Final Project Report:

Characterization of Atmospheric Nitrogen Oxides over the Meadowlands

To the Meadowlands Environmental Research Institute,

The New Jersey Meadowlands Commission

Yuan Gao

Principal Investigator

Department of Earth and Environmental Sciences

Rutgers University

101 Warren Street, Newark, NJ 07102

Phone: (973) 353-1262

Fax: (973) 353-1965

Email: yuangaoh@andromeda.rutgers.edu

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SUMMARY

This research project represents the first comprehensive *in-situ* measurement of atmospheric nitrogen over the Meadowland District. The original goal of this research was to determine the concentrations of atmospheric nitrogen oxides. During the project period and while measuring atmospheric nitrogen oxides, however, additional measurements were made for the ground-level ozone and aerosol nitrate in the spring for a better understanding of the mechanism of nitrogen in atmosphere. Therefore, this project has generated data beyond its original scope.

The results of atmospheric nitrogen oxides and ground-level ozone over the Meadowlands District are presented in 16 figures and 5 tables. Results of aerosol nitrate and its relationships with nitrogen oxides are also included in this report in the form of a manuscript, entitle "Relationships among the Springtime Ground-level NO_x, O_3 and NO_3 in the Vicinity of Highways in the US East Coast" submitted previously to *Water, Air, and Soil Pollution.*

Atmospheric measurements of NO_x and O_3 based at the Meadowlands have generated important results, including the following: The monthly average of O_3 concentrations in the study area ranged from 11.1 to 36.2ppb with relatively higher values in summer than those in winter. No obvious seasonal variations were observed for NO_x, and the NO_x concentrations observed during the one-year period ranged from 17.0 to 29.0ppb, with the yearly average concentration being 22.6ppb. For the diurnal variations, O_3 and NO_x showed different patterns. The peak of O_3 concentrations (~33ppb) happened mainly around 2pm, while the peak of NO_x concentrations (38ppb) occurred around 7am. Obvious weekdays/weekends differences in the NO_x and O_3 concentrations existed in this area, with the yearly average concentrations of NO_x in weekends much lower compared with those on weekdays. The negative correlation between the

hourly average NO_x and O_3 concentrations found in the study area, suggests a potential VOC sensitive nature of the nitrogen cycle mechanism in atmosphere. Certain environmental factors, such as the ambient aerosol nitrate, temperature, humidity, and wind speed were found to affect NO_x and O_3, although the extent of the effects by each varied.

1. STATEMENT OF THE PROBLEMS

Nitrogen oxides (NO_x), highly reactive gases in the ambient air, such as NO and NO_2, are precursor molecules for the production of ground-level ozone (O_3) (Finlayson-Pitts and Pitts, 1986). The O_3 production rate strongly depends on the concentrations of NO and NO_2. High concentrations of O_3 in the ambient air can trigger serious respiratory and other health-related problems. Therefore, an adequate knowledge of the characteristics of NO_x in the ambient air is crucial for the assessment of O_3 pollution and air quality. According to EPA data, the major anthropogenic source of NO_x in ambient air in the United States is motor vehicle emissions, accounting for half of the total emissions. Additional sources of NO_x include electrical utilities and other industrial, commercial, and residential sources. Therefore, high concentrations of NO_x are often found in areas heavily impacted by traffic and power plants, although they can also come from natural sources and be transported over long distances by prevailing winds. Despite the critical role of NO_x in air quality, the concentration levels and temporal variations of NO, NO_2, NO_x over the Meadowlands had not been monitored before the submission of this project proposal; this represents a serious data gap in air quality assessment in the district. With the heavy transportation and the existence of power plants and landfills in this region, the emissions of NO_x and production of O_3 in the district could be substantial. Thus, the measurements of NO_x in the ambient air are critically needed.

2. ORIGINAL GOAL AND OBJECTIVES

The research effort under this plan aims at generating new data of NO_x on ambient levels over the Meadowlands District, which will complement the on-going air quality monitoring research at the Meadowlands Environmental Research Institute (MERI). The ultimate goal of

this project is to contribute to the understanding and control of air pollution in the district, and maintaining the health of the Meadowlands. Within this context, the original objectives are:

(1) To install a new NO-NO_2-NO_x analyzer at MERI and to initiate atmospheric nitrogen monitoring at this location,

(2) To measure the concentrations of atmospheric NO, NO_2, and NO_x in order to assess the current levels of NO_x in the ambient air,

(3) To generate temporal variations in particular seasonal trends of NO, NO_2 and NO_x under ambient environmental conditions.

During the process of conducting this project and while measuring atmospheric NO_x, the following additional measurements were made in order to better understand the characteristics of NO_x: (1) the ground level ozone (O_3), and (2) particulate-phase nitrogen (NO_3^-) in the springtime. This report presents the data of NO_x and O_3; the results of NO_3^- along with NO_x and O_3 were in a manuscript submitted to *Soil, Air and Water Pollution* attached.

3. BACKGROUND

As two of the six principal NAAQS atmospheric pollutants, O_3 and NO_x ($NO + NO_2$) could induce serious adverse effects on human health and the ecological environment at high concentrations (Lee et al., 1996; WHO, 2000; Kampa et al, 2007). NO_x also plays an important role in controlling O_3 concentrations via photochemical reactions in near ground atmosphere as shown below in reactions R1, R2 and R3 (Seinfeld and Pandis, 2006):

$$NO_2 + hv \longrightarrow NO + O \qquad R1$$

$$O + O_2 + M \longrightarrow O_3 + M \qquad R2$$

$$O_3 + NO \longrightarrow NO_2 + O_2 \qquad R3$$

In addition, the photochemical reactions between NO_x and O_3 could greatly influence nitrogen transfer from atmospheric to aquatic and terrestrial systems. During the daytime, HNO_3 could be directly produced via reaction R4, while at night, nitrate products (NO_3^-, HNO_3) could be produced via the mechanisms as shown in R5-R7:

$$NO_2 + OH \longrightarrow HNO_3 \qquad R4$$

$$O_3 + NO_2 \longrightarrow NO_3 + O_2 \qquad R5$$

$$NO_3 + NO_2 + M \longrightarrow N_2O_5 \qquad R6$$

$$N_2O_5 + H_2O \longrightarrow 2HNO_3 \qquad R7$$

Combustion processes, especially vehicle emissions, are the main sources of NO_x in the air. They contributed more than a half of the total NO_x emissions in the eastern US (Butler et al., 2005) and showed an increasing trend since 1990s (Parrish, 2006). Ground level O_3 mainly comes from two sources: regional background O_3 transported from the upper stratosphere via convection (Junge, 1962; Clapp and Jenkin, 2001) and local O_3 production mainly from photochemical reactions shown in R1-R3 (Seinfeld and Pandis, 2006). Therefore, it is important to conduct *in-situ* measurements of both NO_x and O_3 and consequently investigate their characteristics.

4. METHODOLOGY

The on-time monitoring of NO_x and O_3 was conducted from June 1, 2007 to May 31, 2008 at the Meadowlands Environmental Research Institute (MERI) in Lyndhurst, New Jersey. Two new instruments 42i-D NO_x Analyzer (Thermo Electron Corporation, Franklin, MA) and

49i O_3 analyzer (Thermo Electron Corporation, Franklin, MA) (Figure 1), were installed at MERI in the spring of 2007. Measurements of NO_x and O_3 were made by pumping air into the two instruments via two separated plastic tubing lines with inlets installed on the roof of the MERI building. During the sampling period, the two analyzers were calibrated from time to time, and this interruption of the routine sampling resulted in certain gaps of data collection. NO_x was determined on line by detecting the chemiluminescence in the range of 600 nm to 3,000 nm, and O_3 was measured by UV photometric method as O_3 molecules would absorb infrared radiation at a wavelength of 254nm. The relationship between absorbance of the UV-light and the ozone concentration follows the law of Lambert-Beer.

The hourly average data was derived from the original investigation at 5-minute intervals. The data point in each 1-hour range was treated as an outlier if it fell outside of the 3 times standard deviation from the mean, based on the Chauvenet's criterion. In this study, the percentages of the outliers for O_3, NO and NO_x were 0.006%, 0.17% and 0.03%, respectively. In addition, based on the EPA rules on the NO_2 and O_3 data, the 8-hour average, daily average and yearly average data were generated by the hourly average data (A valid day is defined as one with at least 75% of the possible 8-hour averages in the day. If a day is less than 75% complete, the day is counted valid if the daily maximum is greater than the level of the standard) (www.epa.gov). In each day, the hourly average data were divided into two parts in the study: daytime and nighttime. The time period from 7:00 to 19:00 was treated as daytime and the remaining hours were treated as nighttime, according to the average solar radiation changes during a day in the spring time of N.J. (www.wunderground.com). The main processing and visualization of the data were carried out using Matlab and SigmaPlot.

5. RESUTS

5.1 NO_x and O_3 Concentration Characteristics

5.1.1 Summary of O_3 and NO_x Concentrations

The monthly average O_3 concentrations in the study area ranged from 11.1ppb to 36.2ppb with relatively higher concentrations in summer and lower concentrations in winter, respectively (Table 1). Primarily, the time period from October 2007 to February 2008 was considered as the low ozone concentration season, while the March to September was treated as the high ozone concentration season. The yearly average concentration of ozone was 21.0ppb. The standard variations of ozone showed similar patterns in concentration with yearly average variations of ozone being 11.9ppb. As shown in Table 1, in June, July and August, both the concentrations and the variations of O_3 were high compared with other months.

For the monthly average NO_x concentrations, no obvious seasonal variations were observed. In Table 1, the NO_x concentrations ranged from 17.0 to 29.0ppb, and the yearly average concentration was 22.6ppb. Although the monthly concentrations of NO_x were similar in different months, the summer season (June - August) showed relatively low NO_x concentrations ranging from 17.0 to 19.6ppb. The standard variations of the NO_x concentrations were relatively higher compared with ozone, even though their concentrations were at similar levels.

Similar to NO_x, the NO and NO_2 concentrations did not show obvious seasonal variations, with yearly average concentrations being 6.51ppb and 16.1 ppb, respectively (Table 1). However, the daily standard variations of NO concentrations in each month were relatively higher to that of the NO_2, probably due to the more reactive nature of NO. Compared with NO_2, the concentrations of NO showed more significant seasonal variations. In winter (especially

December and January) the NO concentrations were higher than those in summer (especially in June and July).

5.1.2 Comparison with Results from Other Locations in the US East Coast

Compared with other sites along the US East Coast (based on the EPA network), the 1st to 4th maximum concentrations of O_3 observed in the study area during the one-year measurement period were relatively high, with the values being 94.3, 94.0, 93.0 and 92.0 ppb, respectively (Table 2). In the observation period, the day when there was one 8-hour average O_3 concentration that exceeded the EPA standard (75ppb), was counted as the "Days > Std.". In this study, there were 10 days when there was at least one 8-hour average O_3 concentration exceeding the EPA standard, and their concentrations were higher than those at other study sites as shown in Table 2.

The yearly average concentrations of NO_2 observed during this study period satisfied the EPA requirement (53ppb) well. In Table 3, the "# Exceed" was used to indicate the number of yearly average NO_2 concentrations exceeding the EPA standard. Even though the maximum concentrations of NO_2 were high, the average concentration of 16.1ppb was still within the EPA's range of standard concentrations. The 1st and 2nd max concentrations and the mean concentration were comparable to other sites listed in Table 3.

5.2 Seasonal Concentration Variations of NO_x and O_3

5.2.1 Daily-Based Patterns

Temporal variations of the daily average NO_x and O_3 concentrations during the one-year measurement period were shown in Figures 2 and 3, with different patterns for NO_x and O_3. The pattern of NO_x was almost a flat line while the pattern of O_3 was a parabola line with its lowest point in December. The NO_x concentrations were relatively higher in the winter and spring

period (from December to May), while the O_3 concentrations were relatively higher from April to August. Besides, both the daily average NO_x and O_3 concentrations showed no continuous but rather, jumping characteristics, indicating significant variations among different days.

5.2.2 Monthly-Based Patterns

Variations in monthly concentrations of NO_x and O_3 during the one-year measurement period were presented in Figures 4 and 5, respectively. The distribution ranges for NO_x were narrower in June to August and wider in December to May. While for O_3, the wider distributions occurred in June to August, narrower variations were found in October, November and January. The opposite patterns in the concentration distributions of NO_x and O_3 reflect different characteristics of these two species in the ambient air.

5.3 Diurnal Variations of NO_x and O_3

5.3.1 Yearly-average Based Diurnal Variations

Figure 6 showed the diurnal concentrations of O_3 and NO_x with opposite patterns observed during the one-year study period at this location. The peak O_3 concentrations (~33ppb) occurred mainly around 2pm, and its lowest concentrations (~12ppb) occurred around 6am. During the daytime, the O_3 concentrations increased rapidly from 6am to 12pm, and from 12pm to 4pm the concentrations were maintained at very high levels with maximum concentrations around 2pm. However, after 4pm, the O_3 concentrations decreased rapidly until 8pm, and stayed at low levels from 8pm to 2am of the next day. The concentrations started to decrease rapidly again from 2am to 6am to reach the minimum concentration of the day.

The concentrations of NO_x reached maximum (38ppb) around 7am in Figure 6. The NO_x accumulation process mainly started from 4am and the concentration could be diluted rapidly from 7am to 10am, making NO_x concentrations staying at the same level (~18ppb) before 4am

and after 10am. In addition, from 10am to the 4am of the next day, NO_x concentrations changed little, except in cases where there was a slight increase of its concentration around 8pm. The pattern of diurnal variations of NO and NO_2 were primarily similar to that of the NO_x, although some differences existed. NO_2 reached its highest concentrations earlier compared with NO_x. Unlike NO_x, there was no increase of concentration around 8pm for NO. Thus, the slight increase of NO_x concentrations around 8pm could be mainly attributed to the presence of NO_2.

5.3.2 Monthly Average Diurnal Variation Patterns

To further investigate the pattern of seasonal and diurnal variations of NO_x and O_3, their monthly average diurnal variations were shown in Figure 7. In general, the diurnal variations of O_3 concentrations increased from January to June, and then deceased through December. The diurnal variations of O_3 concentrations from June to September were higher compared with other months, especially November to February. In addition, several O_3 concentration peaks were observed for each month, especially for months that showed relative lower diurnal variation levels. The less peaks observed in months with relatively higher diurnal variations might be the result of significant obscuration effect of higher peaks on the lower peaks. No obvious seasonal variations were found for the monthly average diurnal variations for the NO_x concentrations. Comparatively, in April and May the diurnal variations of NO_x concentrations were relatively higher, and in March and November such variations were relatively lower.

5.4 Weekdays/Weekends Differences of NO_x and O_3 Characteristics

5.4.1 Comparison of NO_x and O_3 Concentrations Variations between Weekdays and Weekends

Obvious weekdays/weekends differences in NO_x and O_3 concentrations existed in this area. As shown in Table 4, the yearly average concentrations of NO_x on weekends were much

lower compared with weekdays. This might result from the reduced traffic emissions on weekends. On the other hand, O_3 average concentrations on weekends were higher than that of the weekdays which indicates the possible negative influence of NO_x on O_3. Therefore, O_3 concentrations might be more sensitive to VOC (Volatile Organic Compound) than to NO_x: the higher VOC concentrations lead to higher O_3 concentrations, while higher NO_x concentrations lead to lower O_3 concentrations.

For variations of NO_x and O_3 concentrations on weekdays and weekends, obvious differences were also found, as shown in Figure 8, Figure 9 and Table 4. Both NO_x and O_3 showed smaller variations during weekends compared with weekdays. For the two components of NO_x, NO_2 showed less concentration variations compared with NO. Such difference in variations was also found between Sunday and Saturday. Although the concentrations of NO_x and O_3 were similar on Saturday and Sunday, their variations were both higher on Saturday compared with Sunday.

5.4.2 Diurnal Variations of NO_x and O_3 in Weekdays/Weekends

The average major patterns of diurnal variations of NO_x and O_3 on weekdays and weekends were shown in Figure 10. Diurnal variations of O_3 concentrations in weekdays and weekends were similar, both showing one peak in the early afternoon hours. While for NO and NO_2, two peaks were observed both on weekdays and weekends: the first peak for both NO and NO_2 was much smaller on weekends compared with weekdays, and there was no significant difference between weekdays and weekends on the second peak. In addition, for weekdays, the first peak of NO and NO_2 was much more significant than the second one, especially for NO concentrations.

5.5 NO_x-O_3 Correlations

5.5.1 Overall Correlation

The correlation between hourly average NO_x and O_3 concentrations in the study area showed mainly negative correlations. This may suggest the potential VOC sensitive nature of the study area, which means that higher NO_x concentrations would lead to lower concentrations of O_3. As shown in Figure 11, the maximum concentrations of O_3 decreased with the increase of NO_x.

5.5.2 Weekdays/Weekends and Daytime/Nighttime Differences of the Correlation

Even though the major correlation between NO_x and O_3 concentration were similar, regardless of weekdays or weekends, daytime or nighttime, some differences existed between these time periods (Figures 12 and 13). Compared with weekdays, on weekends, the O_3 could range much smaller for specific concentrations of NO_x, even though the NO_x concentrations were relatively lower, while O_3 concentrations were relatively higher. This may indicate that on weekends, the inhibition ability of the NO_x to O_3 concentrations was more significant.

A similar situation accounted for the difference between weekends and weekdays. As shown in Figure 13, for specific NO_x concentration, the maximum concentration that O_3 could reach was much lower in the daytime compared with nighttime. This also indicates that NO_x concentrations could inhibit the O_3 concentration more significantly in daytime than nighttime and might be attributed to the fact that the main inhibition effects were via photochemical reactions, which would occur mainly at night.

5.6 Effects of Environmental Factors

5.6.1 Effects of Ambient NO_3^- on O_3 and NO_x Variations

To explore the effects of particulate nitrate and nitric acid (jointly defined as NO_3^-) on the variations of O_3 and NO_x in the ambient air, a case study was carried out during the spring of

2007 with daily NO_3^- sampling at the same location for gas-phase NO_x and O_3 sampling in this study. The results show that NO_3^- was involved in the O_3 variations, and a higher NO_3^- level was primarily associated with a lower O_3 level. As shown in Table 5, the daily average concentrations of NO_3^- showed a significantly negative correlation with those of O_3, while no correlations between HNO_3 and O_3 were found. Strong positive correlations between NO_3^- and NO_x were also observed; these can be explained by the reaction equations R5-R7.

5.6.2 Effects of Meteorological Parameters on O_3 and NO_x Variations

Meteorological parameters, ambient temperature, humidity, and wind speed, influenced the atmospheric O_3 and NO_x concentrations, as shown in Figures 14 to 16. Primarily, the concentrations of O_3 were influenced by temperature on both daily and hourly scales as seen in Figure 14. The daily average O_3 concentrations increased exponentially to the increase of temperature as indicated in Figure 14a. The hourly average O_3 concentrations increased with a narrower range when the temperature reached ~80F. On the other hand, the temperature did not show much influence on NO_x concentrations, suggesting that the NO_x might not vary as a function of ambient temperature.

The ambient humidity showed some influence on both O_3 and NO_x. Higher humidity corresponded to the lower O_3 concentrations but with higher NO_x concentrations. The daily average O_3 concentrations mainly decreased linearly with the increase of humidity while the cvdaily average NO_x did not show obvious correlations (Figures 15a and 15c). However, on an hourly averaged scale, their correlations with humidity are much more obvious. As shown in Figure 15b, with the increase of humidity, while the upper boundary of O_3 did not change much, the lower boundary of O_3 decreased obviously. For NO_x, both the upper and lower boundaries obviously increased with the increase of humidity.

The daily average wind speed did not have an obvious influence on O_3 and NO_x concentrations. However, their hourly average values could exert an effect on the O_3 and NO_x concentrations, as indicated in Figure16. Higher hourly average wind speed could increase O_3 concentrations (Figure 16b), while it would reduce the higher boundary and increase the lower boundary of NO_x profiles (Figure 16d). Detailed mechanisms of these patterns need to be further explored.

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Figure Captions:

Figure 1. Instrumentation for NO_x and O_3 measurements.

Figure 2. Temporal variation of the daily averaged NO_x concentrations during the one-year period from June 1st 2007 to May 31st 2008.

Figure 3. Temporal variation of the daily averaged O_3 concentrations (06/01/2007- 05/31/ 2008).

Figure 4. Seasonal variations of monthly averaged NO_x concentrations.

Figure 5. Seasonal variations of monthly averaged O_3 concentrations.

Figure 6. Diurnal variations of NO_x and O_3 observed in the one-year period.

Figure 7. Monthly variation of the diurnal variations of NO_x and O_3.

Figure 8. Concentration variations of yearly averaged NO_x concentrations for weekdays and weekends.

Figure 9. Concentration variations of yearly averaged O_3 concentrations for weekdays and weekends.

Figure 10. Variations of the diurnal variations of NO_x and O_3 for weekdays and weekends.

Figure 11. The overall correlations between NO_x and O_3.

Figure 12. The weekdays/weekends comparison of the correlations between NO_x and O_3.

Figure 13. The daytime/nighttime comparison of the correlations between NO_x and O_3.

Figure 14. The Correlations between Temperature and O_3, NO_x concentrations in daily averaged scale (a, c) and hourly averaged scale (b, d) respectively.

Figure 15. The Correlations between Humidity and O_3, NO_x concentrations in daily averaged scale (a, c) and hourly averaged scale (b, d) respectively.

Figure 16. The Correlations between Wind Speed and O_3, NO_x concentrations in daily averaged scale (a, c) and hourly averaged scale (b, d) respectively.

Table 1. Summary of Monthly and Yearly Averaged Concentrations and Variations

Month	Concentrations (ppb)	O_3	NO	NO_x	NO_2
1	Average± StdEv	14.1±6.3	12.1±19	29.0±24.7	16.9±7.1
	Minimum	1.6	0.9	7.0	6.0
	Maximum	24.9	79.6	109.9	30.3
2	Average± StdEv	15.2±8.8	7.3±7.3	23.2±13.8	15.9±7.2
	Minimum	1.1	1.1	7.0	5.5
	Maximum	29.4	30.0	58.0	29.0
3	Average± StdEv	23.2±8.4	6.4±8.0	22.7±16.3	16.3±9.1
	Minimum	7.2	0.6	4.6	4.0
	Maximum	36.2	38.0	72.8	34.7
4	Average± StdEv	25.0±8.8	7.5±6.7	27.7±16.3	20.2±10.8
	Minimum	7.3	0.8	4.3	3.4
	Maximum	41.7	26.0	73.9	53.5
5	Average± StdEv	27.4±9.3	6.3±7.8	24.0±17.1	17.7±10.4
	Minimum	3.8	0.6	5.2	4.7
	Maximum	45.4	31.7	60.1	37.4
6	Average± StdEv	36.2±11.6	3.7±4.0	19.3±9.5	15.5±6.2
	Minimum	15.3	0.5	4.6	4.1
	Maximum	63.0	15.7	46.9	33.3
7	Average± StdEv	30.5±11.9	2.7±2.3	17.0±9.3	14.3±7.6
	Minimum	9.9	0.2	4.4	4.1
	Maximum	55.6	9.6	38.4	34.0
8	Average± StdEv	29.0±12.9	5.0±3.4	19.6±8.2	14.6±5.9
	Minimum	5.2	0.3	5.4	3.3
	Maximum	52.0	13.7	39.9	28.6
9	Average± StdEv	22.5±9.4	5.0±5.0	20.6±11.5	15.5±7.0
	Minimum	5.5	0.6	7.2	5.8
	Maximum	46.6	17.8	52.1	34.3
10	Average± StdEv	16.3±8.0	7.4±7.9	23.8±14.3	16.4±6.7
	Minimum	6.7	0.5	8.2	7.2
	Maximum	38.1	32.4	65.5	33.1
11	Average± StdEv	11.5±6.0	5.4±6.5	18.2±10.3	12.9±4.9
	Minimum	0.2	0.8	6.0	5.1
	Maximum	20.7	31.0	47.7	24.8
12	Average± StdEv	11.1±7.2	9.1±12.3	25.8±17.1	16.7±8.0
	Minimum	0.3	0.7	6.1	5.4
	Maximum	27.2	64.0	94.4	46.5
Yearly	Average± StdEv	21.9±11.9	6.5±8.9	22.6±15.0	16.1±7.9
	Minimum	0.2	0.2	4.3	3.3
	Maximum	63.0	79.6	109.9	53.5

Table 2. Comparisons of O_3 concentrations with other nearby sites along the US East Coast

Sites	8-Hour Mean (ppb)					
	1st Max	2nd Max	3rd Max	4th Max	Days > Std	# Days
Lyndhurst, NJ (The Study)	94.3	94.1	92.7	92.1	10	282
EPA Standard	75 (8-hour average)					
Oceanville, NJ	76	72	72	72	1	173
Leonia, NJ	89	89	85	82	6	172
Bayonne, NJ	90	86	81	81	7	175
East Brunswick, NJ	94	89	86	83	13	183
West Long Branch, NJ	89	86	86	83	10	183
Chester, NJ	86	84	82	81	9	162
Jackson, NJ	100	90	85	85	15	182
Albany, NY	88	84	78	77	5	195
New York, NY	84	81	78	77	5	203
New York, NY	90	87	82	82	6	207
East Farmingdale, NY	94	93	85	83	8	202
White Plains, NY	101	91	86	82	10	186
Greenwich, CT	105	102	90	88	14	172
Middletown, CT	91	83	83	82	8	182
Hagerstown, MD	84	80	78	75	3	212
Baltimore, MD	82	65	62	62	1	212
Lynn, MA	86	81	79	78	5	182
Boston, MA	83	73	72	72	1	178
Cooleemee, NC	89	84	82	81	6	214
Greensboro, NC	88	83	83	81	5	195
Pittsburgh, PA	84	79	79	79	7	214
State College, PA	81	77	74	74	2	209
East Providence, RI	88	86	85	77	4	175
Mclean, VA	102	90	81	80	6	213
Hampton, VA	88	82	79	79	4	179

Table 3. Comparisons of NO_2 concentrations with other nearby sites in the US East Coast

Sites	1-Hour Mean (ppb)			Annual Mean
	1st Max	2nd Max	Mean	# Exceed
Lyndhurst, NJ (The Study)	77.4	72.7	16.1	0
EPA Standard	-	-	53	-
Leonia, NJ	84	83	19	0
East Orange, NJ	79	76	21	0
Bayonne, NJ	82	80	18	0
East Brunswick, NJ	56	53	11	0
Chester, NJ	49	48	6	0
Elizabeth, NJ	93	89	27	0
New York, NY	89	87	25	0
New York, NY	97	90	36	0
Lynn, MA	61	61	8	0
Boston, MA	54	50	7	0
Pittsburgh, PA	113	94	14	0
State College, PA	42	41	6	0
East Providence	31	31	6	0
Mclean, VA	72	68	13	0
Westport, CT	62	60	12	0
New Haven, CT	64	62	15	0
Beltsville, MD	49	49	9	0
Baltimore, MD	78	73	18	0
Winston-Salem, NC	61	61	11	0
Charlotte, NC	59	58	11	0

Table 4. Weekdays/weekends Variations of NO_x and O_3 concentrations

Weekdays		**Average Concentration (ppb)**			
		O_3	NO	NO_2	NO_x
Monday	Average± StdEv	21.8±13.3	6.68±10.2	16.5±8.0	23.2±18.2
	Minimum	0.3	0.5	3.3	6.1
	Maximum	55.6	66.0	46.5	95.7
Tuesday	Average± StdEv	20.0±12.0	8.4±8.2	18.4±6.6	26.8±14.7
	Minimum	1.4	0.8	8.5	9.9
	Maximum	53.6	39.9	37.4	63.8
Wednesday	Average± StdEv	21.8±12.2	6.9±7.4	16.8±7.8	23.7±15.2
	Minimum	0.2	0.7	5.0	6.0
	Maximum	63.0	32.4	35.7	65.5
Thursday	Average± StdEv	22.1±11.9	7.03±6.2	17.4±7.5	24.4±13.7
	Minimum	3.3	0.5	6.5	7.5
	Maximum	54.4	26.3	42.0	68.1
Friday	Average± StdEv	19.6±12.1	8.23±10.6	19.1±10.0	27.3±20.6
	Minimum	0.6	0.3	4.3	5.1
	Maximum	53.1	64.0	53.5	94.4
Saturday	Average± StdEv	24.0±12.3	4.5±11.3	12.3±5.9	16.8±17.1
	Minimum	2.2	0.5	4.1	4.6
	Maximum	60.6	79.6	30.3	109.9
Sunday	Average± StdEv	24.0±10.0	3.58±6.2	11.6±4.9	15.2±11.1
	Minimum	1.6	0.2	3.4	4.3
	Maximum	50.3	39.2	25.3	64.4

Table 5. Pearson correlations among NO_3^-, HNO_3, NO_x, O_3.

	HNO_3	NO	NO_2	O_3
HNO_3		0.111	0.114	0.106
NO_3^-	0.321**	0.448***	0.588***	-0.513***

** $p < 0.01$, *** $p<0.001$

Figure 1

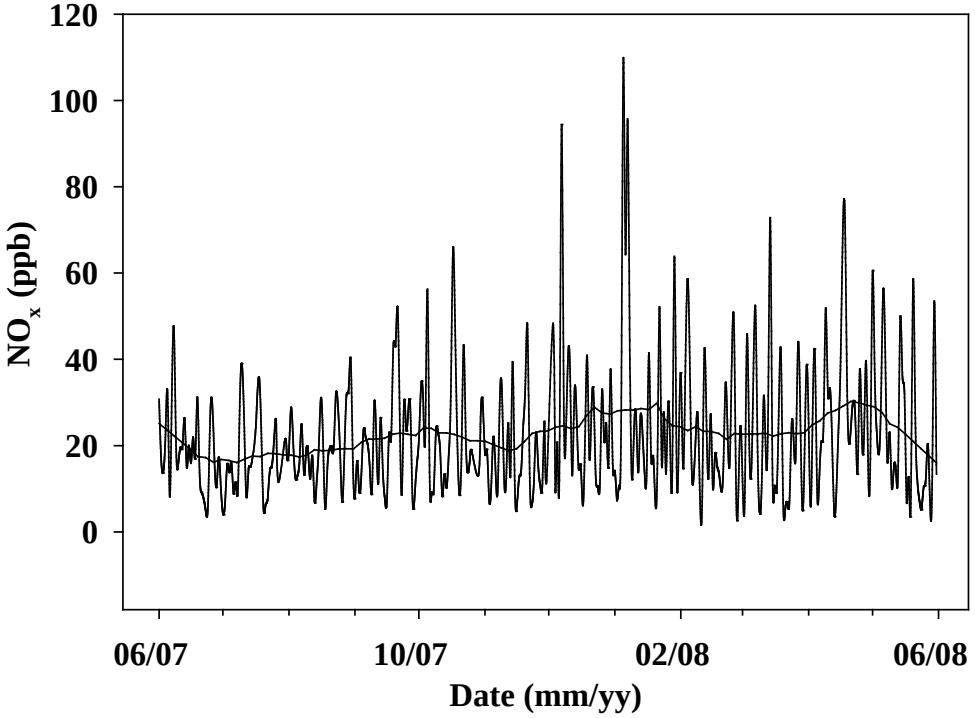

Figure 2

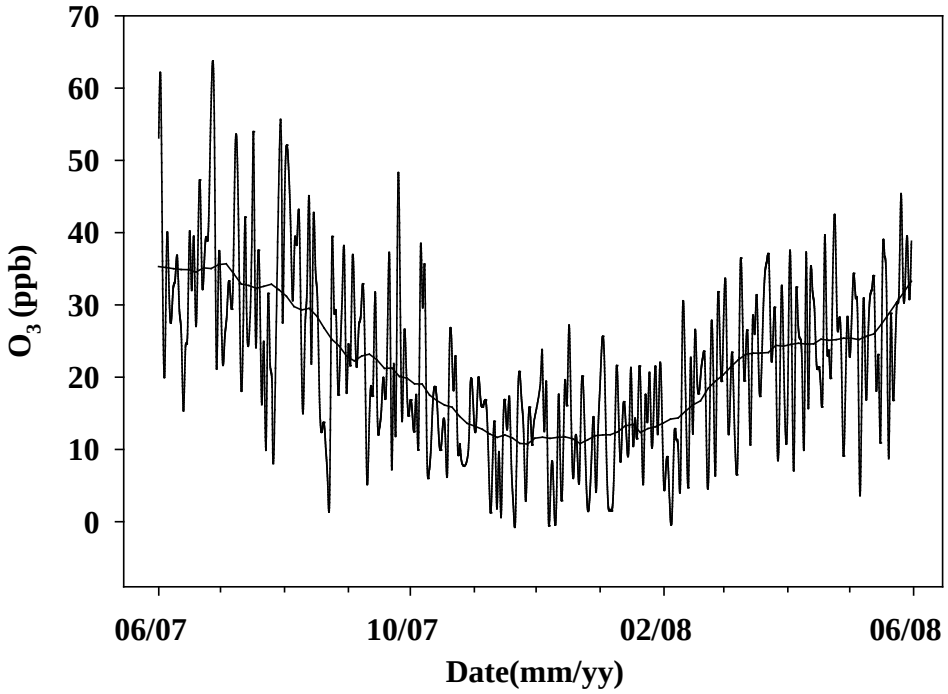

Figure 3

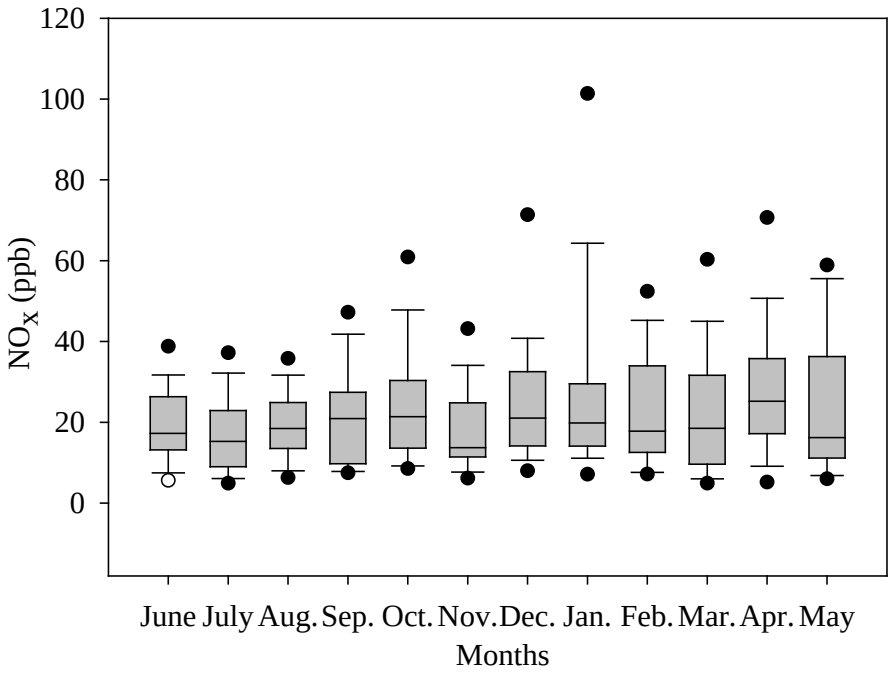
120
100
80
60
40
20
0
NOx (ppb)
June
July
Aug.
Sep.
Oct.
Nov.
Dec.
Jan.
Feb.
Mar.
Apr.
May
Months

Figure 4

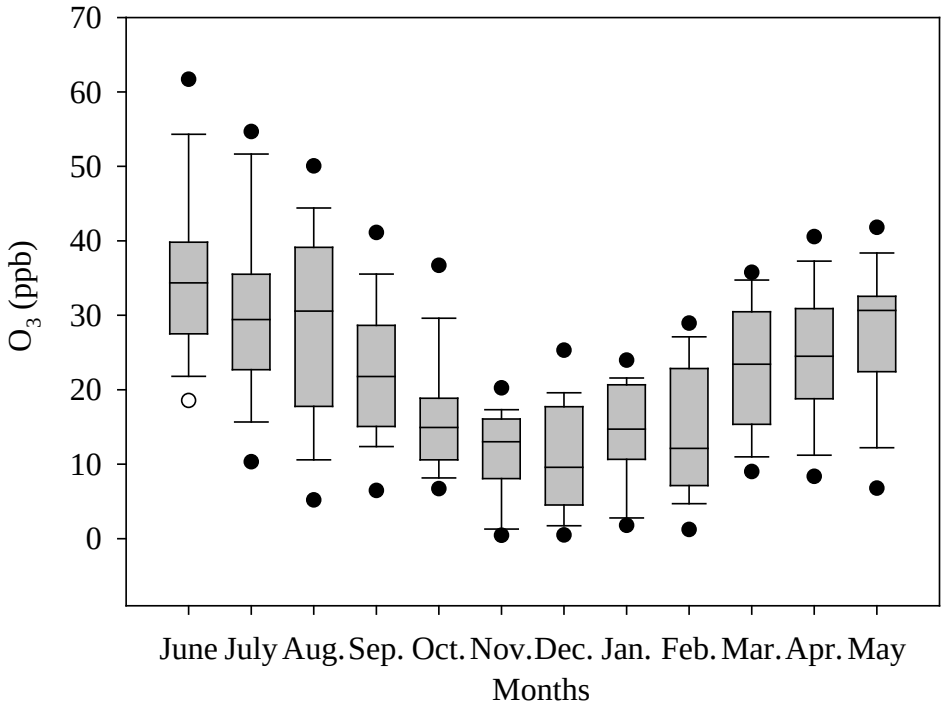
70
60
50
40
30
20
10
0
O3 (ppb)
June
July
Aug.
Sep.
Oct.
Nov.
Dec.
Jan.
Feb.
Mar.
Apr.
May
Months

Figure 5

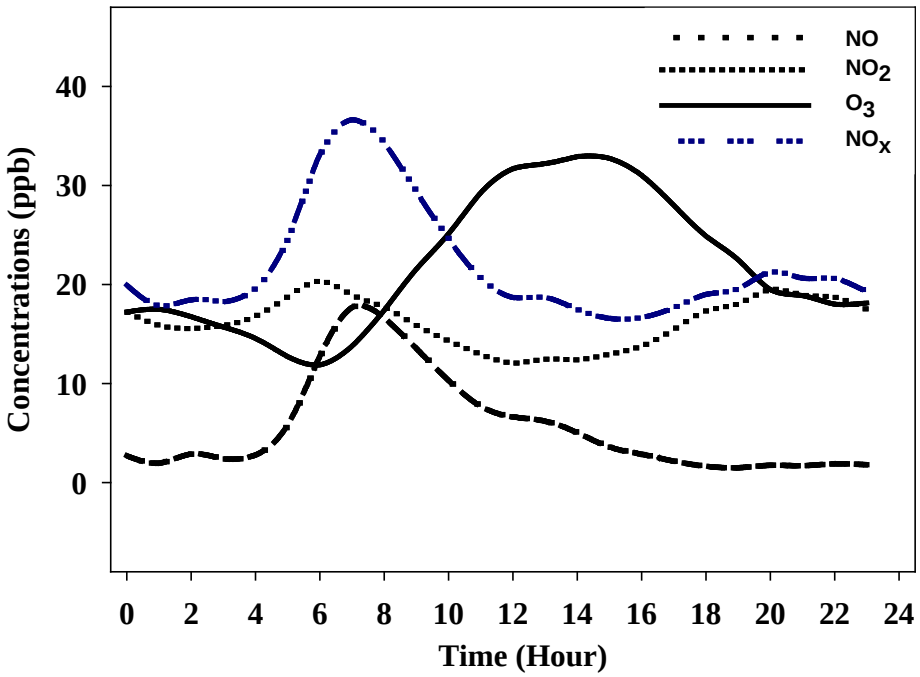
NO
NO2
O3
NOx
Concentrations (ppb)
0
10
20
30
40
0
2
4
6
8
10
12
14
16
18
20
22
24
Time (Hour)

Figure 6

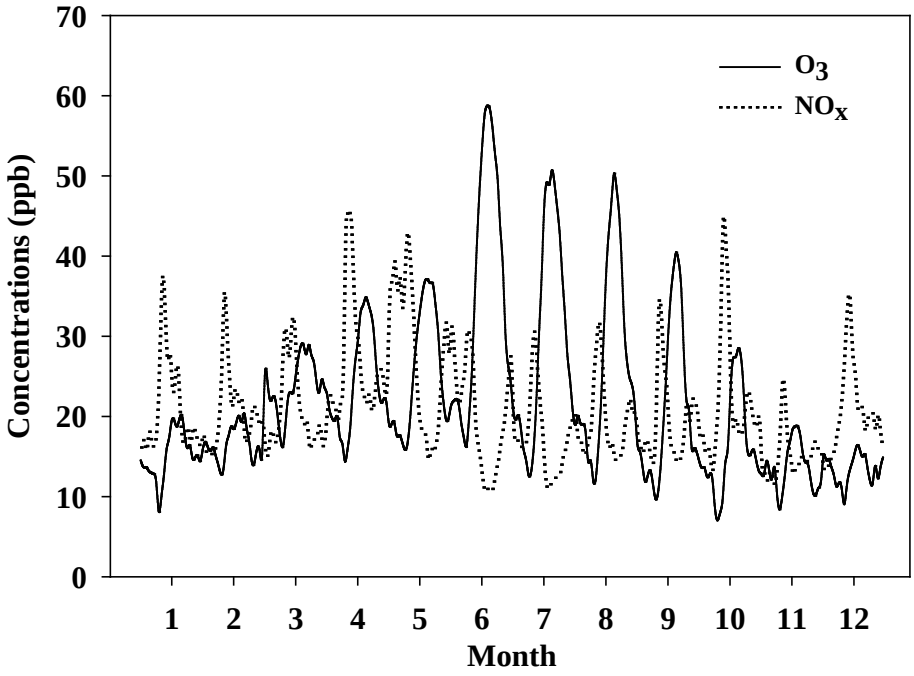
70
60
50
40
30
20
10
0
Concentrations (ppb)
O3
NOx
1
2
3
4
5
6
7
8
9
10
11
12
Month

Figure 7

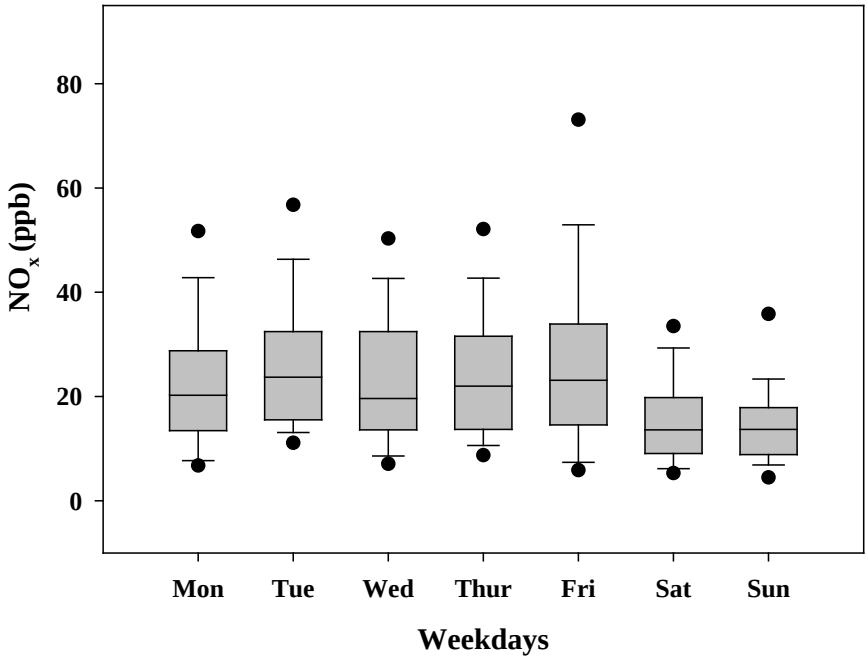

Figure 8

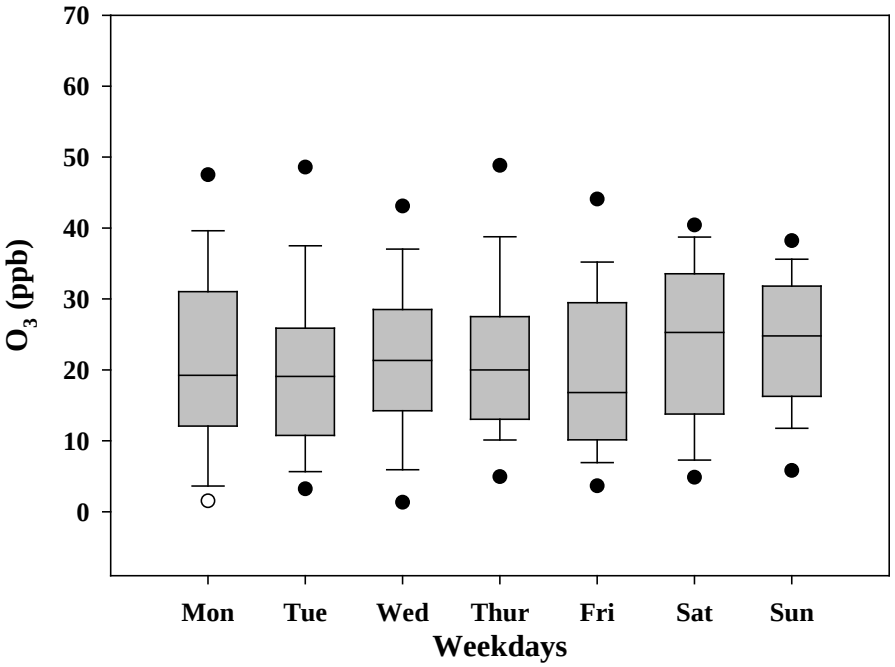
70
60
50
40
30
20
10
0
O3 (ppb)
Mon
Tue
Wed
Thur
Fri
Sat
Sun
Weekdays

Figure 9

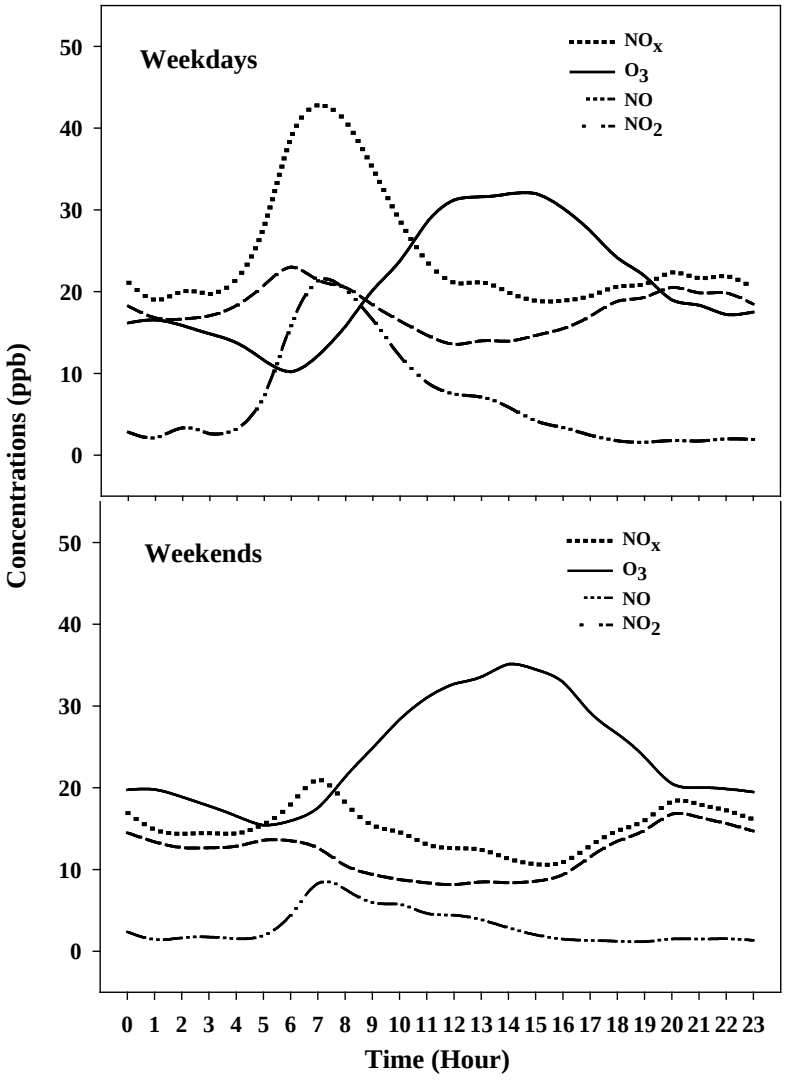
Weekdays
Weekends
NOx
O3
NO
NO2
Concentrations (ppb)
0
10
20
30
40
50
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
Time (Hour)

Figure 10

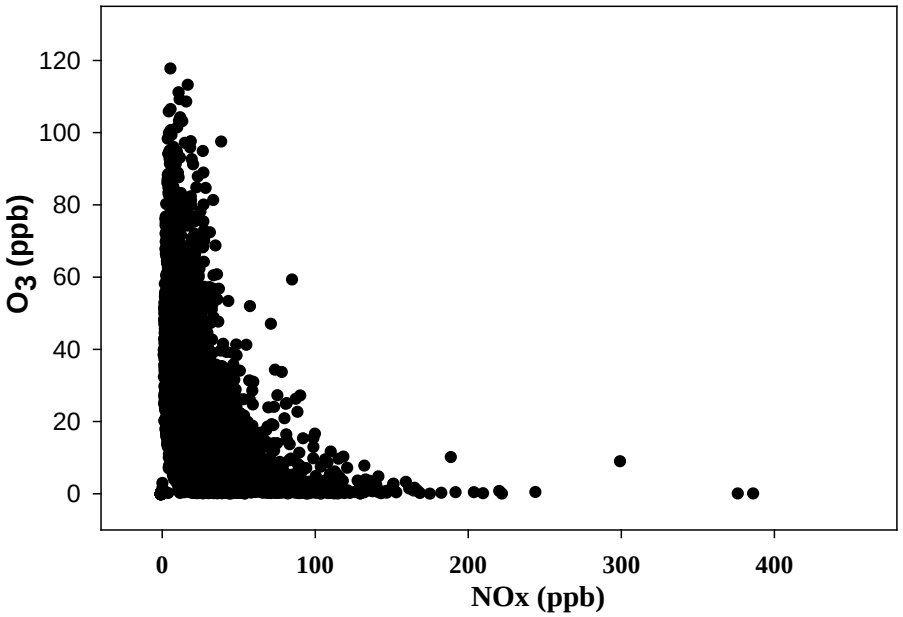

Figure 11

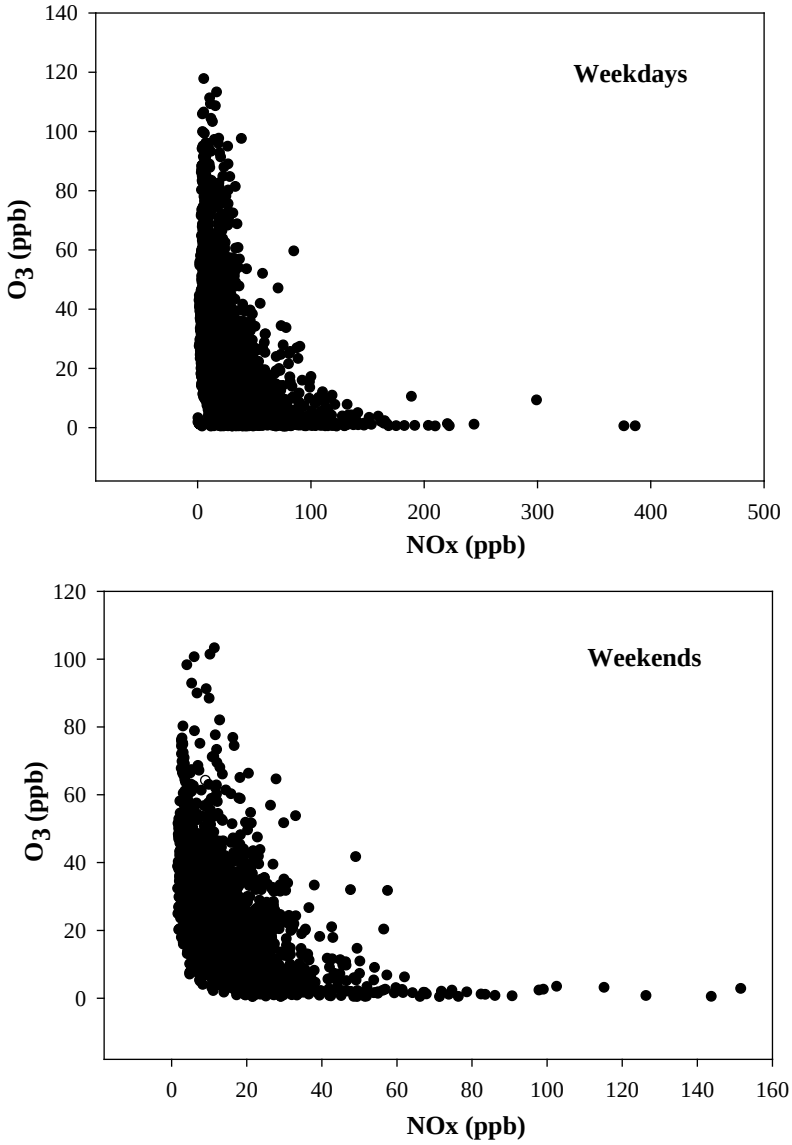
Weekdays
O3 (ppb)
NOx (ppb)
0
20
40
60
80
100
120
140
0
100
200
300
400
500
Weekends
O3 (ppb)
NOx (ppb)
0
20
40
60
80
100
120
140
160

Figure 12

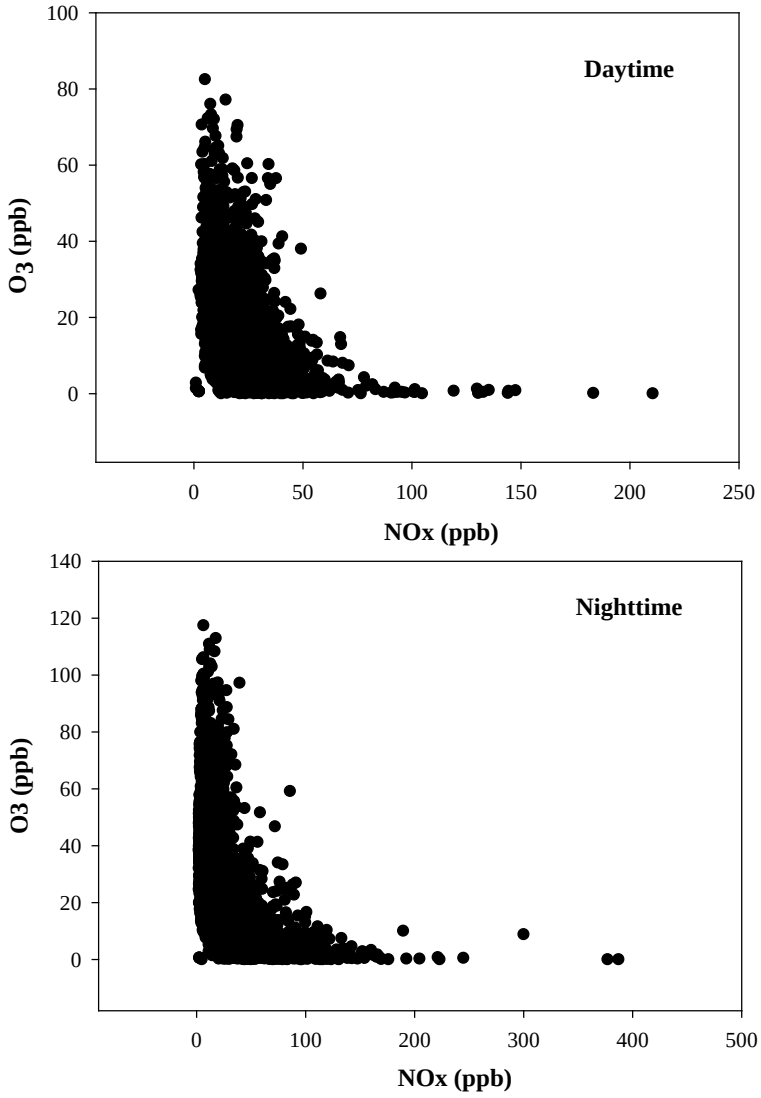

Figure 13

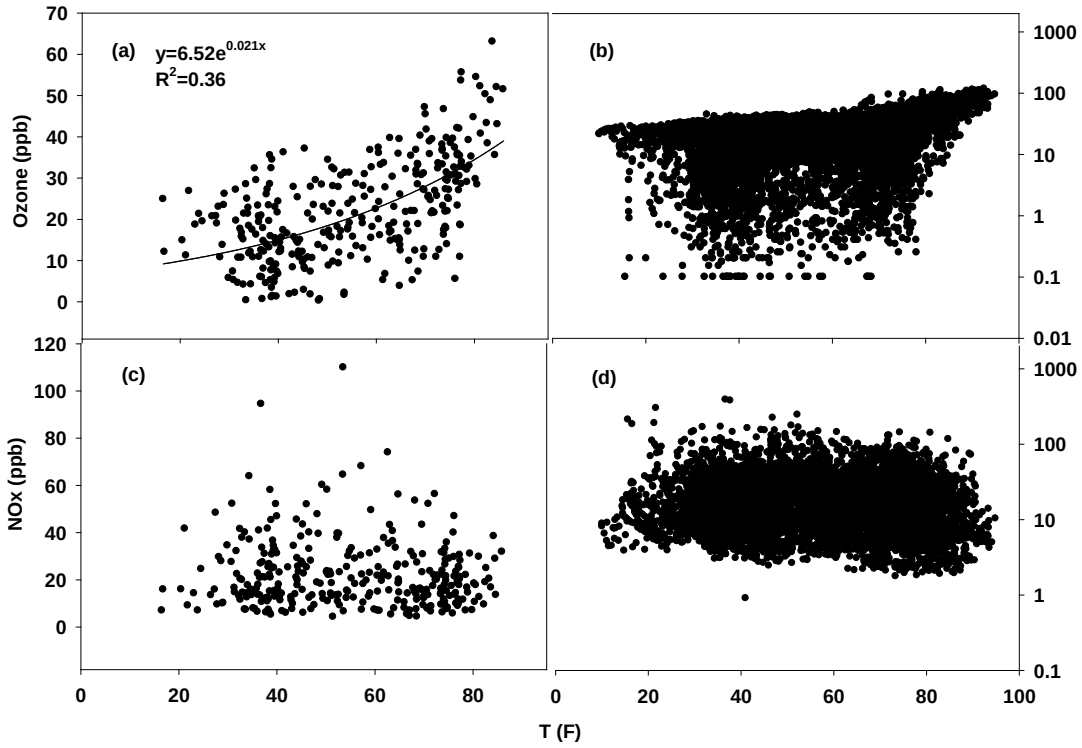
(a)
y=6.52e^0.021x
R^2=0.36
(b)
(c)
(d)
Ozone (ppb)
NOx (ppb)
T (F)
70
60
50
40
30
20
10
0
120
100
80
60
40
20
0
1000
100
10
1
0.1
0.01
0
20
40
60
80
100

Figure 14

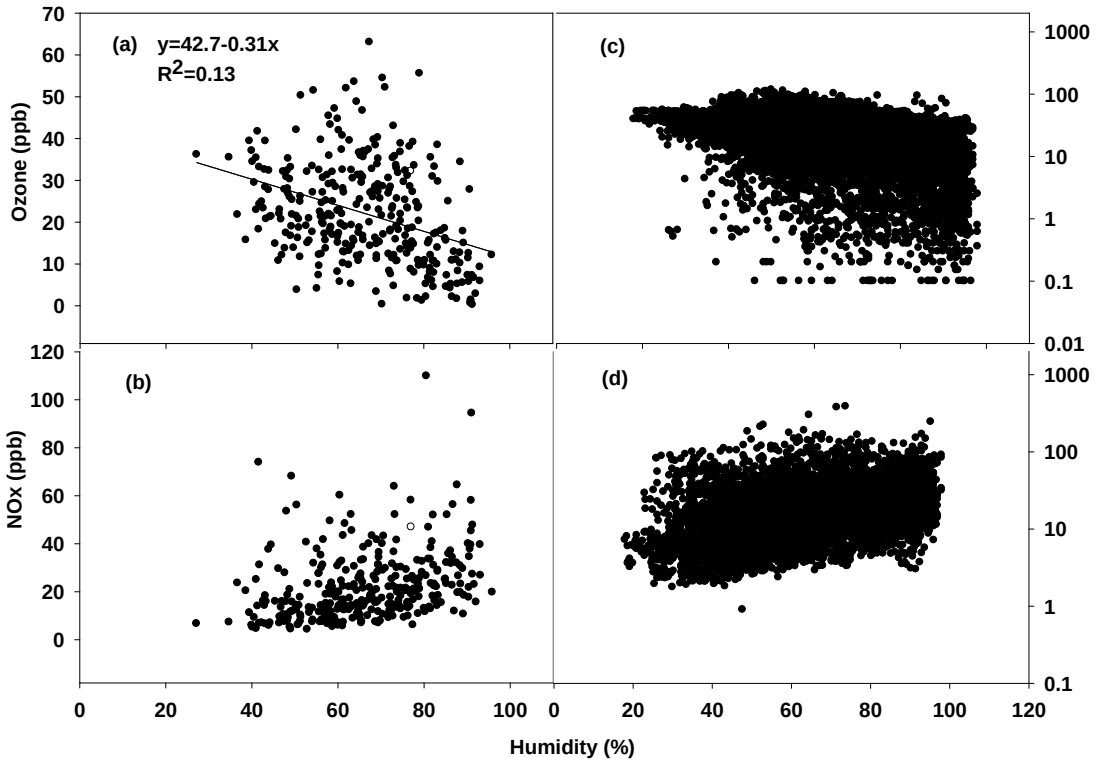
(a) y=42.7-0.31x
R2=0.13
(b)
(c)
(d)
Ozone (ppb)
NOx (ppb)
Humidity (%)
0
10
20
30
40
50
60
70
0
20
40
60
80
100
120
0.01
0.1
1
10
100
1000

Figure 15

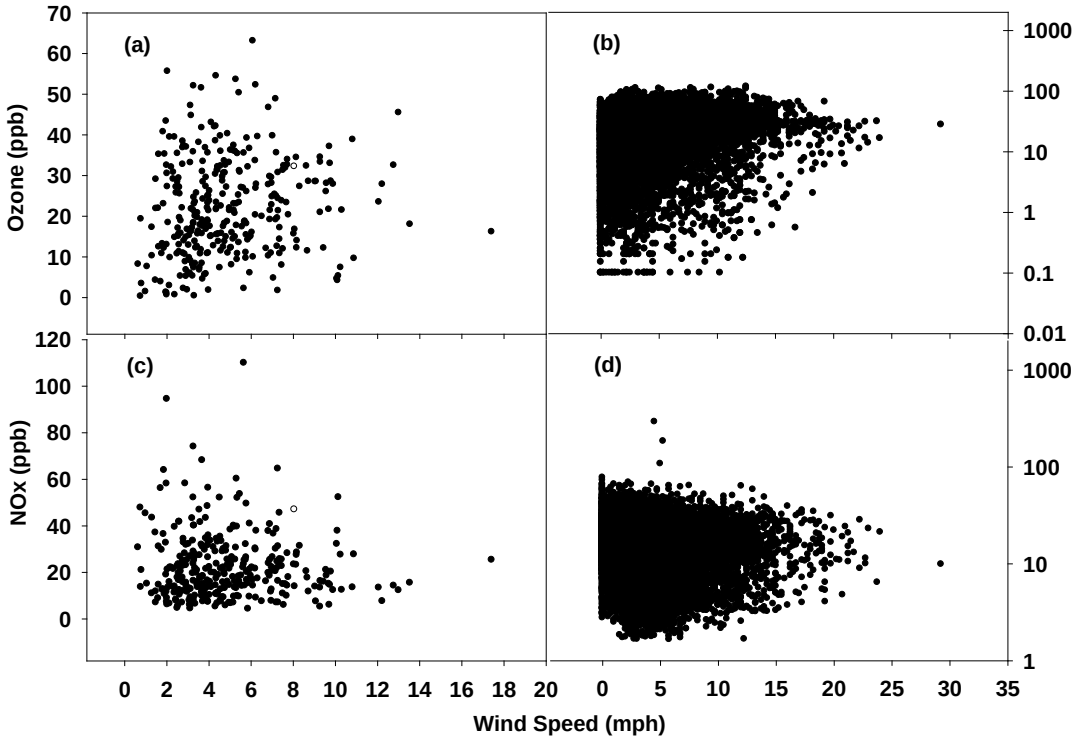
(a)
(b)
(c)
(d)
Ozone (ppb)
NOx (ppb)
Wind Speed (mph)
70
60
50
40
30
20
10
0
120
100
80
60
40
20
0
1000
100
10
1
0.1
0.01
0 2 4 6 8 10 12 14 16 18 20
0 5 10 15 20 25 30 35

Figure 16