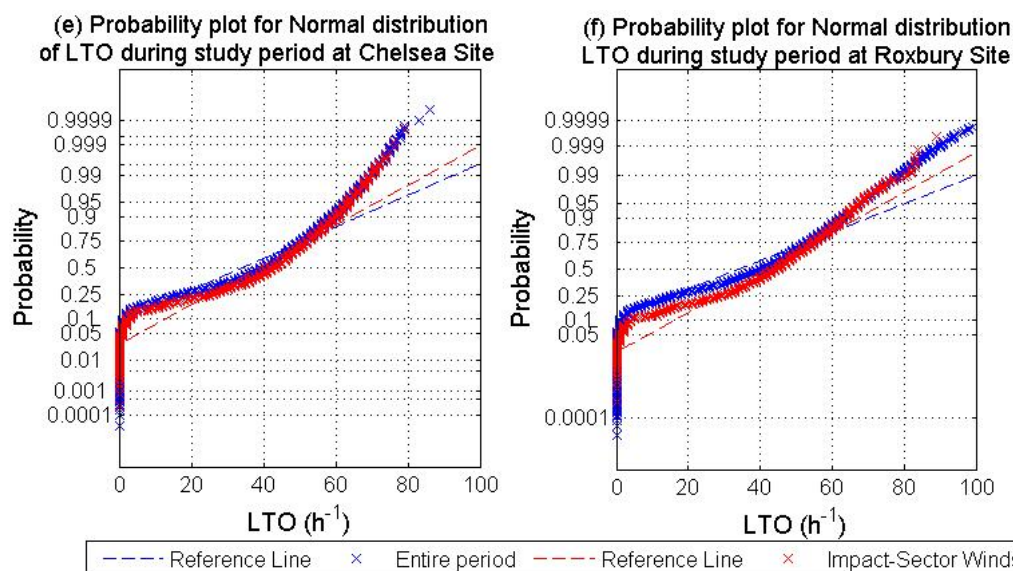


Figure S4 (e)-(f): Distribution of LTO during impact sector winds and the entire study periods at Chelsea and Roxbury sites. Reference lines for normal distributions are shown.

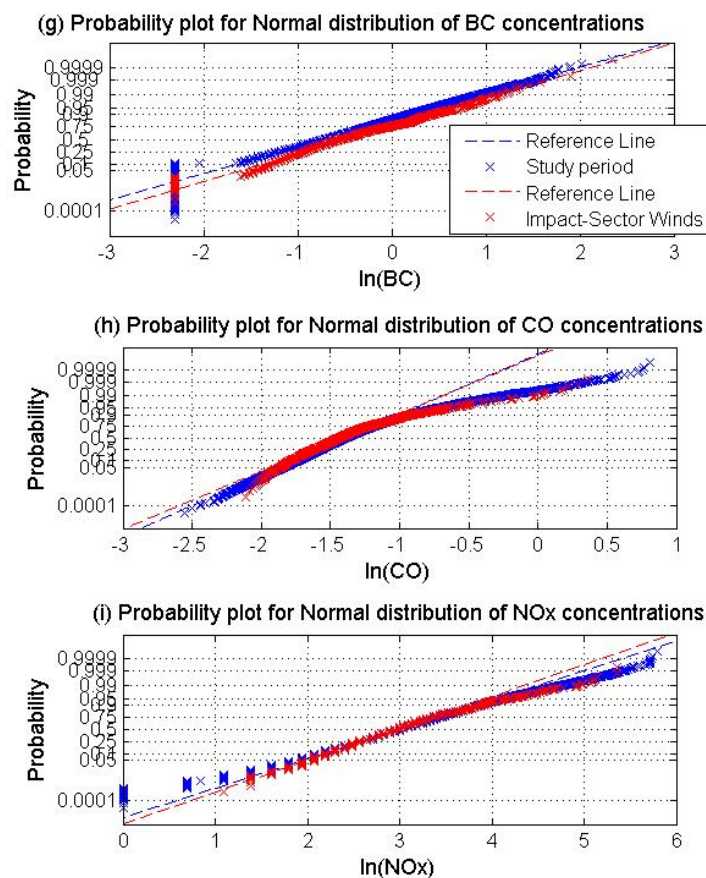


Figure S4 (g)-(i): Distribution of log-transformed concentrations of pollutants during impact sector winds and the entire study period at Roxbury site. Reference lines for normal distributions are shown.

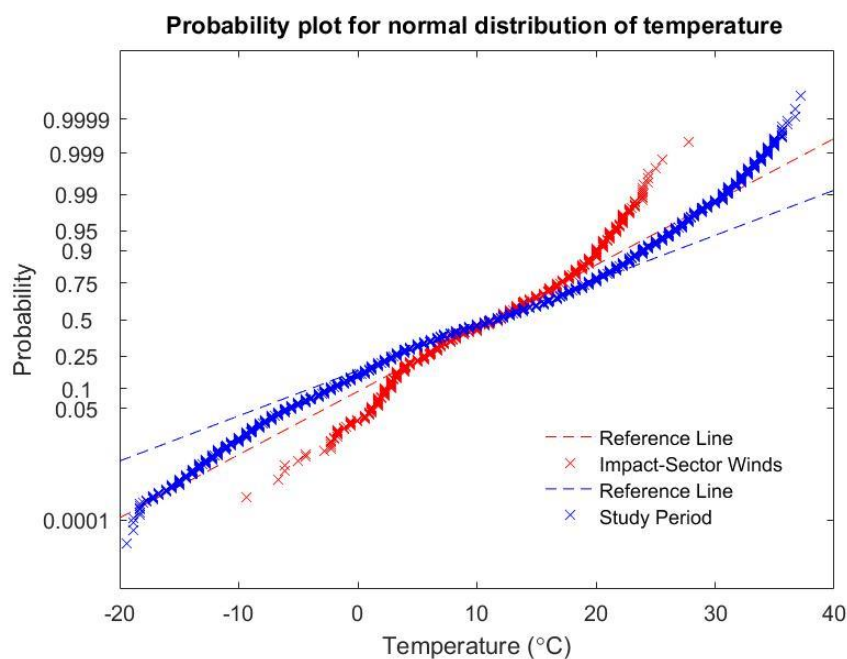


Figure S4 (j): Distribution of temperature during impact sector winds at Roxbury site and the entire study period. Reference lines for normal distributions are shown.

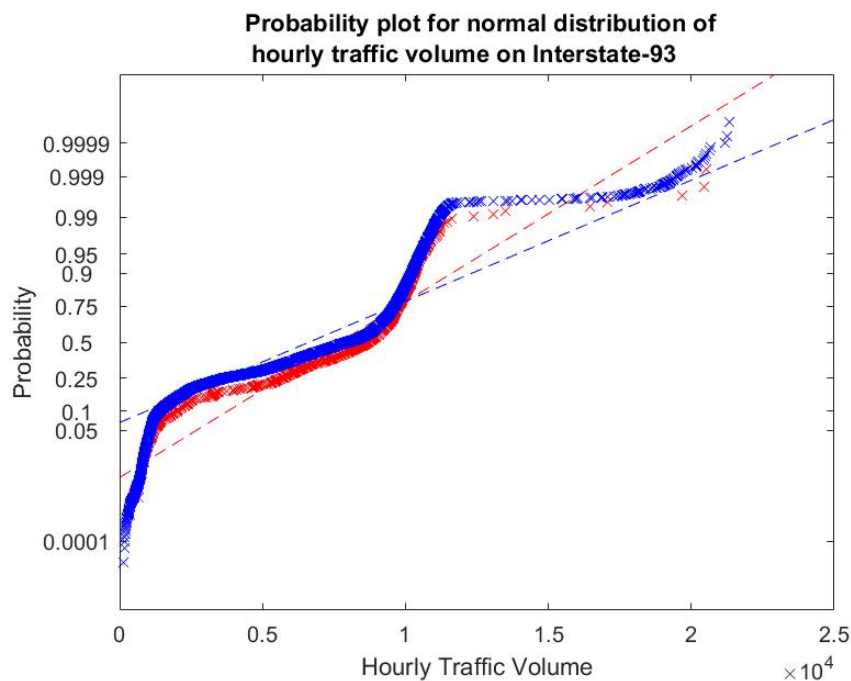


Figure S4 (k): Distribution of traffic volume on Interstate-93 during impact sector winds and the entire study period at Roxbury site. Reference lines for normal distributions are shown.

Traffic Volume Data and Fits

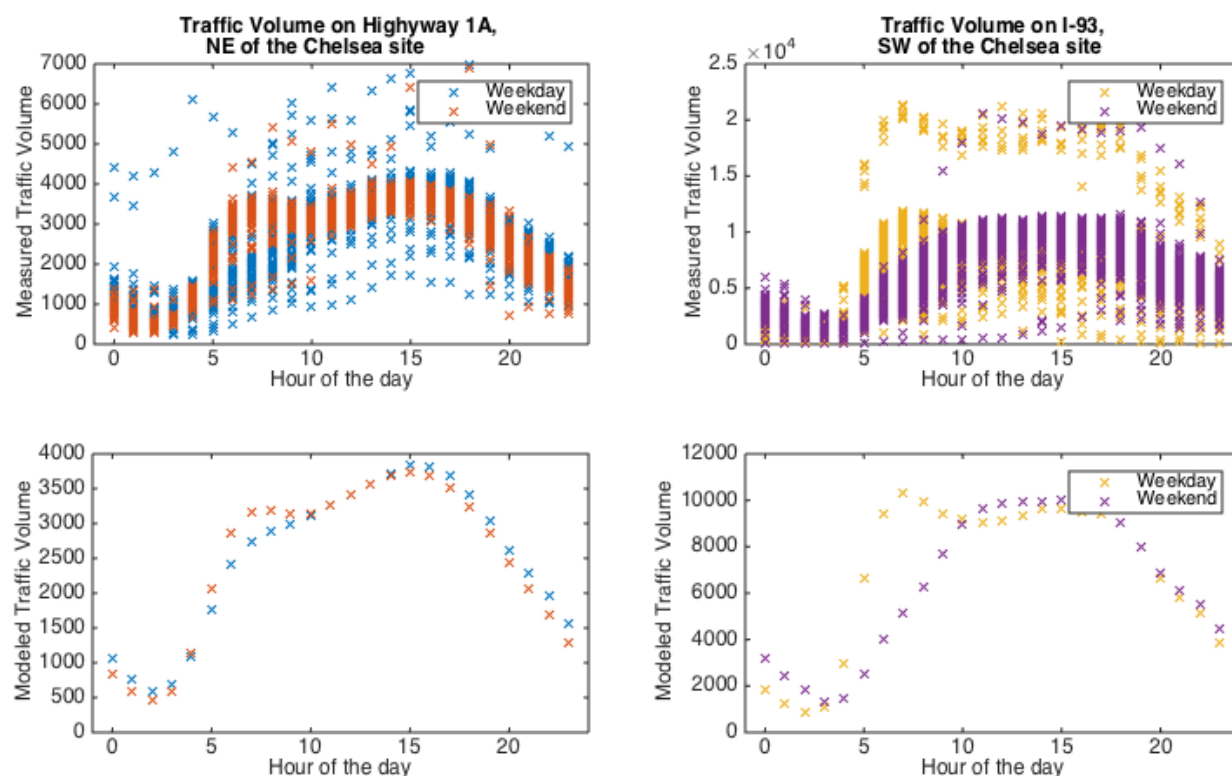


Figure S5 (a)-(d): Traffic volumes (measured and fitted) at a location on Highway 1A and I-93.

Traffic measurements at hourly resolution were available for 165 day at Lee Burbank Highway or Highway 1A at station number 8087 during the January 2014 to August 2015 period monitoring period for Chelsea site. This monitor is located NE of the Chelsea site and north of the airport, and it was the closest traffic monitor to the Chelsea site with real time traffic measurements. Data was modeled using smoothing spline fit (using the curve fitting toolbox in Matlab) separately for weekday and weekend (shown in Figure S5) and modeled output was used to control for local traffic at Chelsea site. For comparison, data from station 8494 on I-93 (station located south of Downtown Boston) for January 2012 - August 2015 was similarly modeled. Goodness of fit statistics are presented in Table S4.

Table S4: Goodness of fit statistics for traffic volume on Highway 1A and I-93.

Cubic spline goodness of fit statistics				
	Highway 1A		Interstate-93	
	Weekdays	Weekend	Weekdays	Weekend
SSE	1.25E+09	1.88E+08	2.45E+10	9.07E+09
R-square	0.79	0.90	0.89	0.88
dfe	4.09E+03	1.43E+03	1.84E+04	7.33E+03
Adjusted r-square	0.78	0.90	0.89	0.88
RMSE	553.2393	363.4974	1.15E+03	1.11E+03
Number of Observations	4104	1440	18464	7341
Smoothing parameter	0.05	0.13	0.01	0.03

Additional Information related to PNC at stationary monitoring sites

Table S5: Particle number concentrations at the three monitoring sites stratified by wind direction.

	Site		
	Chelsea	Boston Globe	Roxbury
Impact sector	130-175°	15-60°	45-65°
Annual (2014) occurrence of impact sector winds	5.3%	7.5%	3.6%
Other sources in impact sectors	Interstate (1.25 km), arterial roads, shipping channel	arterial roads, dry-dock	highways (0.5 & 1.5 km), arterial roads
PNC during impact sector winds (10^3 particles/cm ³)	n=641 h	n=226 h	n=1,051 h
Mean Hourly Average Baseline (relative standard deviation)	29 (±56%)	20 (±119%)	24 (±54%)
Mean Hourly Average (relative standard deviation)			
All Hours	34 (±75%)	25 (±118%)	28 (±54%)
High Activity Hours (0600-2359)	40 (±69%)	32 (±103%)	31 (±48%)
Low Activity Hours (0000-0559)	22 (±81%)	10 (±118%)	15 (±50%)
Minimal to No Activity Hours (0100-0359)	15 (±69%)	9 (±154%)	13 (±70%)
PNC during wind other than from impact sectors (10^3 particles/cm ³)	n=12,500 h	n=939 h	n=26,277 h
Mean Hourly Average Baseline (relative standard deviation)	14 (±76%)	19 (±116%)	16 (±67%)
Mean Hourly Average (relative standard deviation)			
All Hours	18 (±70%)	31 (±109%)	21 (±65%)
High Activity Hours (0600-2359)	19 (±68%)	30 (±102%)	23 (±60%)
Low Activity Hours (0000-0559)	14 (±71%)	33 (±125%)	14 (±67%)
Minimal to No Activity Hours (0100-0359)	13 (±69%)	29 (±114%)	12 (±62%)
Closest major roadway, distance, direction	Route 1, ~300 m, SW-NW	I-93, ~100 m, SSW-NNW	Route 28, ~500 m, W-NW
PNC downwind of roadway (10^3 particles/cm ³)	n=5,247 h, in dataset	n=511 h, in dataset	n=7,544 h, in dataset
Mean of Hourly Average Baseline (relative standard deviation)	15 (±66%)	26 (±102%)	18 (±68%)
Mean Hourly Average (relative standard deviation)	19 (±61%)	44 (±88%)	25 (±64%)

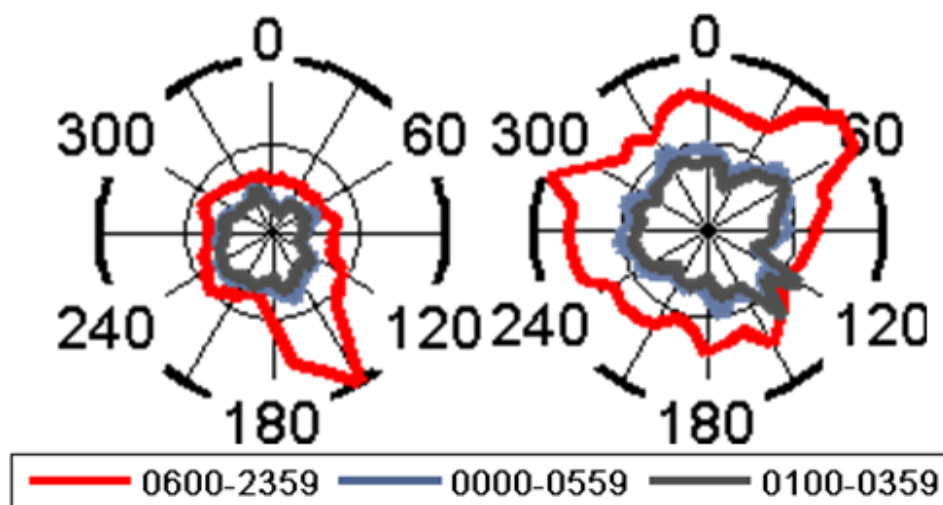


Figure S6: 2014 PNC roses for the Chelsea and Roxbury sites (normalized to the maximum) during high and low flight activity hours.

Chelsea Monitoring Site

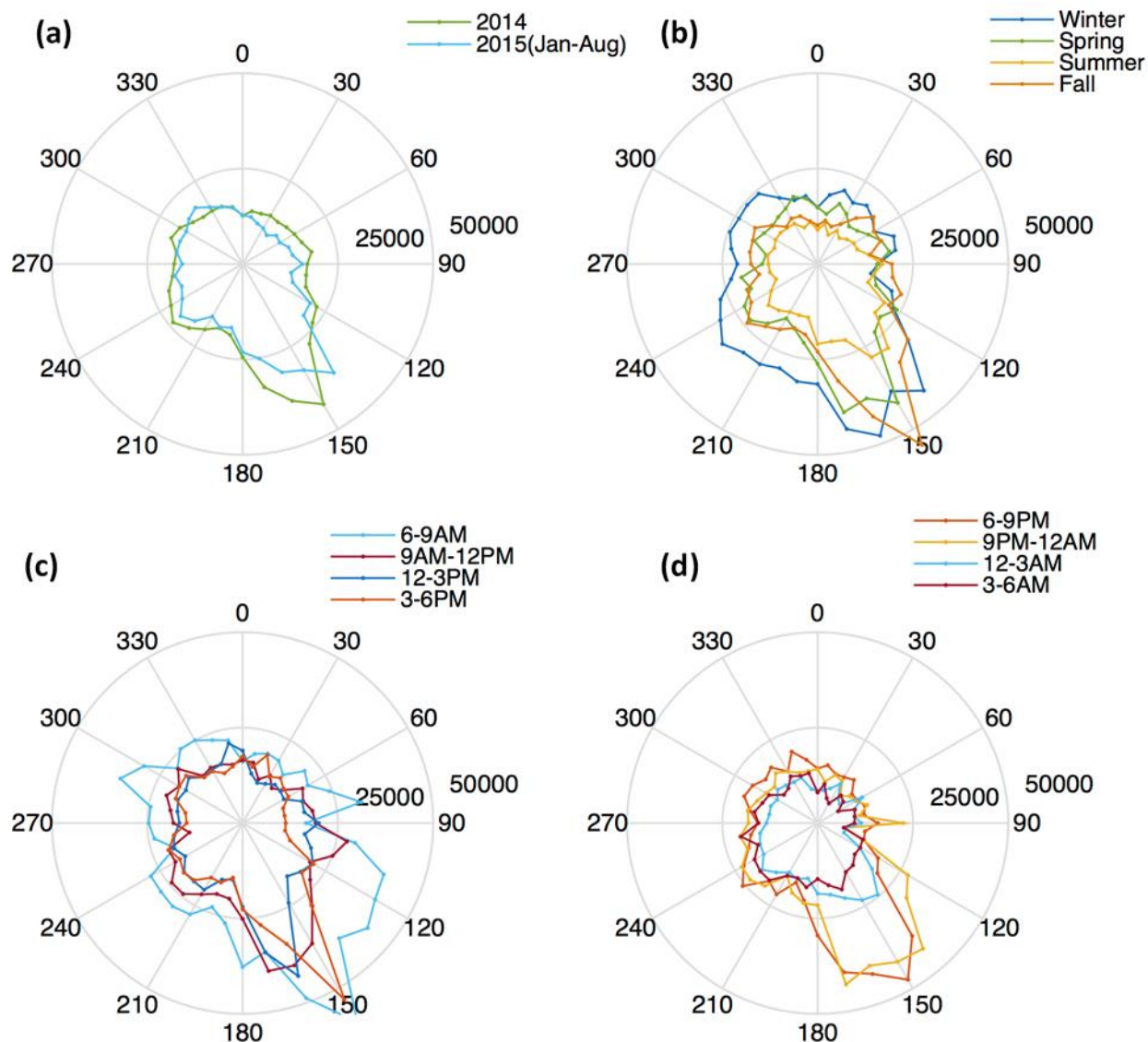


Figure S7 (a)-(d): 10° wide sector average PNC at Chelsea for different years, seasons and time periods of the day during the monitoring period January 2014-August 2015.

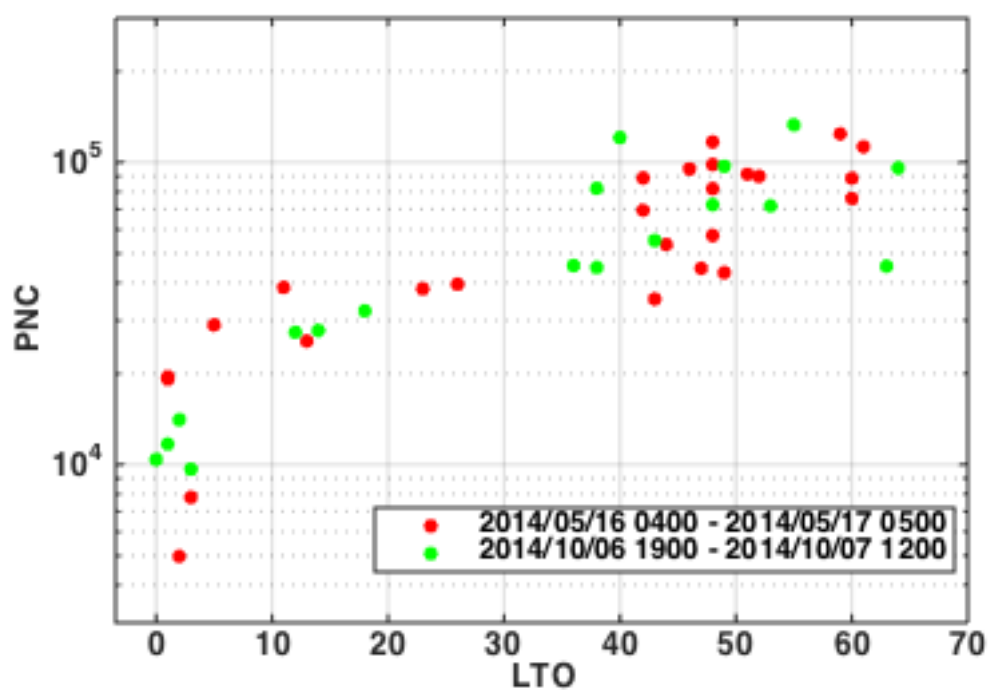


Figure S7 (e): Hourly average PNC vs LTO during the two longest, continuous periods of impact-sector winds at Chelsea site

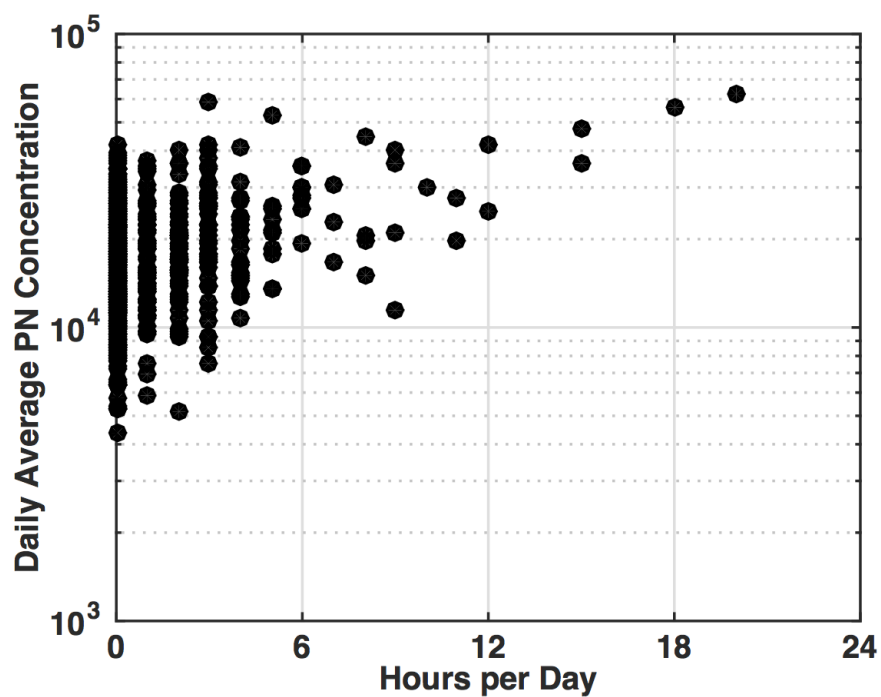


Figure S7 (f): Daily average PNC vs hours of impact-sector winds per day at Chelsea site

Boston Monitoring Site

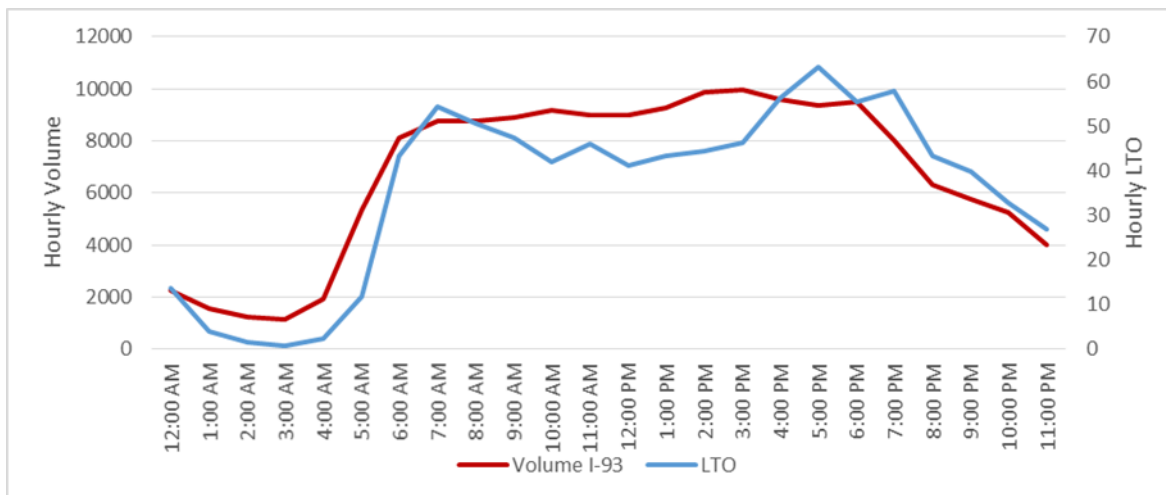


Figure S8 (a): Hourly average diurnal pattern of traffic volume on I-93 and flight operations (sum of landing and takeoffs) at Logan International Airport for the entire month May 2011.

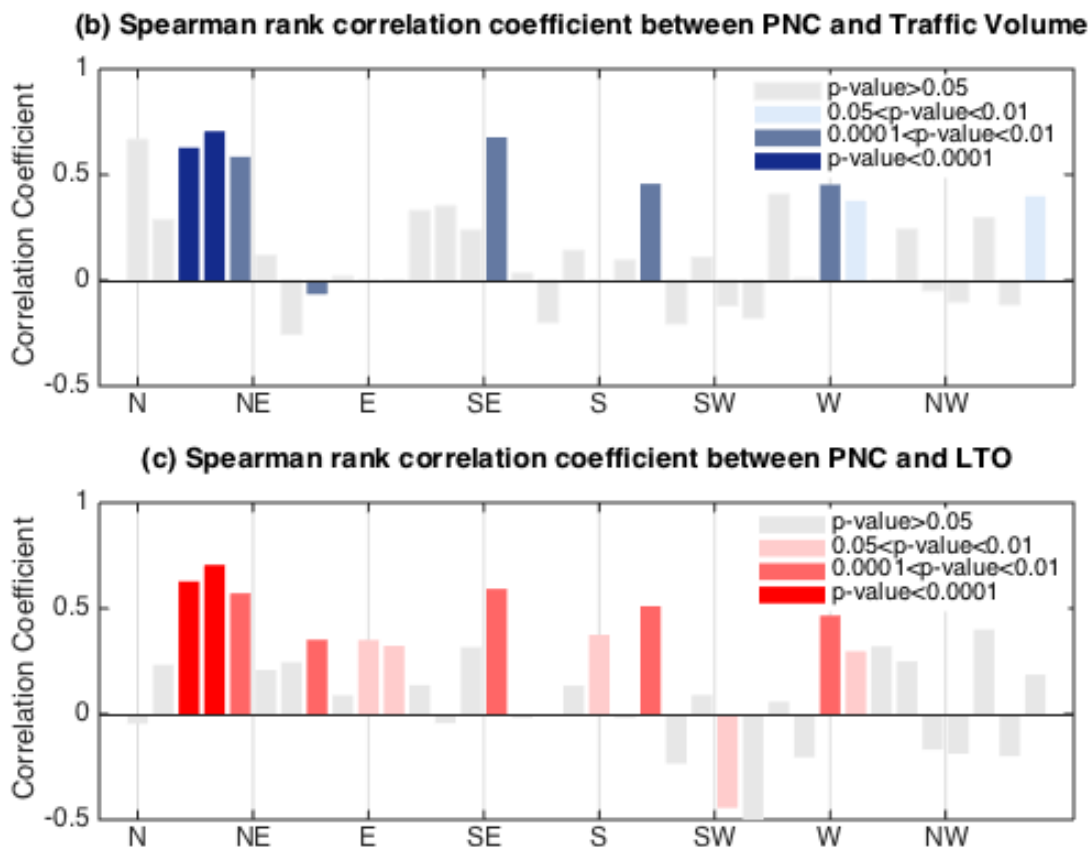


Figure S8 (b)-(c): Correlation coefficient between hourly average PNC measured at Boston Globe site and traffic volume on I-93, and PNC and LTO at the airport for all 36 10°-wide-sectors.

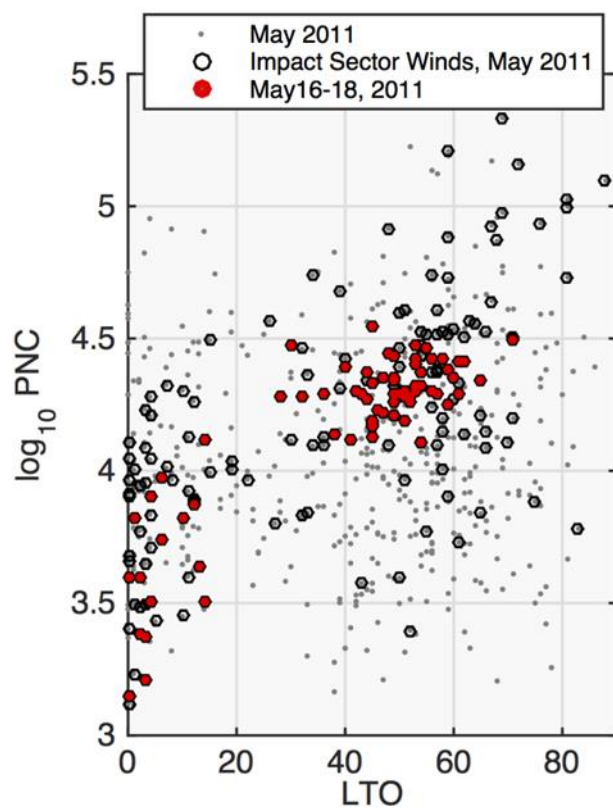


Figure S8 (d): May 2011 hourly average PNC plotted against LTO. The 72 h period (May 16-18) of continuous impact-sector winds is highlighted.

Roxbury Monitoring Site

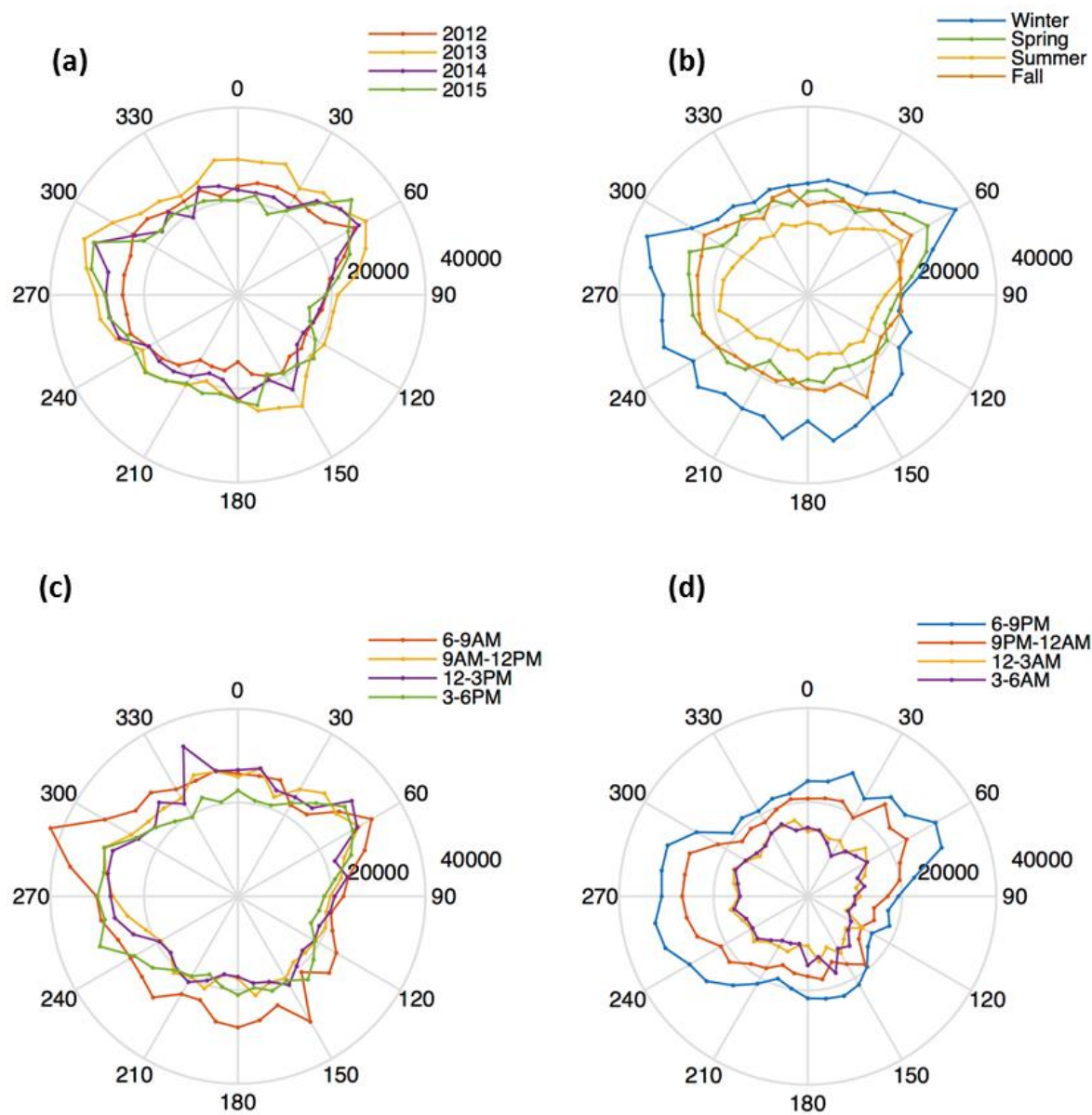


Figure S9 (a)-(d): 10° wide sector average PNC at Roxbury for different years, seasons and time periods of the day during the monitoring period January 2012-August 2015.

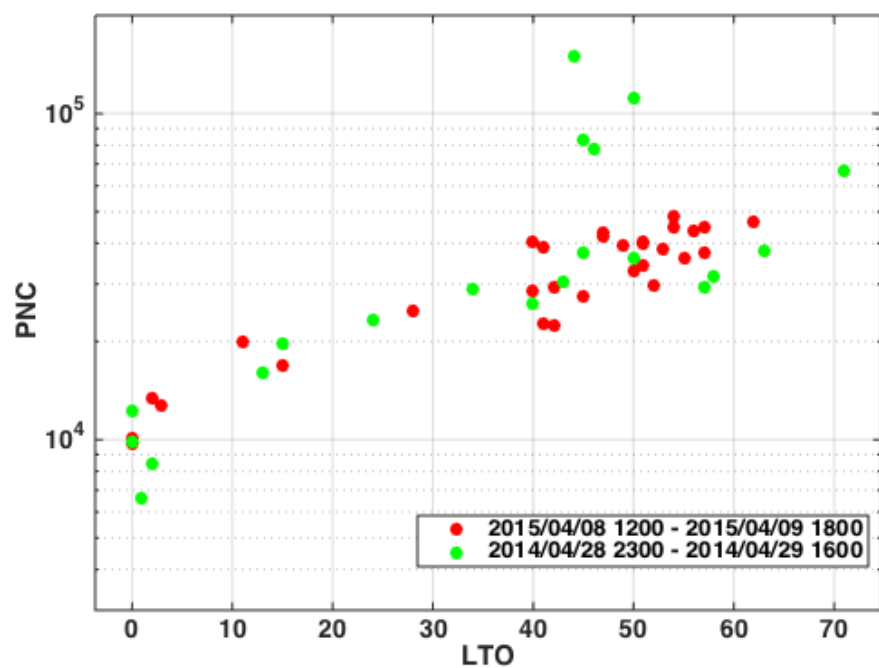


Figure S9 (e): Hourly average PNC vs LTO during the two longest, continuous periods of impact-sector winds at Roxbury site

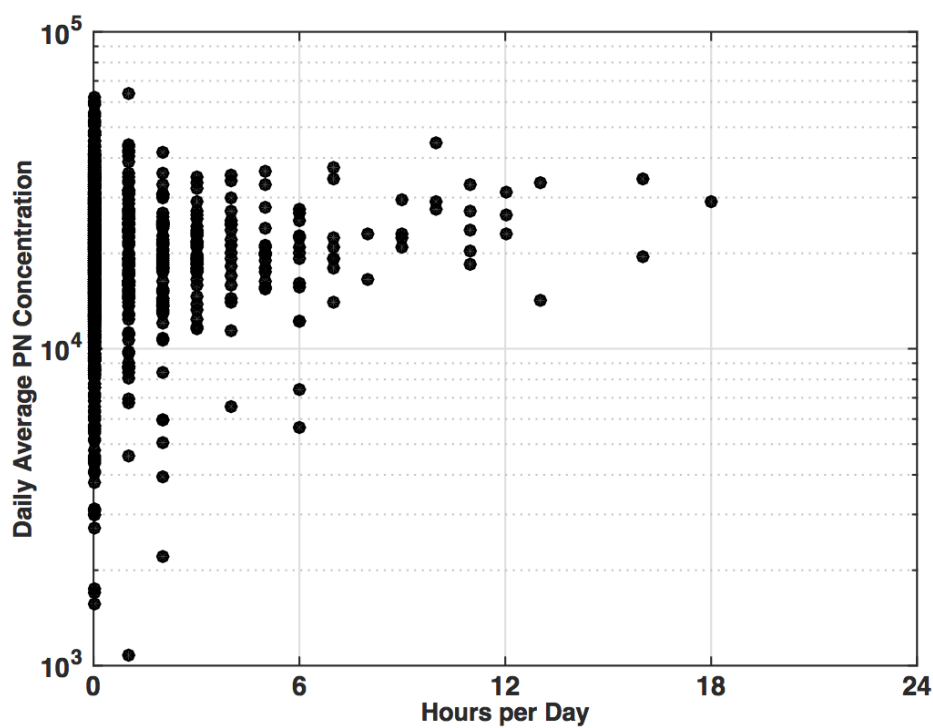


Figure S9 (f): Daily average PNC vs hours of impact-sector winds per day at Roxbury site

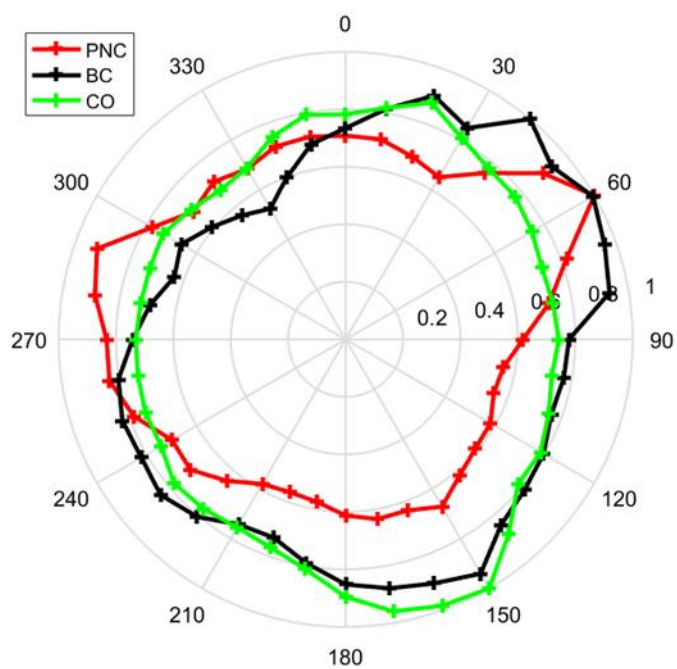


Figure S10 (a): Pollutant roses (normalized by maximum in any 10° -wide sector) for hourly average concentrations measured at Roxbury site.

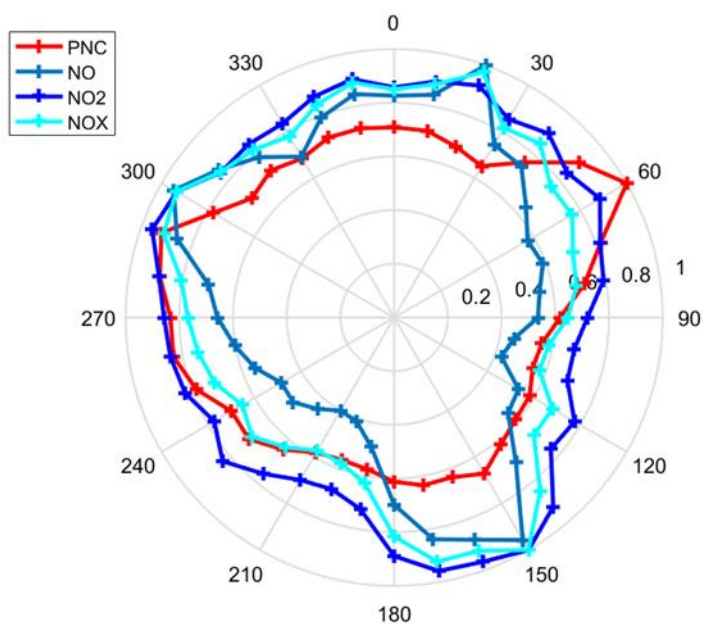


Figure S10 (b): Pollutant roses (normalized by maximum in any 10° -wide sector) for hourly average concentrations measured at Roxbury site.

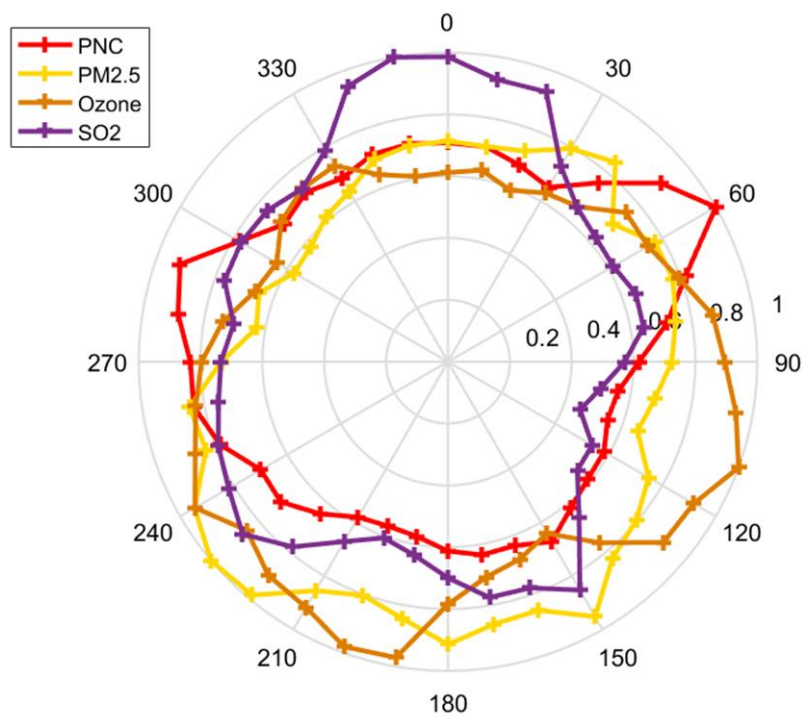


Figure S10 (c): Pollutant roses (normalized by maximum in any 10°-wide sector) for hourly average concentrations measured at Roxbury site.

Spearman's Partial Correlation Coefficients

Table S6: Spearman's partial correlation coefficients and p-values for correlation between hourly PNC and LTO at the airport.

Roxbury Site														
LTO		X				X								
Landings			X											
Takeoffs				X										
Temperature, Wind Speed, Solar Radiation	Variables controlled					X		X						
Sine and Cosine of Hour, Weekday/Weekend							X				X			
Concurrent Traffic Volume on I-93								X			X			
Modeled Traffic Volume on I-93										X				
NOX, CO											X			
PM2.5, Ozone												X		
PNC (hourly average)		r	0.44	0.38	0.44	0.45	0.28	0.36	0.29	0.36	0.31	0.24	0.23	
	p-value	1.18E-42	5.86E-32	5.39E-43	1.02E-43	1.73E-17	1.49E-27	1.56E-14	1.49E-27	8.90E-17	8.66E-09	1.35E-07		
PNC (median)	r	0.44	0.38	0.44	0.45	0.28	0.36	0.29	0.36	0.31	0.24	0.23		
	p-value	1.05E-42	2.90E-32	1.20E-42	1.00E-43	7.12E-18	1.03E-27	9.32E-15	1.03E-27	7.70E-17	5.78E-09	1.01E-07		
PNC (hourly average baseline)	r	0.42	0.37	0.42	0.45	0.28	0.36	0.28	0.36	0.3	0.24	0.23		
	p-value	9.60E-40	1.93E-30	2.92E-39	1.16E-41	1.35E-17	3.15E-26	4.24E-14	3.15E-26	4.80E-16	7.73E-09	1.95E-07		
BC	r	0.19	0.1	0.22	0.16	0.17	0.12	0.08	0.12	-0.04	0.01	0.02		
	p-value	1.72E-09	2.21E-03	1.11E-12	4.18E-07	4.64E-08	3.21E-04	2.31E-02	3.21E-04	2.40E-01	7.83E-01	7.22E-01		
CO	r	0.24	0.21	0.24	0.29	0.07	0.15	0.07	0.15					
	p-value	6.71E-14	3.06E-10	4.33E-13	5.84E-19	2.41E-02	5.27E-06	7.32E-02	5.27E-06					
NO	r	0.3	0.18	0.35	0.24	0.11	0.15	0.09	0.15	-0.05	-0.08	-0.07		
	p-value	7.22E-23	3.93E-09	7.77E-30	1.01E-13	4.18E-04	2.09E-06	9.90E-03	2.09E-06	1.50E-01	4.65E-02	1.21E-01		
NO2	r	0.17	0.11	0.2	0.34	0.11	0.24	0.2	0.24	0.1	0.13	0.14		
	p-value	1.18E-07	1.06E-03	9.46E-10	5.34E-25	7.81E-04	4.06E-13	3.60E-08	4.06E-13	3.50E-03	6.16E-04	1.26E-03		
NOX	r	0.23	0.14	0.26	0.31	0.11	0.23	0.18	0.23					
	p-value	1.40E-12	1.73E-05	2.61E-16	1.32E-21	4.44E-04	9.98E-12	2.22E-06	9.98E-12					
SO2	r	0.19	0.13	0.22	0.1	0.04	0.01	-0.01	0.01	-0.11	-0.09	-0.11		
	p-value	5.70E-09	6.66E-05	5.96E-12	1.98E-03	2.46E-01	6.57E-01	8.68E-01	6.57E-01	2.10E-03	2.29E-02	1.16E-02		
PM2.5	r	0.02	0	0.04	-0.05	0.01	-0.08	-0.06	-0.08	-0.13	-0.1			
	p-value	4.88E-01	9.08E-01	2.60E-01	1.67E-01	8.61E-01	2.14E-02	1.04E-01	2.14E-02	3.60E-04	1.56E-02			
Chelsea Site														
LTO		X				X								
Landings			X											
Takeoffs				X										
Temperature, Wind Speed	Variable s control led				X		X	X						
Sine and Cosine of Hour, Weekday/Weekend						X								
Modeled Traffic Volume on Highway1A									X					
PNC (hourly average)		r	0.27	0.25	0.29	0.35	0.15	0.22	0.22					
	p-value	1.55E-13	2.70E-11	2.47E-15	3.94E-21	8.24E-05	6.45E-09	6.45E-09						
PNC (median)	r	0.26	0.23	0.28	0.33	0.14	0.21	0.21						
	p-value	1.97E-12	1.84E-10	3.43E-14	9.18E-20	1.93E-04	2.01E-08	2.01E-08						
PNC (hourly average baseline)	r	0.22	0.2	0.35	0.31	0.12	0.19	0.19						
	p-value	1.17E-09	2.96E-08	1.88E-11	7.70E-17	1.70E-03	3.02E-07	3.02E-07						

Effect of Wind Speed on Pollutant Concentrations

Effect of Wind Speed on PN Concentrations

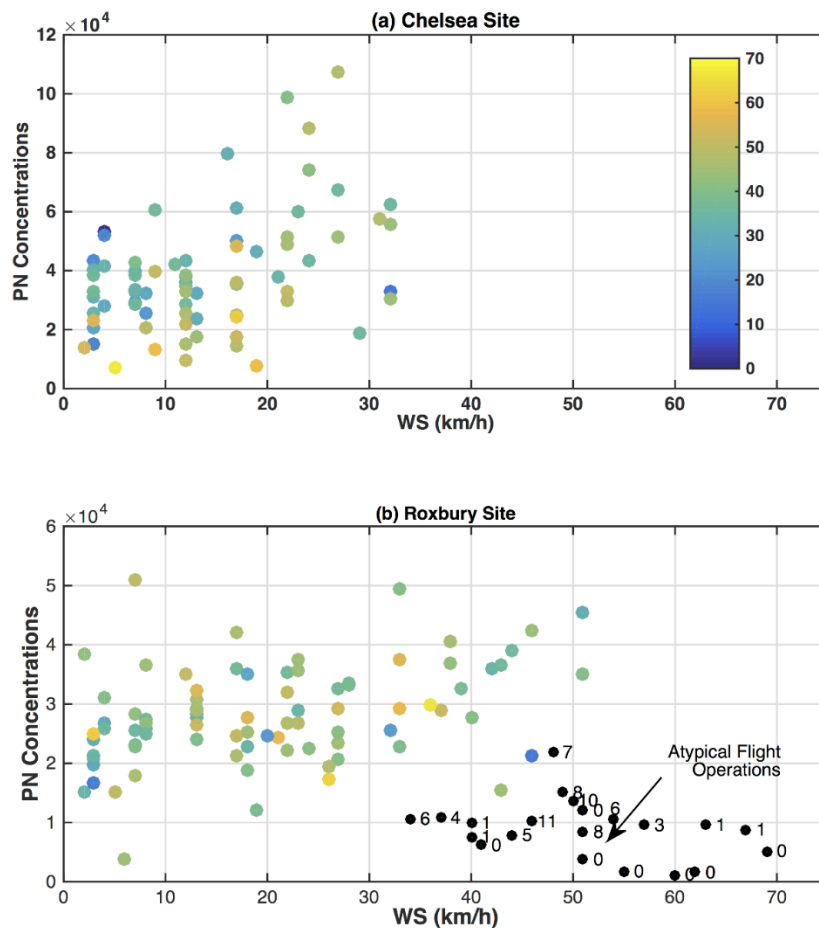


Figure S11 (a)-(b): PN concentration at Chelsea and Roxbury sites aggregated in 5 km h^{-1} wide wind speed and 5° C wide ambient temperature bins colored by average LTO. Hours when normal flight operations at Logan were interrupted due to extreme weather are plotted as black dots and data labels show LTO values for these hours.

For hourly data points (and not bin aggregated values), see Figure S12 on the following page.

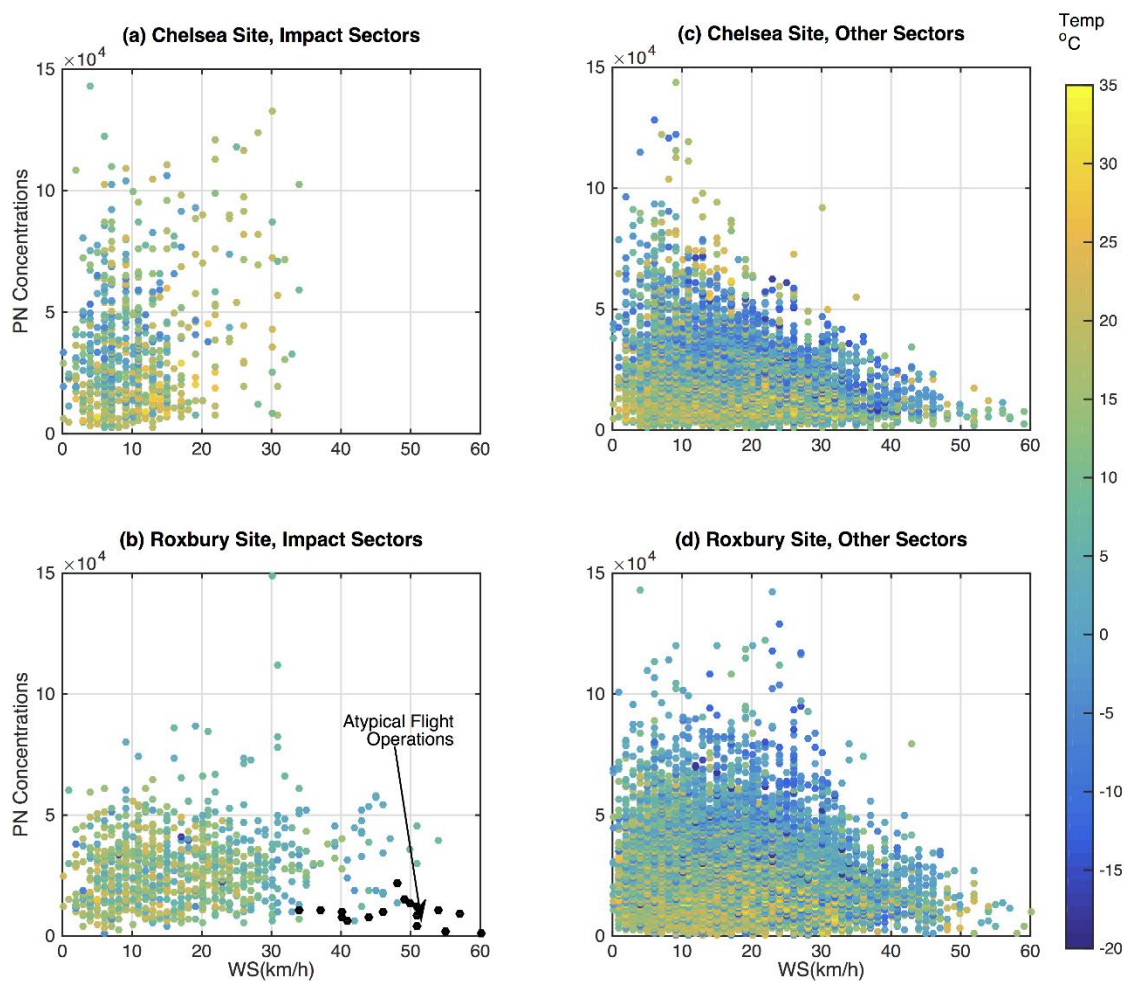


Figure S12 (a)-(d): Hourly PN concentration at Chelsea and Roxbury sites plotted versus hourly average wind speed. Hours when normal flight operations at Logan were interrupted are plotted as black dots.

Discussion of Data from Hurricane Sandy

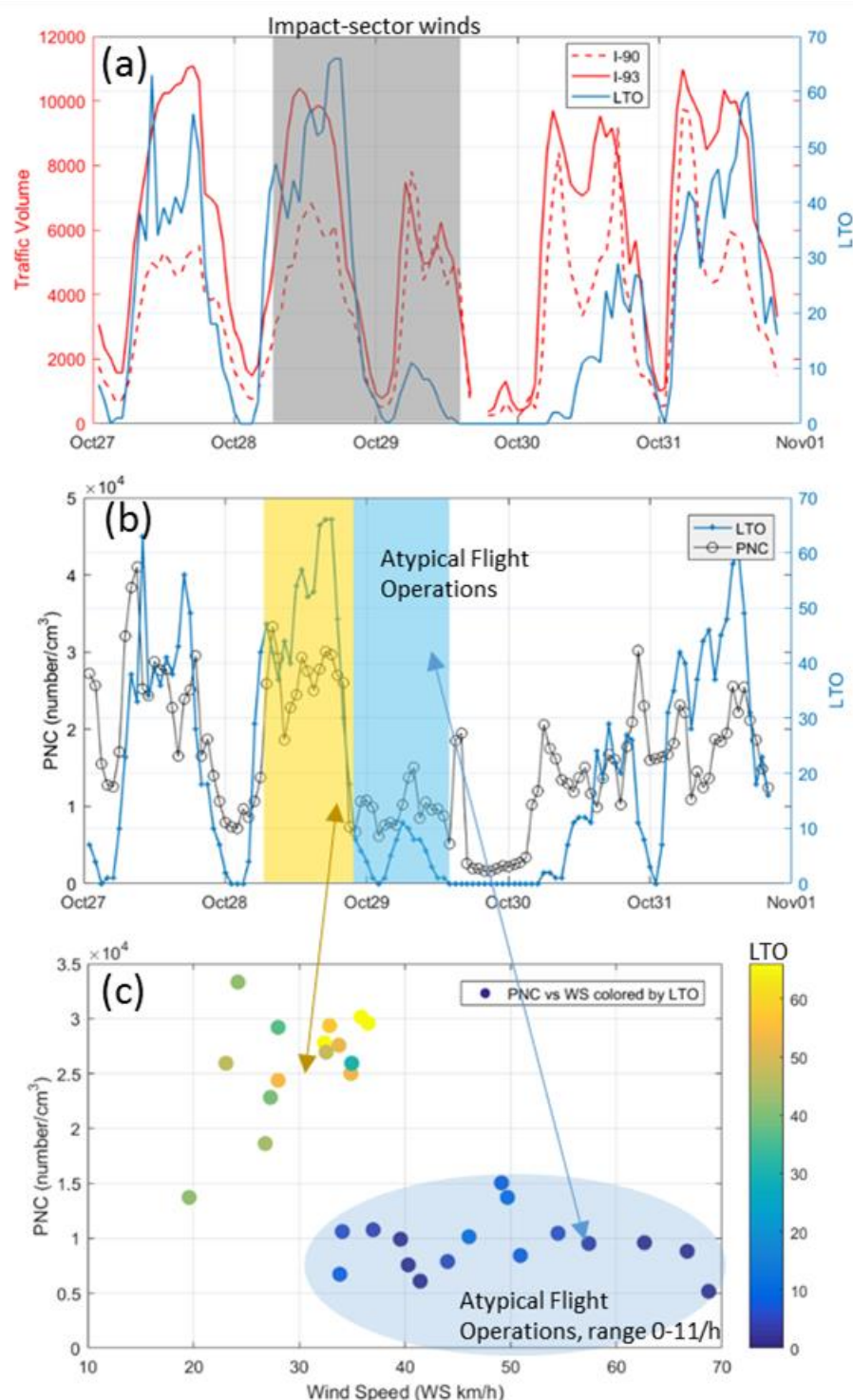


Figure S13: (a)-(b) Time-series for traffic activity, LTO, and hourly-average PNC at Roxbury site during Hurricane Sandy, October 27-31, 2012. (c) PNC vs WS with atypical flight operations highlighted. Color ramp is based on LTO/h.

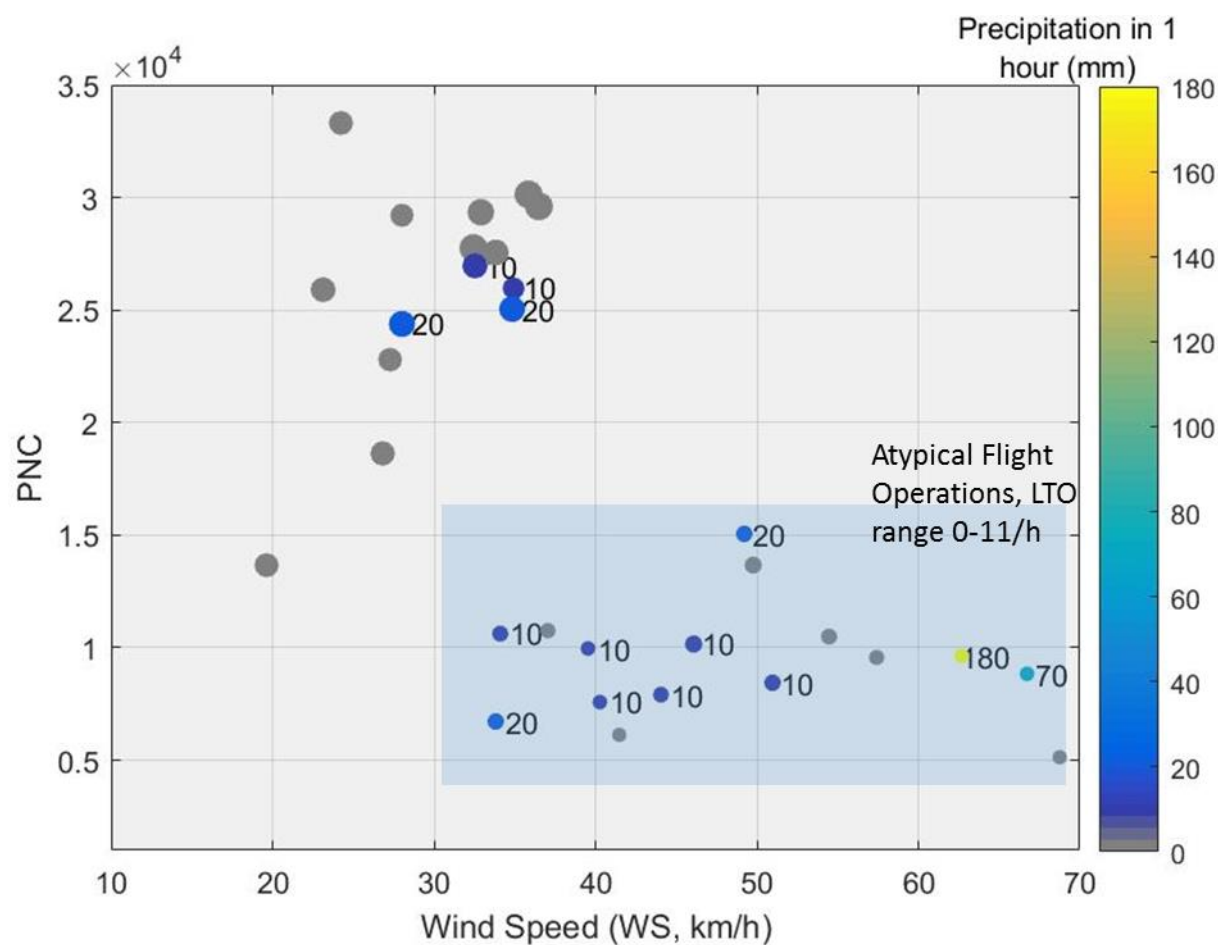


Figure S14: Hourly-average PNC vs WS for impact-sector winds on October 28-29, 2012 during Hurricane Sandy. Dot size is proportional to LTO. Color ramp is based on hourly precipitation (mm/h) and data labels also indicate hourly precipitation accumulation.

Effect of Wind Speed on Other Pollutant Concentrations

The units for the pollutants in the following figure are as follows:

- PNC: number of particles/cm³
- BC, non-volatile at 25°C in PM_{2.5} STP: µg/m³
- CO: parts per million
- NO, NO₂, NO_x and SO₂: parts per billion

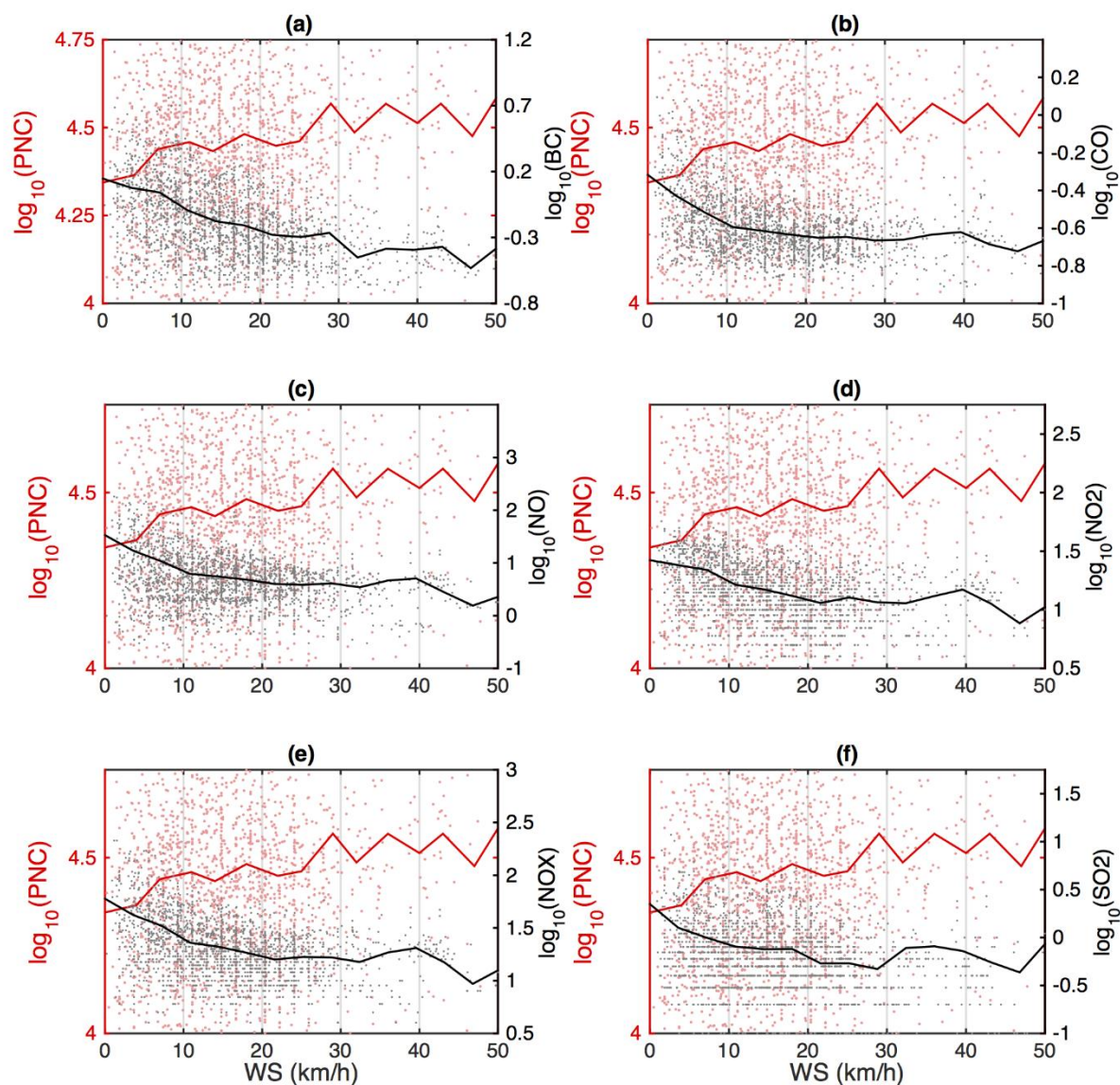


Figure S15 (a)-(f): Wind speed dependence of pollutant concentrations at Roxbury site. Hourly average concentrations of pollutants at Roxbury for impact sector winds are plotted against hourly average wind speed at Logan International Airport (points). Lines show trends in hourly data aggregated by 3.6 km h⁻¹ (or 1 m s⁻¹) wide wind speed bins for PNC (red line) and other pollutants (black lines) for impact sector winds.

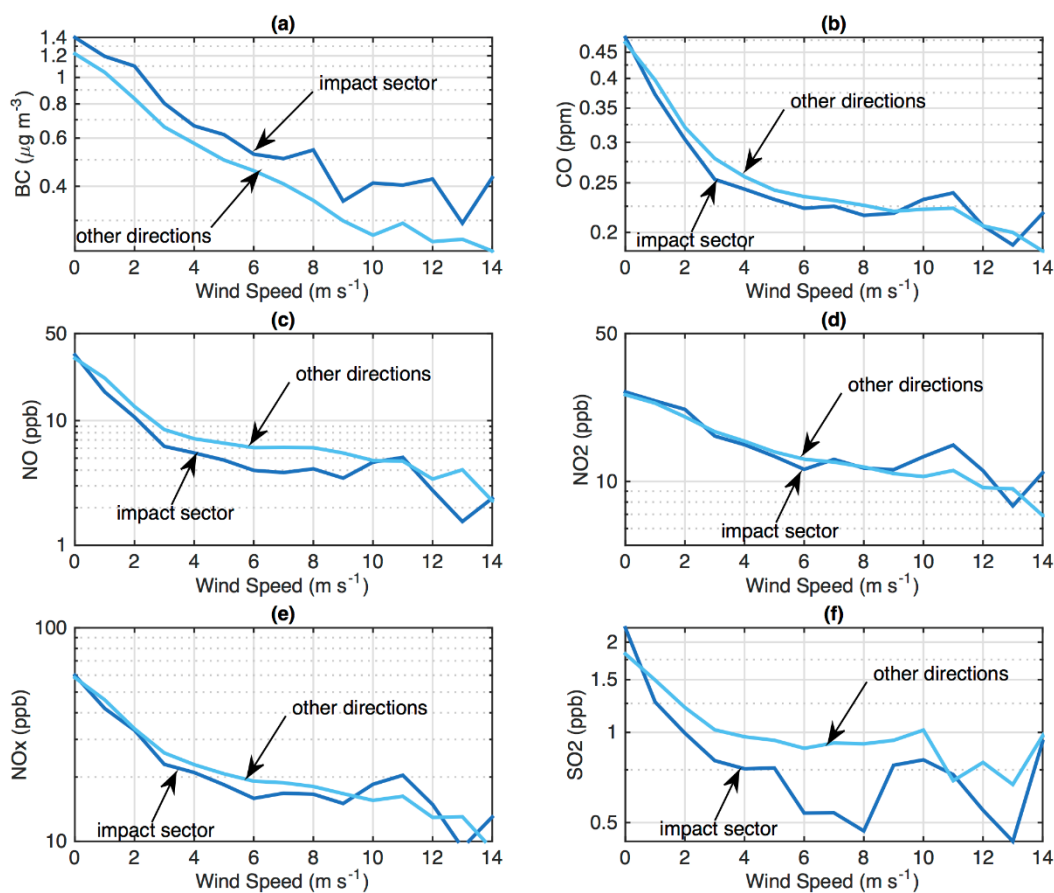


Figure S16 (a)-(f): Wind speed dependence of pollutant concentrations at Roxbury site. Similar trends in hourly data aggregated in 3.6 km h^{-1} (or 1 m s^{-1}) wide wind speed bins are shown for impact sector and all other wind directions.

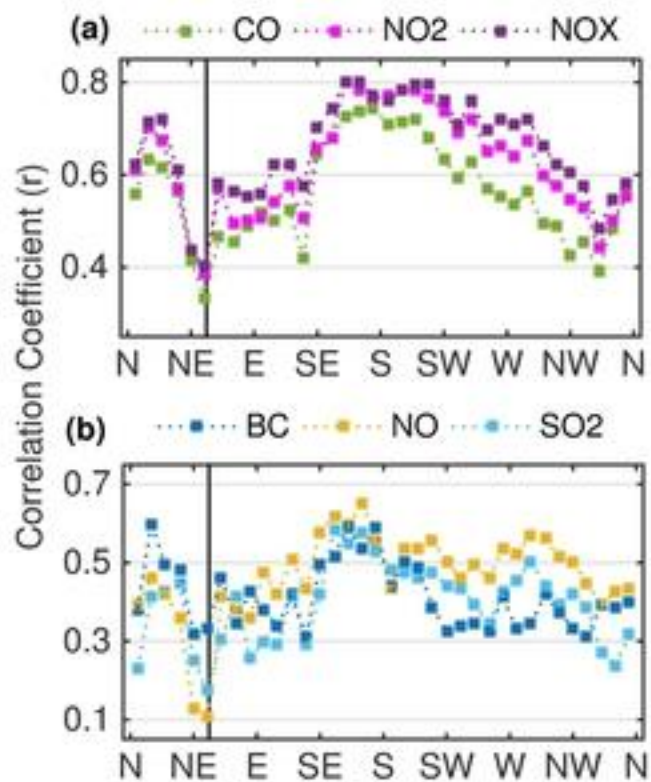


Figure S17 (a)-(b): Correlation (Spearman's rank) between PNC and other pollutant concentrations for 10°-wide wind sectors at Roxbury site. Vertical line marks the azimuth angle between the site and the airport.