$PM_{2.5}$ CONCENTRATIONS IN LOW- AND MIDDLE-INCOME NEIGHBORHOODS IN BANGALORE, INDIA

A THESIS
SUBMITTED TO THE FACULTY OF THE GRADUATE SCHOOL
OF THE UNIVERSITY OF MINNESOTA
BY

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IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF
MASTER OF SCIENCE

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September 2012

Acknowledgements

I gratefully acknowledge my advisor, Dr. Julian Marshall and the Marshall Research group at the University of Minnesota for all the guidance and encouragement. I thank research assistant Arun Balakrishnan and the four study households in Bangalore for allowing us regular access. I acknowledge the Global Modeling and Assimilation Office (GMAO) and the GES DISC for the dissemination of MERRA mixing height estimates. Partial funding came from a Grant-in-Aid from the University of Minnesota. I thank my dear friends and family and community at Aldrich Avenue Presbyterian Church for their support and encouragement.

Dedication

I dedicate this thesis to my parents and grandparents. I'm only able to see what I see because I stand on your shoulders.

Abstract

This study measured outdoor fine particulate matter ($PM_{2.5}$) concentrations in a low- and a nearby middle-income neighborhood in Bangalore, India. Each neighborhood included two sampling locations: near and not-near a major roadway. One-minute mean concentrations were recorded for 168 days during September 2008 - May 2009 using a nephelometer (TSI DustTrak). Wind speed and direction were also measured, as well as $PM_{2.5}$ concentration as a function of distance from roadway. Mean concentrations are 21-46% higher in the low- than in the middle-income neighborhood (64 µg m^{-3} versus 53 µg m^{-3} [neighborhood median]). In the middle-income neighborhood, median concentrations are higher near roadway than not-near roadway (56 µg m^{-3} versus 50 µg m^{-3}); in the low-income neighborhood, the reverse holds (68 µg m^{-3} near roadway, 74 µg m^{-3} not-near roadway), likely because of within-neighborhood residential emissions (e.g., cooking; trash combustion). These concentrations exceed long-term US EPA and WHO standards (15 µg m^{-3} and 10 µg m^{-3}, respectively). A moving-average subtraction method used to infer local- versus urban-scale emissions confirms that local emissions are greater in the low-income neighborhood than in the middle-income neighborhood; however, relative contributions from local sources vary by time-of-day. Real-time relative humidity correction factors are important for accurately interpreting real-time nephelometer data.

Table of Contents

List of Tables v
List of Figures vi
1.0 Outdoor Air Pollution in the Developing World 1
2.0 Introduction 3
3.0 Objectives 4
4.0 Methods 5
4.1 Equipment 5
4.2 Zero Check 7
4.3 Field Study Set-up 9
4.4 Data Coverage 11
4.5 Data Distribution 12
5.0 Results/Discussion 18
5.1 Weather 18
5.2 Relative Humidity 22
5.3 $PM_{2.5}$ Measurements 28
5.4 Weekend/Weekday Effect 32
5.5 Wind Effect 41
5.6 Spatial Variability: Moving Average Subtraction 45
5.7 Transects 52
6.0 Conclusions 57
6.1 Next steps 57
7.0 References 59
Appendix - Literature Review of Outdoor Air Quality in the Developing World 64

List of Tables

Table 1 - Data Coverage 12
Table 2 - Monitoring location unpaired t-test p-values 31
Table 3 - Weekend/Weekday effect statistics 35
Table 4 - Sunday/Monday-Saturday effect statistics 36
Table 5 - Weekend/Weekday effect statistics (equal daily weighting) 38
Table 6 - Sunday/Monday-Saturday effect statistics (equal daily weighting) 39

List of Figures

Figure 1 - DustTrak field set-up 6
Figure 2 - Zero Check.. 8
Figure 3 - Study Locations...10
Figure 4 - Data coverage..12
Figure 5 - Data histograms 14
Figure 6 - Data distribution tests..16
Figure 7 - Study period wind rose 18
Figure 8 - Seasonal wind roses 19
Figure 9 - Typical Weibull distribution 19
Figure 10 - Wind intensity distribution..20
Figure 11 - Wind classification by time-of-day..21
Figure 12 - Relative humidity by location and time-of-day......................................22
Figure 13 - Data coverage with relative humidity 23
Figure 14 - Change in geometric mean vs relative humidity correction 24
Figure 15 - Data censoring vs relative humidity correction......................................24
Figure 16 - RH correction factor by time-of-day 26
Figure 17 - Comparison of RH correction methods...26
Figure 18 - Median $PM_{2.5}$ concentration by time-of-day 29
Figure 19 - Median $PM_{2.5}$ concentration by time-of-day with standard error 31
Figure 20 - PM2.5 concentration by day-of-week..33
Figure 21 - Weekend/weekday effect 35
Figure 22 - Sunday/Monday-Saturday effect..36
Figure 23 - Different day grouping effect...37
Figure 24 - Weekend/weekday effect (equal daily weighting) 38
Figure 25 - Sunday/Monday-Saturday effect (equal daily weighting) 39
Figure 26 - Different day grouping effect (equal daily weighting)..............................40
Figure 27 - Wind condition box plot 41
Figure 28 - Median $PM_{2.5}$ concentration by time-of-day and wind condition 43
Figure 29 - Sample of raw data and moving-average baseline 45
Figure 30 - Median $PM_{2.5}$ concentration by local- and urban-scale contribution 47
Figure 31 - Percentage of $PM_{2.5}$ concentration by local- and urban-scale contribution...49
Figure 32 - Weekend/weekday effect by local- and urban-scale contribution 51

List of Figures (continued)

Figure 33 - Pollution concentration vs distance from roadway (Zhu et. al 2002) 53
Figure 34 - All normalized $PM_{2.5}$ concentration vs. distance from roadway 54
Figure 35 - Median normalized $PM_{2.5}$ concentration vs. distance from roadway.............55

1.0 Outdoor Air Pollution in the Developing World

Background

The unique problems of outdoor (ambient) air pollution in developing countries can be understood from the perspective of environmental risk transition. The first category of environmental health risks (category I) result from the household level (poor household fuel, water, sanitation, ventilation, food quality). As they are addressed during development, a second category (category II) of risks develops at the community level (urban air quality, occupational hazards, toxic chemicals, motorization). As a society progresses, it is able to address the community level risks while developing a third category (category III) of risks at the global level (climate change). The risks are often compounded for outdoor air pollution in developing countries as the three categories of risk often overlap. The urban centers of the developing world are experiencing severely degraded urban air quality (category II) resulting from their development while also experiencing an influx of rural populations possessing the typical household risks (category I). In contrast, the historical development seen in the Western world saw the population move the risks out of the house and into the community. The urban centers of the developing world are also moving the risks out of the house and into the community, but seeing an enormous influx of rural-to-urban migrants bringing those household risks back into urban households, particularly the use of solid fuels for cooking and heating.

The World Health Organization (WHO) estimates that annually, approximately 800,000 deaths and 6.4 million lost life-years worldwide are the result of urban air pollution and more than 2/3 of these occur in developing countries (Cohen et al., 2005) There is a severe lack of monitoring data and epidemiological studies done in developing countries. As a result, most of our knowledge and estimates of health effects are based on work done in North America and Europe. However, air pollution from the developed world can differ from that in the developing world in chemical nature and magnitude of exposure, resulting in substantial uncertainties in extrapolating from developed country findings to developing country questions.

General Trends

Every city has unique pollution problems, particularly in the developing world, though general trends still emerge. A trend of particular concern is the widespread nature of problematic levels of particulate matter (PM). Concentrations in developing country urban areas often exceed standards (e.g., from the World Health Organization, US Environmental Protection Agency [National Ambient Air Quality Standards], or European Union) (Mage, et al., 1996; Gurjar, et al. 2008). Developing countries typically see a higher percentage of particles being coarse particles, as a result of 'natural' sources such as windblown dust and PM kicked up by unpaved roads (Harrison and Yin, 2000; Etyemezian et al., 2005).

Solid fuels, which often are "dirtier" (have larger emission factors) than other fuels, can also play a significant role in ambient air pollution in the developing world. While it's been demonstrated that vehicular traffic and roadways are the most important source of emissions (up to 82% in Malaysia) (Afroz et al., 2003), as this Master's thesis shows, lower-income areas (slums) that have a high usage of solid fuels may experience higher concentrations away from a major roadway as next to the roadway.

Other pollutants of concern for human health are black carbon, carbon monoxide (CO), sulfur dioxide (SO_2), nitrogen oxides (NO_x), and lead (Pb). Levels of SO_2 and Pb have seen steady declines with the implementation of fuel standards limiting leaded gasoline and sulfur in coal. Areas of the developing world that have implemented emissions standards or measures to curb vehicle emissions (India, Indonesia) have seen reductions in many pollutants, including NO_x and PM (Mage, et al., 1996; Tri-Tugaswati, 1993)

A summary of existing literature on the topic of outdoor air pollution in the developing world is included as an Appendix.

2.0 Introduction

Outdoor fine particulate matter ($PM_{2.5}$) is associated with an increased risk of chronic cough, allergic disorders, decreased lung function, cognitive deficits, brain abnormalities, cardiopulmonary disease and death (Dockery et al., 1993; Calderon-Garciduenas et al., 2008; Padhi & Padhy, 2008; Samet et al., 2000; Zemp et al., 1999). Health effects of PM may occur for a range of exposure durations, from one hour or less (Delfino et al., 1998; Delfino et al. 2002; Michaels & Kleinman, 2000; Salyi et al. 1999) to more than a decade (Dockery et al., 1993; Padhi & Padhy, 2008; Samet et al., 2000). Much of the research on outdoor $PM_{2.5}$ has been conducted in developed countries, yet the poorest air quality is generally found in cities in the developing countries which hold 2.6 billion people and where the temporal and spatial variability and general degree of severity remain unknown (van Donkelaar et al. 2010; Smith et al. 1994; United Nations 2007; Gupta & Kumar 2006).

The city of Bangalore, India (population: 8 million people; area: 710 km^2) is experiencing rapid urban growth and rising automobility: population nearly quadrupled in 40 years, to 5.1 million in 2001, and motor vehicle registration increased more than 6-fold in just 20 years, to nearly 2 million vehicles in 2003 (United Nations 2007; Government of Karnataka Transportation Department 2008). With the Government of Karnataka's regulation of vehicle emissions and fuel quality, some areas of Bangalore have shown improvement in SO_2 and PM_{10} concentrations (Nagendra, Venugopal, & Jones, 2007; Sabapathy, 2008). However, annual mean PM_{10} concentrations at 5 of 6 government monitoring sites did not decrease from 1999-2009, and 5 of 6 sites exceed national standards (60 $\mu g\ m^{-3}$; 120 $\mu g\ m^{-3}$ industrial) (Karnataka State Pollution Control Board, 2009). For 2008-2009, monitored annual mean PM_{10} concentrations ranged from 63 $\mu g\ m^{-3}$ in a designated sensitive area (standard = 50 $\mu g\ m^{-3}$) to 183 $\mu g\ m^{-3}$ in a designated industrial area (standard = 120 $\mu g\ m^{-3}$) (Karnataka State Pollution Control Board, 2009).

3.0 Objectives

This study explores spatiotemporal variability in outdoor $PM_{2.5}$ in Bangalore, India. Existing data, such as annual means at central monitoring sites provide little information about spatiotemporal variability of air pollution (Ghose, Paul, & Banerjee, 2005; Kaushik, Ravindra, Yadav, Mehta, & Haritash, 2006; Van Atten et al., 2005). Here, we explore spatial and temporal variability in $PM_{2.5}$ concentrations using real-time measurements of outdoor $PM_{2.5}$ in two Bangalore neighborhoods (low-income, middle-income).

One aim is to infer spatial patterns in the emissions based on the measured concentrations' temporal variability. Some "rules of thumb" from developed country contexts may or may not apply in Bangalore. For example, I hypothesized that $PM_{2.5}$ concentrations would decrease at increasing distance from a roadway. However, in the low-income neighborhood, mean concentrations were lower near the roadway than not near the roadway. I similarly hypothesized that near roadway concentrations would be greater when the wind is blowing from the roadway (i.e., measurements are downwind of the roadway) than the reverse (measurements are upwind). This finding is observed at the middle-income neighborhood but not the low-income neighborhood. The cause for these trends is likely attributable to within-neighborhood emissions (residential cooking using solid fuels, combustion of household waste) in the low-income area.

The main contributions of this study are developing and applying a set of analyses for real-time concentrations, and reporting how air pollution concentrations differ between low- and middle-income communities in a developing country. Methodologically, these findings highlight the importance of real-time relative humidity correction when using a nephelometer to discern temporal patterns.

4.0 Methods

4.1 Equipment

The equipment consisted of two optical aerosol detectors and a weather station data logger. The direct-reading optical aerosol detector, a Model 8520 DustTrak™ (TSI Inc., Shoreview, MN) aerosol monitor, was employed to measure $PM_{2.5}$ mass concentrations. The DustTrak is a light-scattering laser photometer with a laser diode directed at a continuous aerosol stream used to measure mass concentrations of particulate matter in air. The intensity of light scattered from particles is measured and then converted to a mass concentration based on diffusion theory and a factory calibration by the respirable fraction of the ISO 12103-1, A1 Arizona test dust (ISO: Road Vehicles—Test Dust for Filter Evaluation—Part 1: Arizona Test Dust (ISO 12103-1) [Standard]. Geneva: ISO, 1997). The particle size range of the DustTrak is from 0.1 to 10 µm, with a concentration detection range from 0.001 to 100 mg m^{-3} and a mass resolution of ±0.1% or 0.001 mg m^{-3}, whichever is greater (TSI, 2006). An inlet impactor with a cut size of 2.5 µm was attached to the inlet. The air sampled was first drawn through a 10 mm Nylon Dorr-Oliver Cyclone designed to separate the respirable fraction of airborne particulate matter from the non-respirable fraction, and then through a 0.5-m piece of Tygon® tubing to the impactor plate at a flow rate of 1.7 L/min as recommended by NIOSH for the operation of the cyclone. The cyclone was included to prolong the efficiency of the impactor plate by eliminating the expected high concentration of coarse particulate matter (>2.5 µm), and also to keep out macroscopic objects (e.g., insects). The DustTrak was placed inside a locally fabricated metal box for security and weatherproofing purposes. The cyclone was secured to the exterior of the security box with its inlet in an unobstructed position. The DustTrak was plugged in to the local power grid using an extended 8 meter power cord; a generic-model spike buster was used to stabilize the AC voltage resulting from inconsistent power grid voltages. In addition, locally fabricated battery inputs with alligator clips were soldered to the factory battery inputs to connect to a 6-V 10 amp battery. Up to two 6-V 10 amp batteries were connected in parallel to prolong the battery life when the local power was blacked out or the instrument was unplugged.

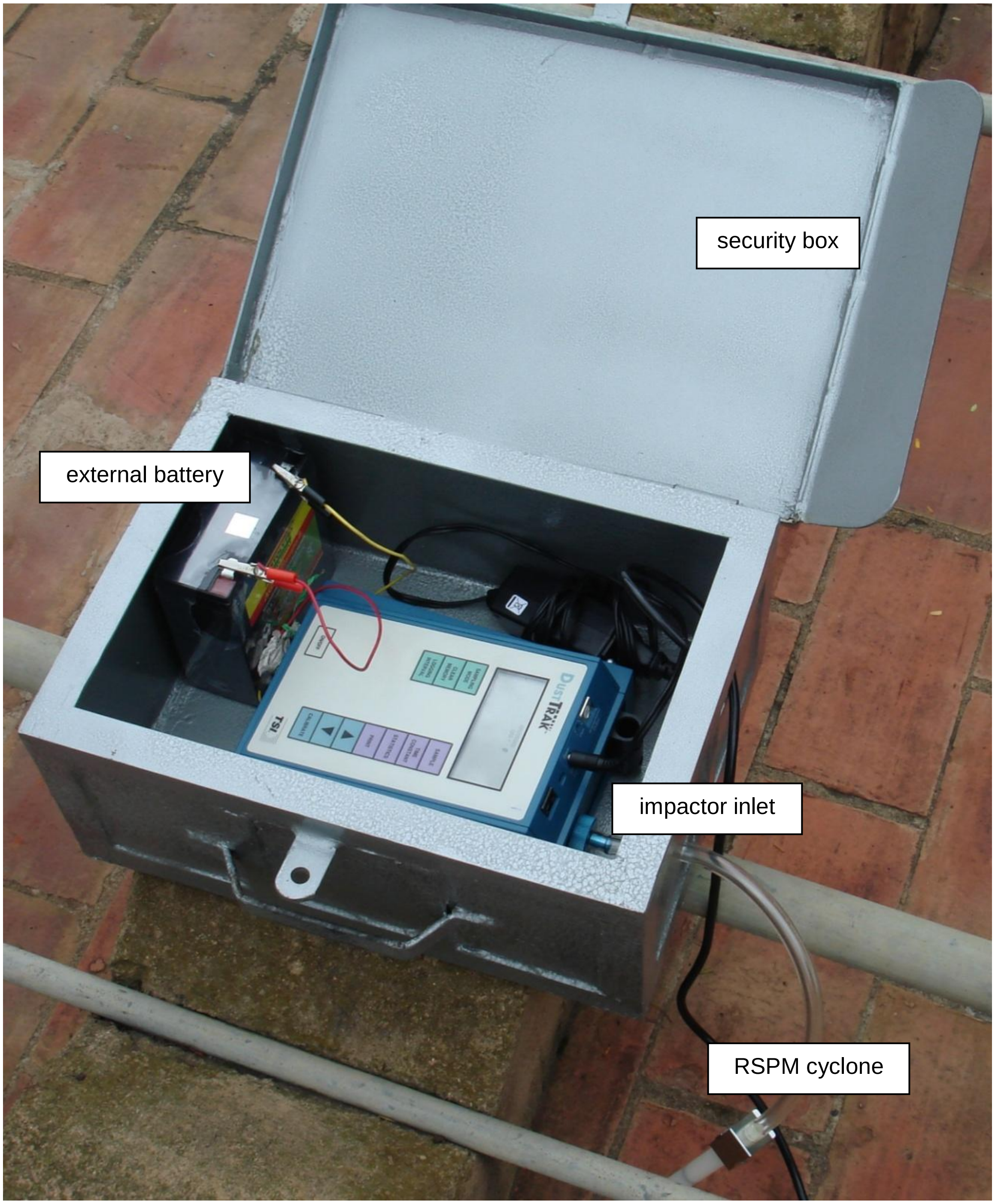

Figure 1 - DustTrak field set-up.

The weather station data logger used was a PWS 1000 TB (Zephyr Instruments, East Granby, CT). The weather station consisted of a rain gauge, anemometer, weather vane, and a multi-input probe that measures temperature and relative humidity (RH). The four elements are attached to a central pole and data is sent wirelessly to a base display every 15 seconds and recorded as 5 minute mean data points.

DustTrak data was imported using TrakPro™ Data Analysis Software v.4.1.1.4 from TSI Inc. and meteorological data was imported with EasyWeather v.2.0 from Fine Offset Electronics Co., Ltd. Analyses were done using Microsoft Office Excel 2007 and MATLAB R2009a.

4.2 Zero Check

TSI, the manufacturer of the DustTrak 8520, recommends performing a zero check each day the DustTrak monitor is used or before running any extended tests. Every time the monitors were inspected and moved to a new location, a zero check was performed by attaching the TSI zero filter on the aerosol sample inlet and the DustTrak monitor in Survey mode with a time-constant of 10 seconds. After waiting 10–60 seconds for it to settle to zero, if the displayed value was outside -0.001 and +0.001 mg m^{-3}, the instrument was re-zeroed.

Each monitor was zero checked 24 times between August 2008 and May 2009 and the mass concentration readings from each zero check are in Figure 2. All but one reading for Monitor 2 on November 18th, 2008, were within the allowed window. Data collected for this period before November 18th on monitor two was not used in this study.

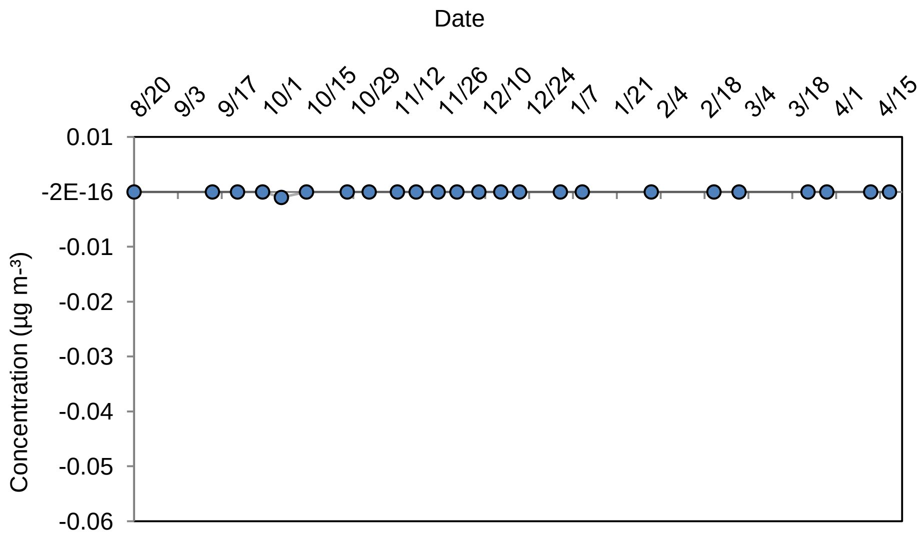

Figure 2a - Zero check for monitor 1 performed upon every installation from August 2009 to May 2009.

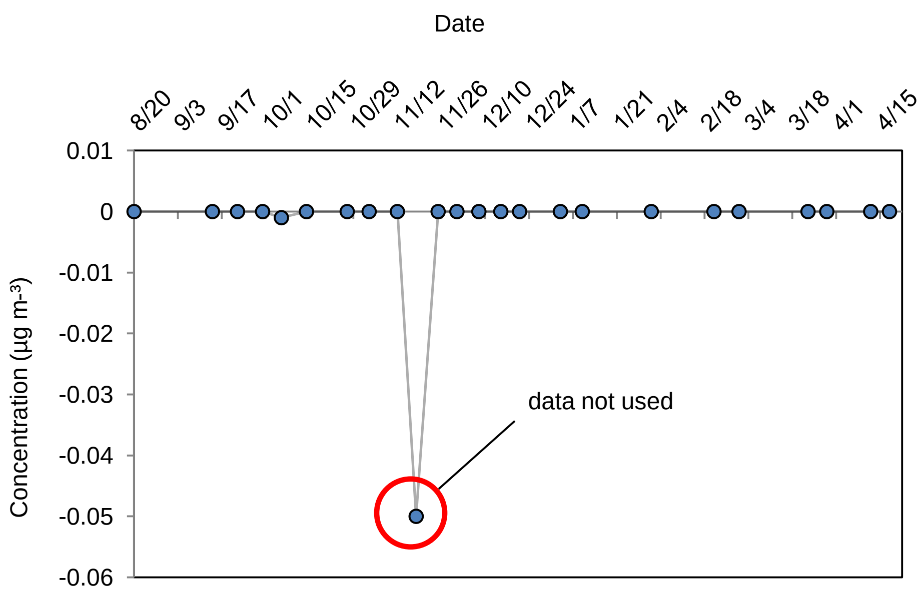

Figure 2b - Zero check for monitor 2 performed upon every installation from August 2009 to May 2009. Data point highlighted from 11/18/2008 was outside zero-check range so data from this monitoring period was not used.

4.3 Field Study Set-up

Measurements were carried out in two neighborhoods in the Koramangala area of Bangalore, India (see Figure 3). The two neighborhoods were identified by study partners at St. John's National Academy of Health Sciences (NAHS) as meeting the criteria of being a low- and middle-income neighborhood, being near a major roadway, and having secure locations for placing equipment. The low-income neighborhood (Rajendra Nagar; population: 6500 [approx]; area: 0.15 km^2 [approx]) is one of the largest slums in Bangalore (Bageshree, 2008). The site is characterized by densely populated 1-5 story housing and no vegetation. The neighborhood is bordered by similarly dense residential on the east and west sides, agricultural wetlands to the north and a major roadway to the south. The middle-income neighborhood (faculty housing complex for St. John's National Academy of Health Sciences (NAHS); population: 300 [approx]; area: 0.05 km^2 [approx]) is characterized by low-density 2-3 story housing with trees (5-10 m tall) and other vegetation. The neighborhood is bordered by a 3 meter privacy wall with medium-density housing to the north, west and south and a major roadway to the east.

In each neighborhood two fixed monitoring sites were identified; near a major roadway (<50m) and not near a major roadway (>250m) (see Figure 3). The nephelometers were placed on the roofs (~10m high) of three-story residential buildings in Rajendra Nagar slum. The residential buildings were inhabited by individuals who were employees or were acquainted with employees of St. John's NAHS. In the middle-income neighborhood, monitors were placed on the roofs (~7m high) of two-story residences inhabited by faculty of St. John's NAHS. Monitoring equipment was placed in a neighborhood for approximately a 2-week monitoring period. One monitor was placed on a roof near the roadway and one not-near the roadway. The weather station was set up at the roof site near the roadway. Data were collected during September 2008 through May 2009. The monitoring equipment was rotated from one neighborhood to the other approximately every two weeks.

Regular transect samples also were conducted, to measure $PM_{2.5}$ as a function of distance from the roadway. Transects involved walking the monitor from the bordering major roadway past both monitoring locations to the back of the neighborhood, recording time at specific landmarks.

After I completed the study design and had gathered and evaluated pilot data, a research assistant, Mr. Arun Balakrishnan, was hired to conduct the measurements during the study period. He had prior experience as an air pollution research assistant at the India Institute of Science, Bangalore.

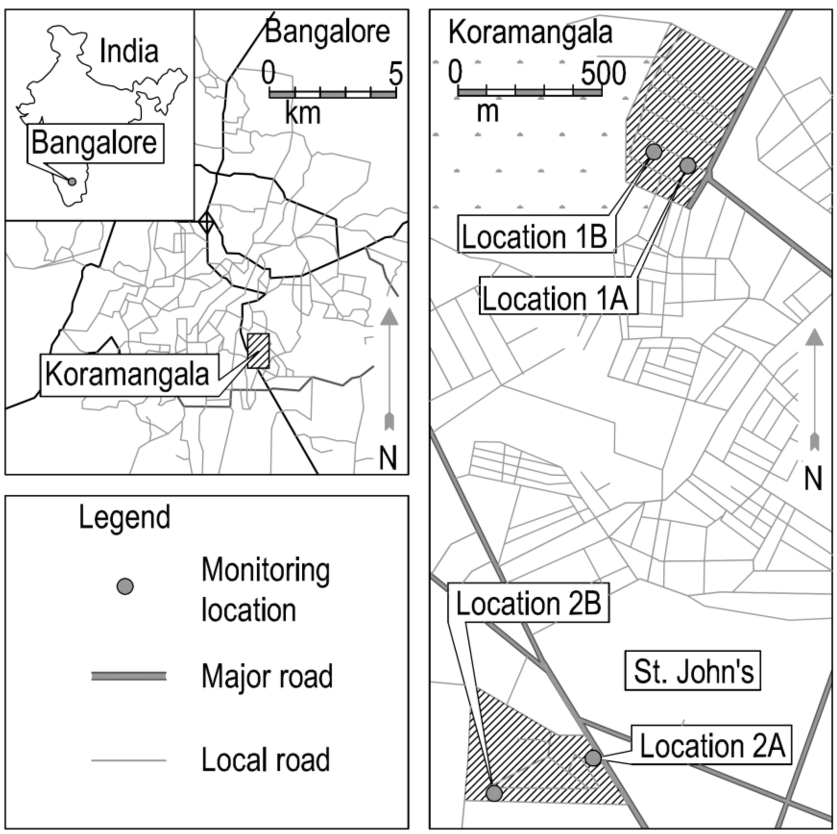

Figure 3 - Study locations: (1A) low-income near roadway, (1B) low-income not-near roadway, (2A) middle-income near roadway, (2B) middle-income not-near roadway.

4.4 Data Coverage

We collected over 7,032 instrument hours of data as 1 minute means from the two monitors at the four monitoring locations during September 2008 through May 2009. There were a total of 2,405 instrument hours of data for which the two monitors and the weather station were operating: 883 hours in the low-income neighborhood and 1,522 hours in the middle-income neighborhood. See Table 1 for data coverage statistics. Only the data paired with its alternate monitoring location was used in the analyses.

Monitor operation was consistent and reliable in the middle-income neighborhood. In the low-income neighborhood, monitoring was more problematic. While participants whose residence housed the monitor agreed to keep the monitors plugged in, frequently the RA found the instruments unplugged and therefore not operating. Though the batteries provided some back-up, much of the monitoring time in the low-income neighborhood didn't have usable data. Starting in January 2009, participants were reimbursed a small sum for their electricity, and monitor operation rates increased.

In January 2009, one of the DustTrak monitors experienced significant problems and was unable to log data. Several diagnostic procedures were unsuccessfully performed. In March 2009, the monitor was rebooted and the monitor once again was able to log data. After a zero-check and side-by-side comparison was performed, the monitor was returned to the monitoring rotation. Thereafter, actual time spent in the low-income neighborhood was doubled relative to time spent in the middle-income neighborhood, with the goal of coming closer to equilibrating the instrument-hours of data successfully gathered in the two neighborhoods.

Table 1 – Data Coverage[1]

	Days	Hours	Minutes
Total	293	7,032	421,920
Dual Coverage at Either	139 (47%)	2,405 (34%)	144,317
Dual Coverage at Loc 1	53 (18%)	883 (13%)	52,979
Dual Coverage at Loc 2	86 (29%)	1,522 (22%)	91,338
Equipment Downtime	68 (23%)	1,632 (23%)	97,920
Electricity Failure	86 (29%)	2,995 (42%)	179,683

[1]Values in parentheses display percentage of coverage of total study time. The three columns (days, hours, minutes) give the same information but in different units; the values in each column are not intended to be summed.

Paired nephelometer data was aligned with its respective meteorological data. Raw data outside the nephelometer operating limit of 95% relative humidity was eliminated (see section 5.2).

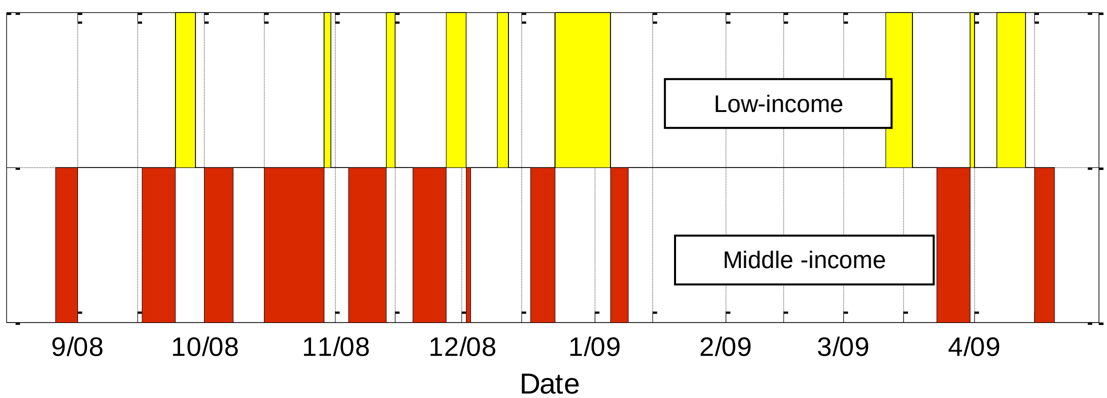

Figure 4 - Data coverage for both neighborhoods during the study period. Shaded areas represent times when there was paired monitoring data (both nephelometers, plus the meteorological data).

4.5 Data Distribution

Histograms for the data were produced from each of the sites (see Figures 5a-5d). All four histograms had moderate peaks between 30 and 60 µg m^{-3}. All four histograms also had long 'tails' representing a small number of significantly higher mass concentrations and symptomatic of log-normal distributions. When histograms of log mass concentrations were plotted, the results more closely mirrored a normal distribution.

When the data and the log of the data were plotted as a standard normal cumulative distribution function (Z-score), the results (see Figure 6a-6d) again suggest a log-normal distribution.

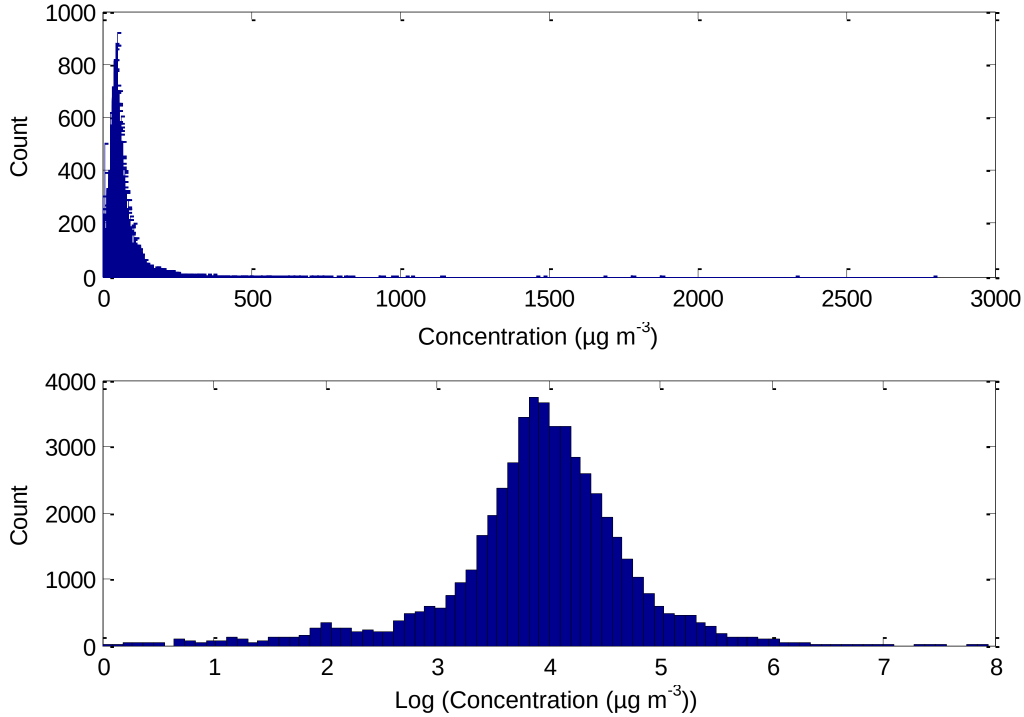

FIGURE 5a – Concentration histograms from low-income neighborhood, near roadway.

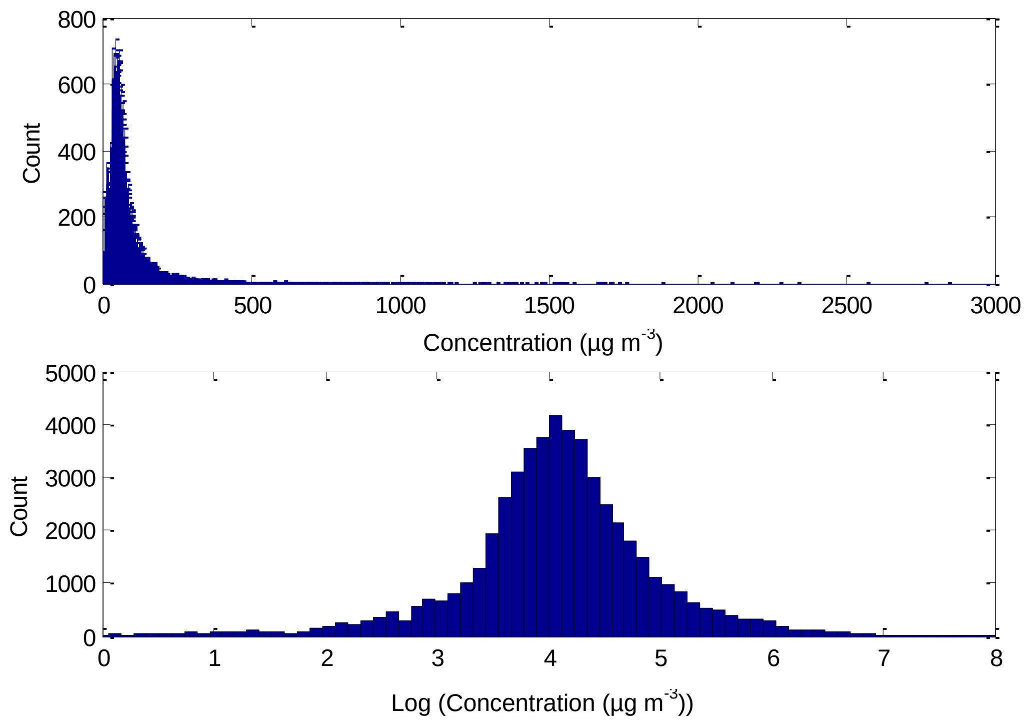

FIGURE 5b – Concentration histograms from low-income neighborhood, not-near roadway.

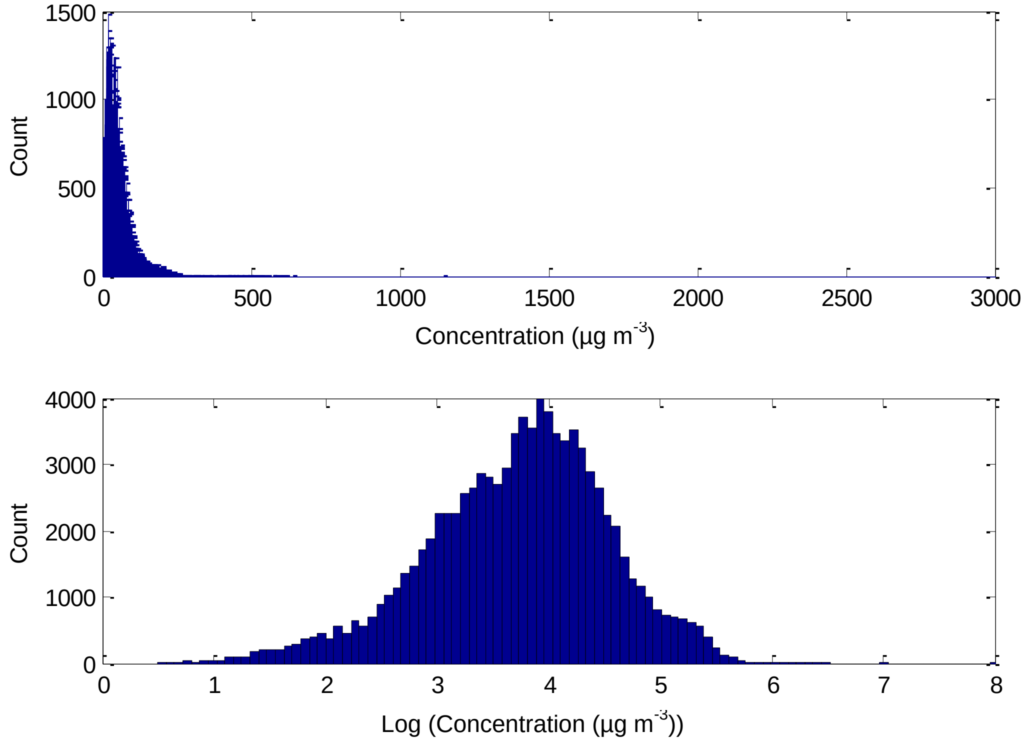

FIGURE 5c – Concentration histograms from middle-income neighborhood, near roadway.

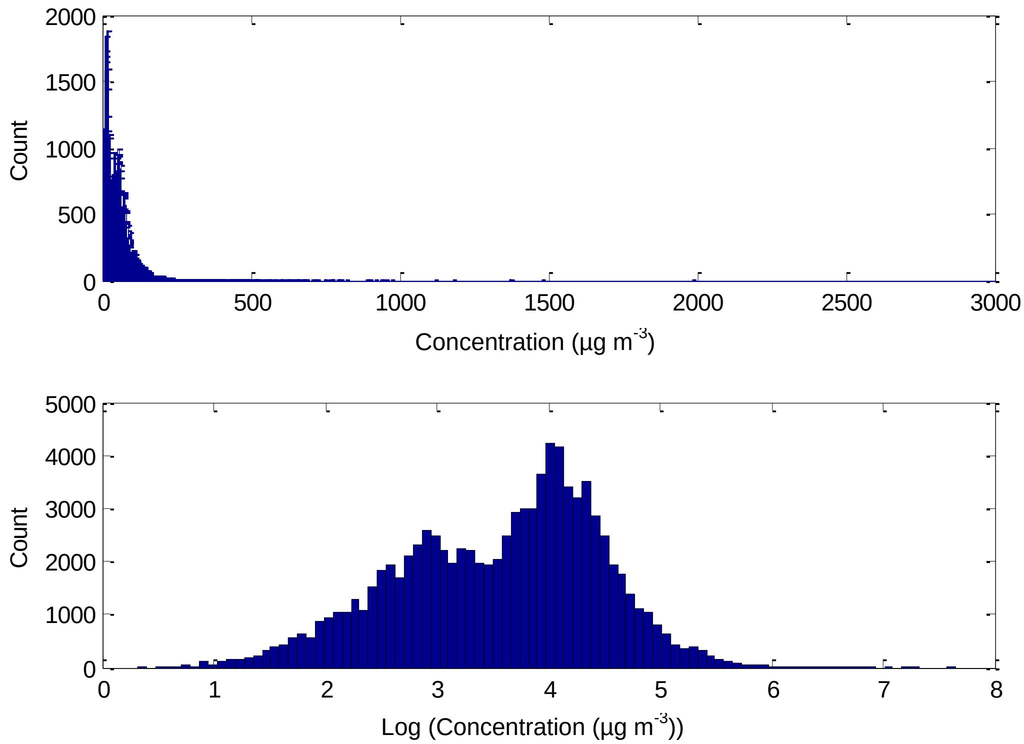

FIGURE 5d – Concentration histograms from middle-income neighborhood, not-near roadway.

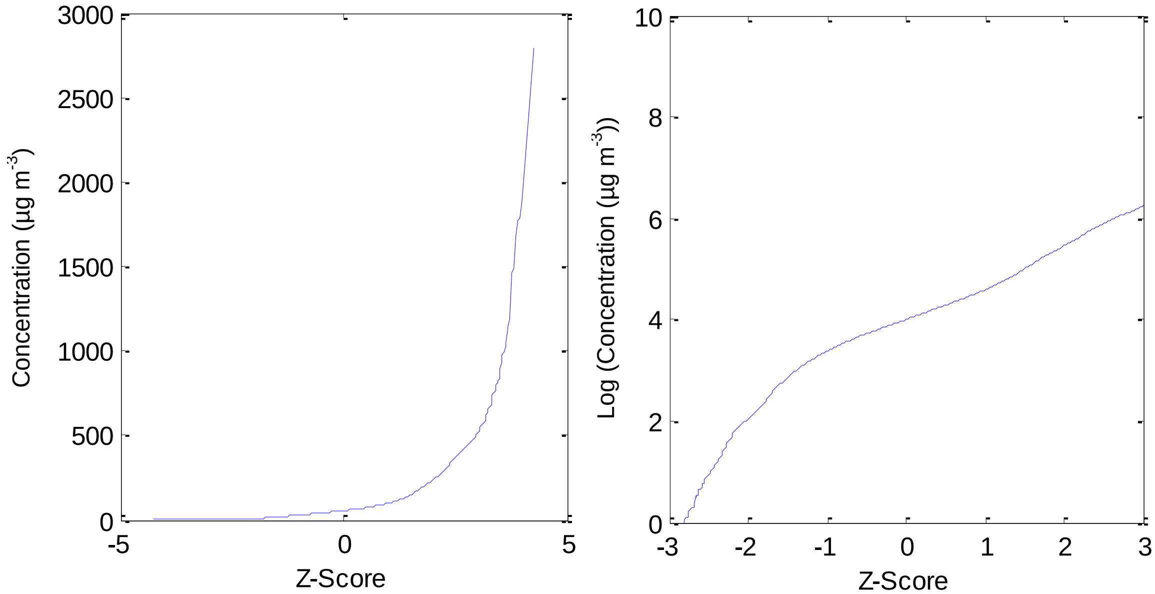

FIGURE 6a – Normal and log-normal normality tests from low-income neighborhood, near roadway.

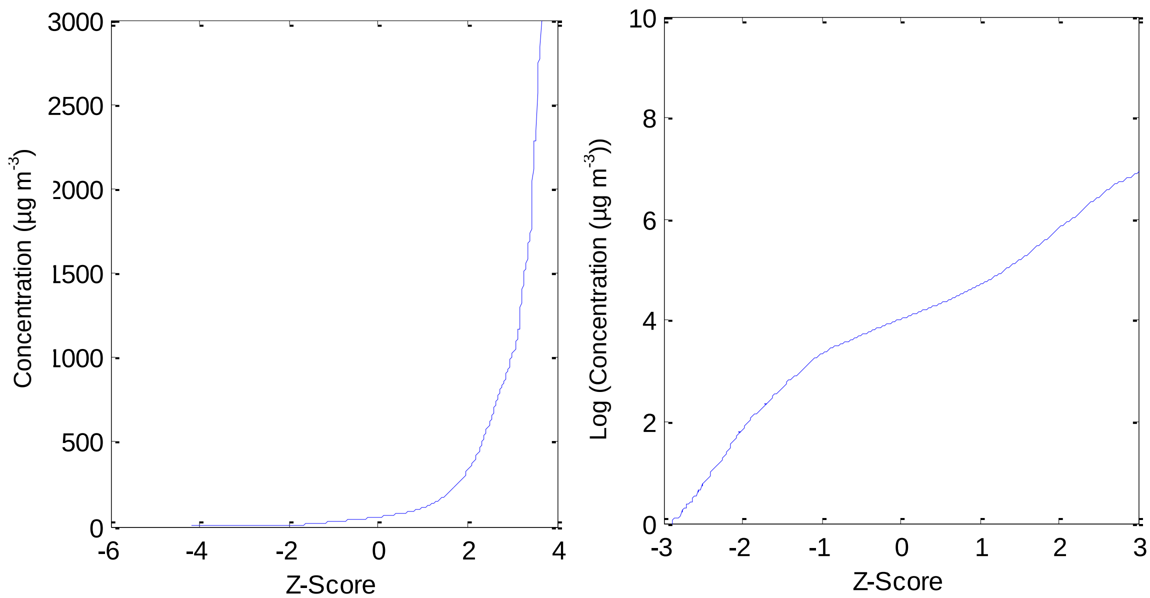

FIGURE 6b – Normal and log-normal normality test from low-income neighborhood, not-near roadway.

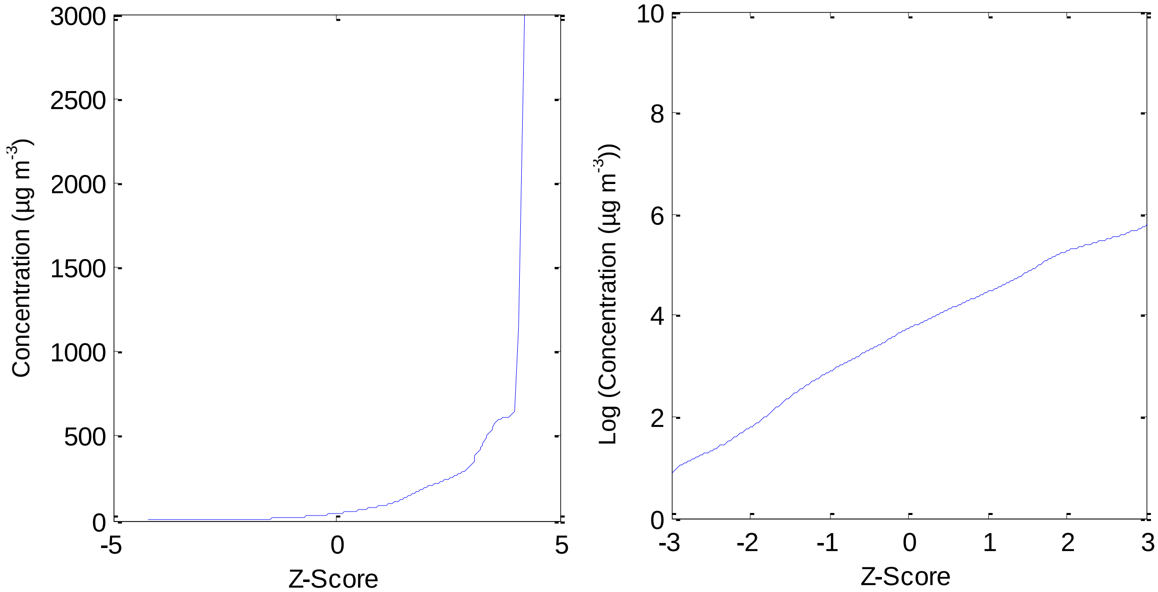

FIGURE 6c – Normal and log-normal normality test from middle-income neighborhood, near roadway.

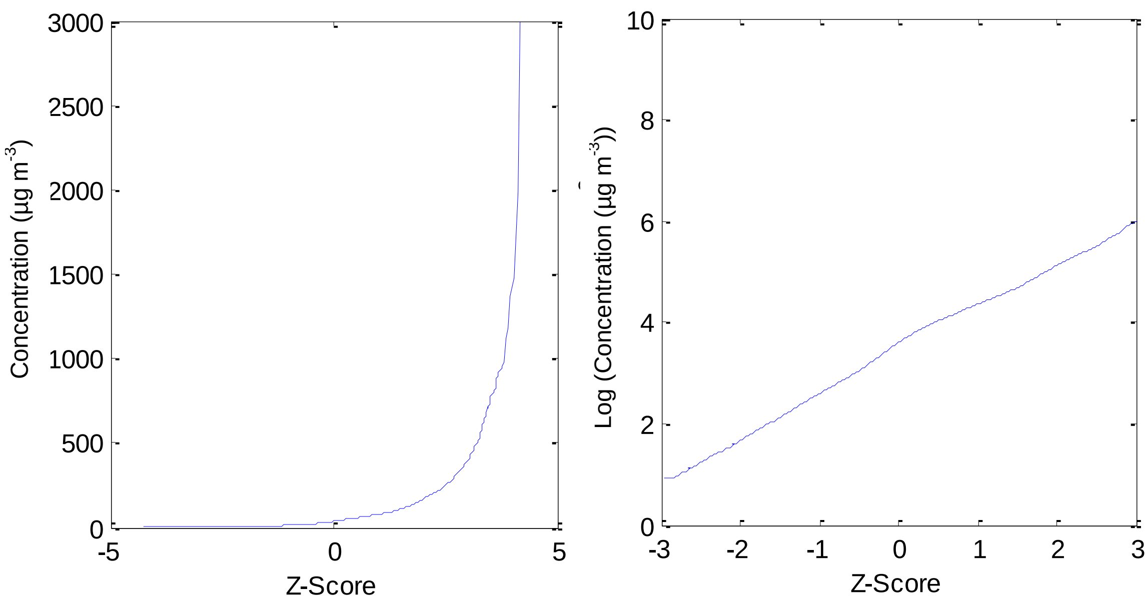

FIGURE 6d – Normal and log-normal normality test from middle-income neighborhood, not-near roadway.

5.0 Results/Discussion

5.1 Weather

The weather data analyzed were wind speed/direction and relative humidity (RH) (See Section 5.2). Wind data was analyzed and graphically displayed as a wind rose in Figure 7 for the entire monitoring period and in Figure 8 for each distinct season (monsoon: June-September, post-monsoon: October-May). Predominant wind direction was from west to east during the monsoon and the reverse (from east to west) post-monsoon. This weather pattern from our data is consistent with documented seasonal weather patterns of Bangalore (Burroughs, 1999).

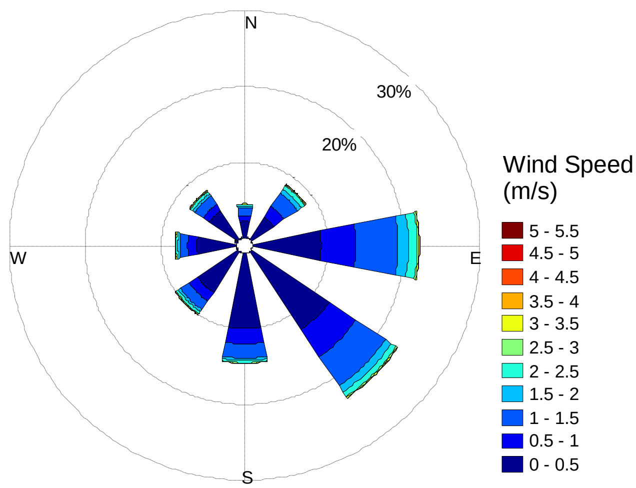

FIGURE 7 - Wind rose showing the wind intensity and direction for the monitoring period (August-May).

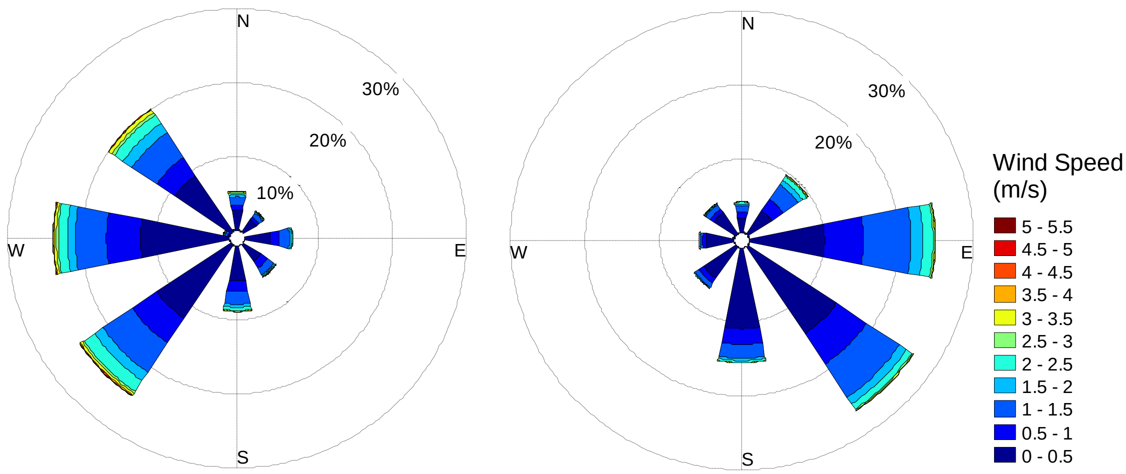

FIGURE 8(a&b) - Wind roses showing the wind intensity and direction for the monsoon season (June-September) in 8a (right) and post-monsoon (October-May) in 8b (left).

Wind intensity distribution typically follows a Weibull Distribution, shown in Figure 9 (DWPA, 2009). The wind intensity distributions for the two seasons are shown in Figure 10. However the plots do not show the initial increase in count from 0 m/s, which suggests that the first rise of the histogram isn't captured by the resolution and limit of detection of our weather station. The distributions also suggest that wind speeds are higher during monsoon season than during post-monsoon season.

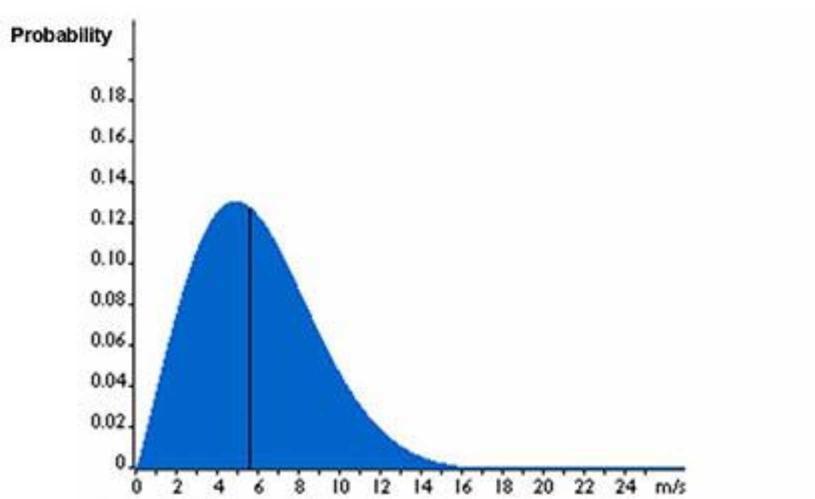

FIGURE 9 – Typical Weibull distribution used for wind intensity (DWPA, 2009).

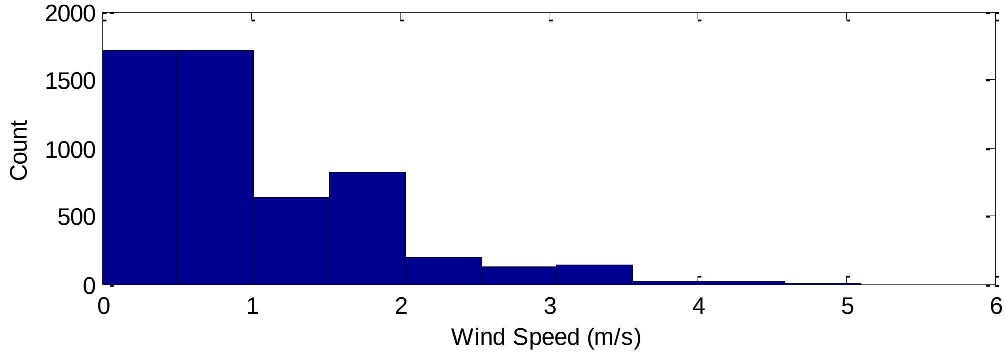

FIGURE 10a – Wind intensity distribution during monsoon season (June-September).

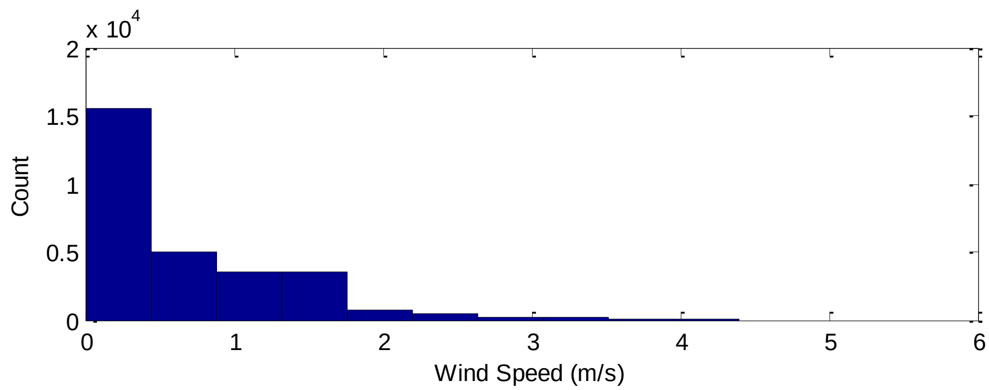

FIGURE 10b – Wind intensity distribution during post-monsoon season (October-May).

Wind data were separated into five wind conditions: (1) toward: wind consistently blowing from the road toward the monitors (within 45^o and for at least twice the distance from the roadway to the near roadway monitor); (2) away: wind consistently blowing from the monitors toward the roadway (within 45^o and for at least twice the distance from the roadway to the near roadway monitor); (3) perpendicular: wind direction parallel to roadway (i.e., neither toward nor away from the monitors and at least twice the distance from the roadway to the near roadway monitor); (4) variable: wind direction is not consistent; and (5) calm: wind speed is less than 0.3 m/s.

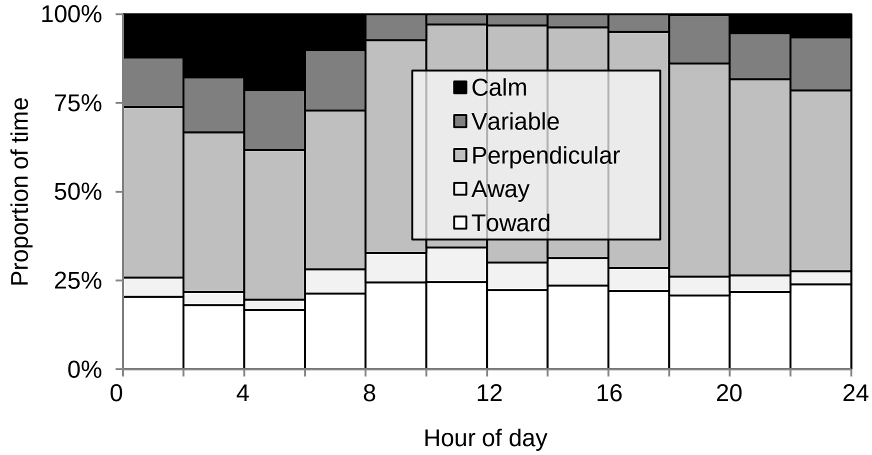

FIGURE 11a – Wind classification by time-of-day for low-income neighborhood.

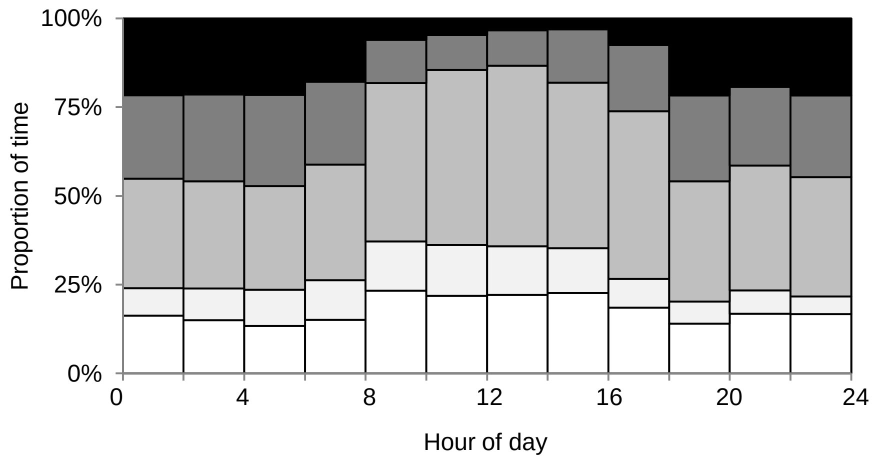

FIGURE 11b – Wind classification by time-of-day for middle-income neighborhood.

As shown in Figures 11a & 11b, the dominant wind condition for both neighborhoods is perpendicular. Perpendicular tends to be the most common during the middle of the day. Calm conditions occur mostly during late evenings and early mornings. The Away condition is least common which is likely because the majority of measurements occurred during post-monsoon season when the predominant wind condition is east to west which is the Toward condition for both locations.

5.2 Relative Humidity

The measured relative humidity exhibits a typical diurnal pattern at both locations (Figure 12) with a mid-afternoon trough consistent with increased afternoon temperatures. The low-income neighborhood had lower RH than the middle-income neighborhood throughout the day, likely the result of the dense vegetation in the middle-income neighborhood (Zhang, 1986).

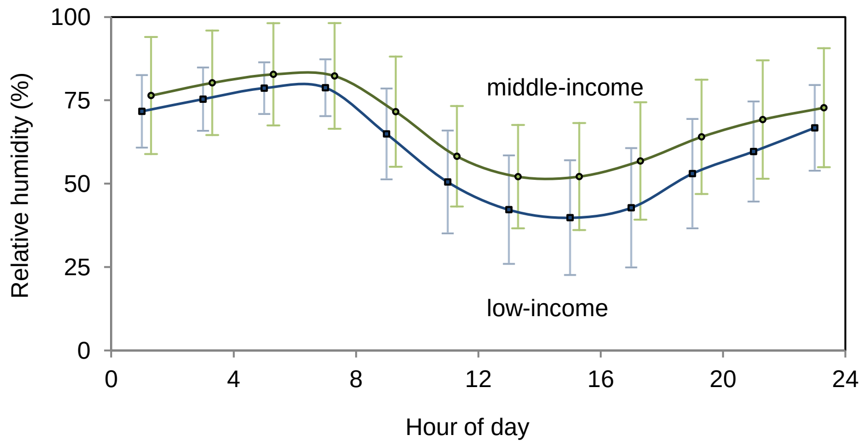

FIGURE 12 – Mean relative humidity by location and by time-of-day. Error bars indicate 1 standard deviation.

Measured RH also exhibited a seasonal pattern as shown in Figure 13, with a higher RH during the monsoon season (June-September) and declining to a low prior to the start of the next monsoon season. From Figure 13 we are also able to see the difference in neighborhood RH; RH tended to be lower when measurements were taken in the low-income neighborhood (top, yellow). The effect of RH is different for each neighborhood because a higher proportion of the low-income neighborhood data was collected in the post-monsoon season compared to the middle-income neighborhood. This observation, combined with known RH effects of nephelometers (described next), supports the importance of correcting for RH in this study.

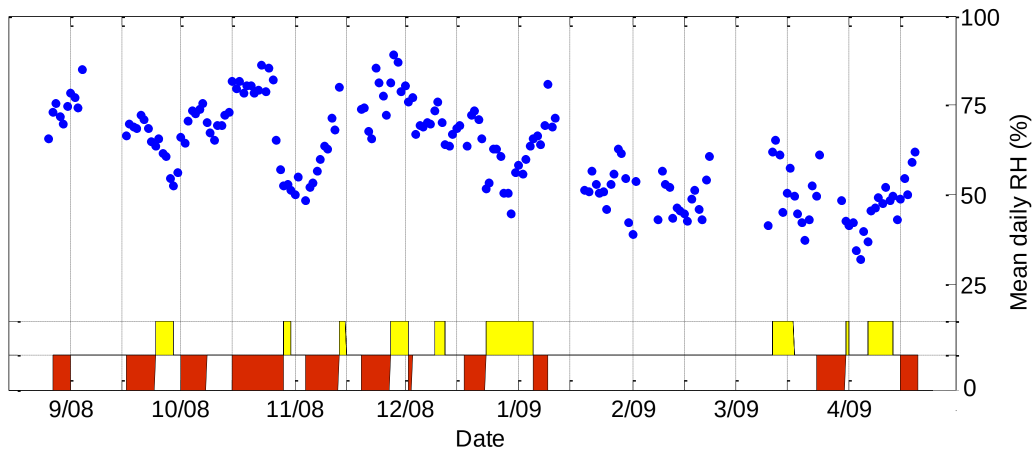

FIGURE 13 – Mean daily relative humidity with data coverage for low-income (top, yellow) and middle-income (bottom, red) neighborhoods.

Mass measurements made by a light-scattering laser photometer, such as a DustTrak, have been shown to be particularly vulnerable to error at high RH (Day, Malm, & Kreidenweis, 2000; Laulainen, 1993; Sioutas, Kim, Chang, Terrell, & Gong Jr., 2000). A particle that experiences hygroscopic growth resulting from an increase in RH will not only scatter light at with a different coefficient (Laulainen, 1993), but the water volume accumulated can account for more than half the aerosol mass at an RH greater than 80% (McMurry, 2000), an RH not uncommon in Bangalore. Of particular concern are particulates with a large amount of hydrophilic sulfate, as the particle scattering coefficient has been shown to correlate strongly with sulfate concentrations (Laulainen 1993).

To evaluate the effect of censoring the data based on an upper limit to the DustTrak's RH range, a sensitivity analysis was conducted. The geometric mean was compared when different upper limits to the RH were applied (Figure 14). As shown in Figure 14, the geometric mean saw only minor changes when data with an RH above 90% were censored.

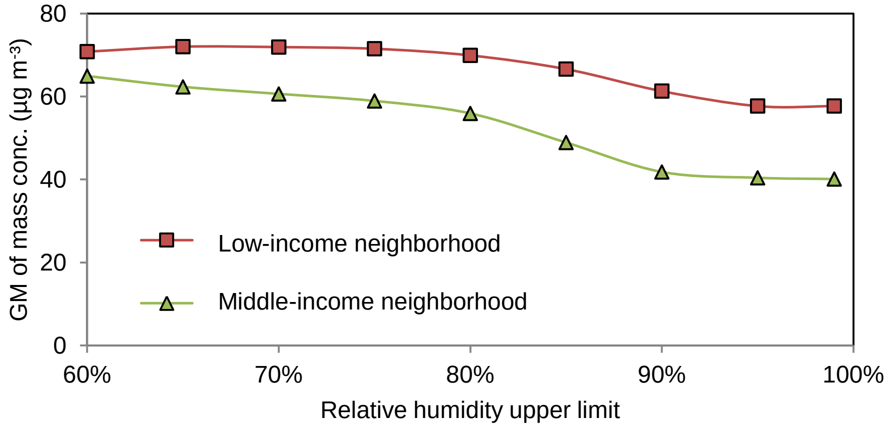

FIGURE 14 – Changes in calculated geometric mean as data above a specific relative humidity were censored.

Data at an RH above 90% and 95% only made up a small fraction of the total data (Figure 15). Because of this sensitivity analysis and the stated DustTrak RH range of 0-95%, all data occurring during times with a RH greater than 95% were omitted (<0.1% of the paired data)

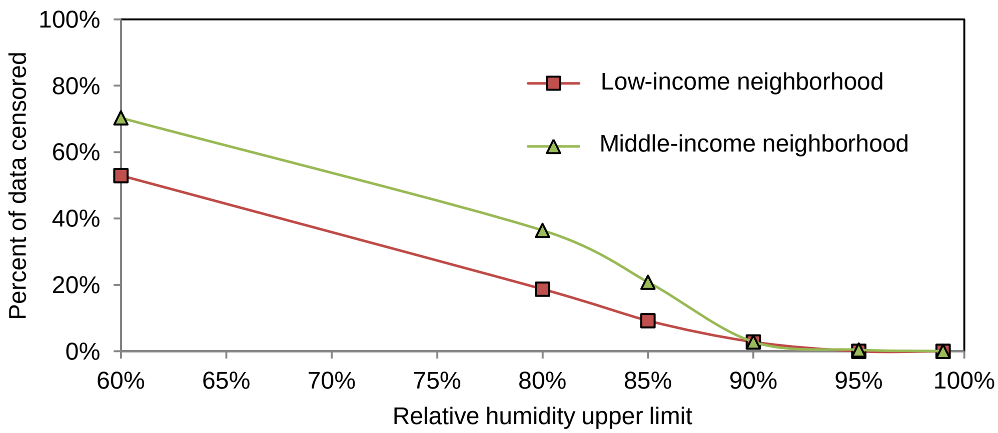

FIGURE 15 – Percent of data censored as data above a specific relative humidity is censored.

RH within the operating limit must still be accounted for since the water vapor absorbed by particulate matter changes the mass, density and optical properties and scattering coefficients of the particulate matter. Laulainen (1993) evaluated and modeled the effect of RH on light scattering properties of an aerosol. Sioutas et al. (2000) similarly showed that a nephelometer (DataRAM, Mie Inc.) overestimates particle concentrations at RH levels above 60%. I applied the following correction factor (CF) developed by Laulainen (1993):

$$\mathrm{CF} = 1 + 0.25\,\frac{\mathrm{RH}^2}{1-\mathrm{RH}} \qquad (1)$$

This correction has been shown to be a good fit in Los Angeles, California (Chakrabarti, Fine, Delfino, & Sioutas, 2004), Minneapolis, Minnesota (Ramachandran, Adgate, Pratt, & Sexton, 2003), southern Italy (Donateo, Contini, & Belosi, 2006) and the Great Smokey Mountain National Park (Day, Malm, & Kreidenweis, 2000) despite potential differences in composition of particles measured at sites. Chemical composition affects not only the hygroscopic growth of a particle but also the volatilization and chemical reactions that may take place on an exposed filter of a standard gravimetric reference method thereby influencing the response of a light-scattering correction factor.

Times of the day that typically experienced a lower RH, such as mid-afternoon, had correction factors near 1, while times of higher RH, such as early morning, saw correction factors as high as 2 which would substantially change mass concentrations during the morning diurnal peak. The RH correction factor varies by time of day, averaging 1.78 during 4:00-8:00 am and 1.09 during noon-6:00 pm (Figure 16); the overall mean is 1.35. The potential importance of using real-time RH to correct real-time nephelometer data is illustrated in Figure 16. At times-of-day when RH is approximately equal to the daily mean RH (e.g. 14:00 in Figure 13), the real-time approach and the time-invariant (i.e., 24-hour mean) approach yield similar results. At other times, however, those two approaches diverge. For example, at 8:00 in Figure 17, concentration estimates are 68% higher for the time-invariant approach than for the real-time approach; here, use of time-invariant (24-hour-mean) corrections would yield dramatic over-estimation of the size of morning concentration peaks.

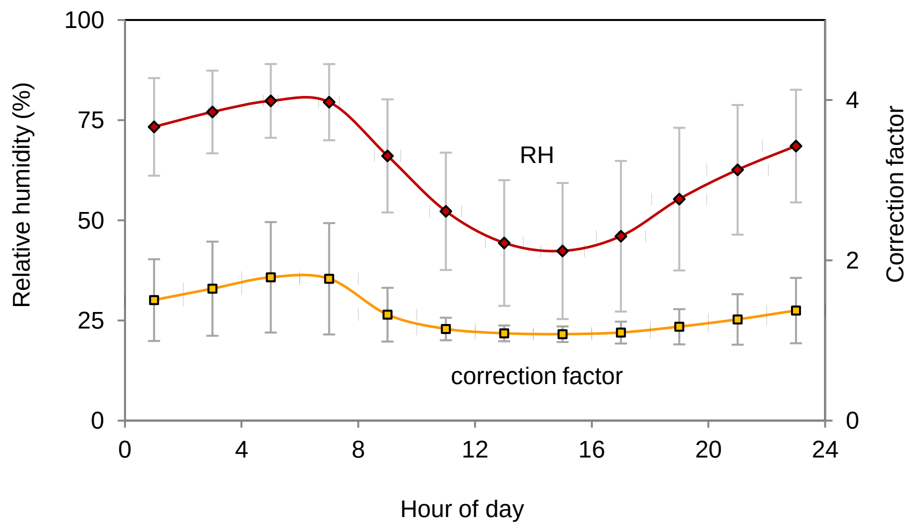

FIGURE 16 – Mean relative humidity and nephelometer correction factor by time-of-day. Error bars indicate 1 standard deviation.

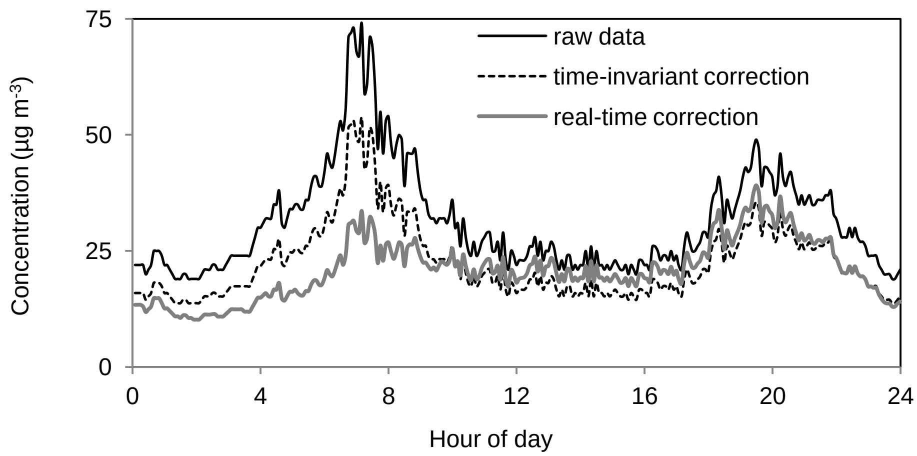

FIGURE 17 – Comparison of relative humidity correction techniques for real-time $PM_{2.5}$ concentration. The black line is nephelometer output (uncorrected). The grey line uses real-time correction and reflects our best estimate for the true concentration. The dashed line reflects a single correction factor based on the daily mean RH. Results from the time-invariant correction over-estimated morning peak concentrations by ~68%. Data are for Sept. 18th at the middle-income near roadway location.

Besides the effect of RH, light scattering measurements are subject to error resulting from a difference in the aerosol used for calibration and for field study. The aerosol properties such as shape, size, density and refractive index, likely differ to create an error when measured with a nephelometer. To correct for this error, a gravimetric mass-based calibration relationship for the RH-corrected DustTrak measurements was developed using a total of 32 co-located $PM_{2.5}$ filter samples in multiple settings, including an ambient residential site and in auto-rickshaws in Delhi, India between March and June, 2010. These measurements were carried out by Josh Apte (2011). Apte used an SKC PEM $PM_{2.5}$ impactor (MSP Corporation, Shoreview, MN) and a SKC Leland Legacy sampling pump operating at 10 L min^{-1} (SKC, Inc, Eighty Four, PA) to achieve a 2.5 µm aerodynamic diameter size cut on the sample aerosol before deposition on a pre-weighed 37 mm Teflon filter held by a rigid, porous backing plate. The median total volume of air sampled was 1.6 m^3 (10% trimmed range: 0.86 – 4.3 m^3). Filter samples were conditioned for 24-72 hours before each weighing using a controlled chamber equilibrated to between 35-45% RH and 22-25 ºC. Each filter was discharged of static electricity using a Po source and weighed once before and after sampling on a 0.1 µg precision Sartorius SE-2 Microbalance (Sartorius AG, Göttingen, Germany) at Lawrence Berkeley National Laboratory (LBNL) in Berkeley, USA. A total of 18 blank filters were retained for quality control, of which 3 were stored at LBNL, 11 were taken to India and returned unhandled, and 4 handling blanks were loaded and unloaded into the filter apparatus at the rooftop field site. A small number of filters were rejected during the second weighing session due to visible damage, such as separation of the filter medium from its support ring. All blank filters recorded a loss in weight between the first and second weighing sessions (January 2010 and June 2010, respectively). To correct for this change in weight, Apte added the mean weight change for the handling blanks (8.5 µg) to each sample weight before calculating final gravimetric $PM_{2.5}$ concentrations. However, there was substantial variation in weight change among the blank filters (standard deviation for all 18 blanks = 5.7 µg).

In order to develop a gravimetric calibration curve for the DustTrak measurements, Apte calculated the time average of the RH-corrected DustTrak $PM_{2.5}$ concentration measurements for the duration of each filter sampling session. Exploratory data analysis by Apte revealed that simple linear regressions performed poorly at predicting the relationship between DustTrak and gravimetric $PM_{2.5}$ measurements, especially at relatively low ambient concentrations for Delhi (< 75 µg m^{-3}). Apte found that a power-law regression relationship satisfactorily fit the observed data while also accommodating the zero calibration point:

$$\mathrm{G} = \mathrm{a}(\mathrm{D})^{\mathrm{b}} \tag{2}$$

Here, G is the predicted gravimetric $PM_{2.5}$ concentration (units: µg m^{-3}), D is the DustTrak $PM_{2.5}$ concentration, and a and b are empirically determined fitting parameters via linear regression of the log-transformed data points. In order to account for the non-linear behavior of the power-law relationship, Apte used an iterative fitting algorithm, as follows:

1. Compute unadjusted time-integrated mean concentration for each DustTrak calibration session by simple average of the RH-corrected DustTrak time series.

2. Calculate power-law regression coefficients a and b based on unadjusted time integrated mean DustTrak concentrations.

3. Apply power-law correction relationship with parameter values a and b to the time-resolved DustTrak time series for each calibration session.

4. Re-compute time-integrated mean of corrected, time-resolved DustTrak concentrations for each calibration session, as calculated in step #3.

5. Re-calculate power-law regression coefficients a and b based on corrected DustTrak readings.

6. Repeat steps 3-5 until coefficients a and b converge to stable values. For this dataset, a total of four iterations was required for a and b to converge.

This procedure resulted in the following calibration relationship:

$$G = 3.91*(D)^{0.706},\ r^2 = 0.79 \qquad (3)$$

Notably, the estimated regression coefficients from the iterative fitting algorithm differ only slightly from those estimated by the first step of the regression (step #2 above). The iterative approach used here is perhaps more rigorous, but does not appear to make a large overall difference in the resulting regression relationship.

5.3 $PM_{2.5}$ Measurements

Paired and RH corrected data were binned by the minute of the day in which it was recorded. The median from each minute (Figure 18a) illustrates the typical daily patterns of $PM_{2.5}$ at each monitoring locations. Fifteen-minute means of the data described above are displayed in Figure 18b to attenuate the varying spikes of one minute measurements.

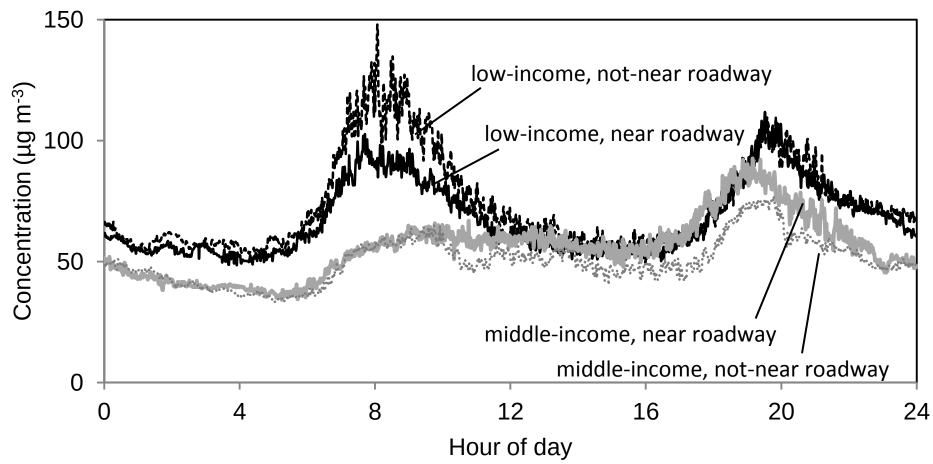

FIGURE 18a – Median $PM_{2.5}$ concentration by time of day for the four locations.

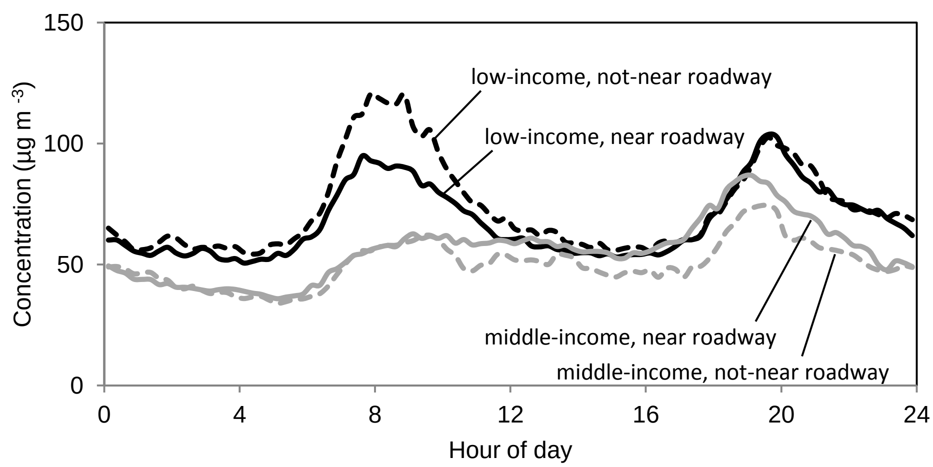

FIGURE 18b – Fifteen-minute means of the median $PM_{2.5}$ concentration by time of day for the four locations.

Concentrations are ~33% higher in the low-income than in the middle-income neighborhood and for the middle-income neighborhood are ~11% higher near roadway than not-near roadway. Concentrations are ~36% and ~43% higher during the morning (7:00-9:00) and evening (18:00-21:00) peaks, respectively, than during other times. The two neighborhoods are similar in land area, but because of the ~20× difference in population density, many more people breathe the more-polluted air (low-income neighborhood) than the comparatively “cleaner” air (middle-income neighborhood).

Two aspects of Figure 18 are especially noteworthy. First, the degree of spatial variability changes strongly by time of day. During afternoons (12:00-16:00), concentrations are similar among the four locations (spatial coefficient of variability [CV]: 12%); during morning peaks (7:00-9:00), the four locations are most variable (spatial CV: 51%). At night (midnight-6:00 am), concentrations differ by ~60% between neighborhoods, but exhibit near-zero within-neighborhood difference (CV: ~5%). This finding, which is consistent with a recent report from Southern California that found the spatial impacts of roadway PM varies by time-of-day (Hu et al., 2009), has important implications for exposure assessment. For example, it highlights the need to include diurnal variability explicitly in land use regression (LUR), especially LUR derived from mobile monitoring (Larson et al., 2007; Van Atten et al., 2005), because spatial patterns change by time-of-day. In addition, it highlights that incorporating mobility into exposure estimates is likely to yield smaller changes in exposure estimate during afternoons than during other times of day. The second noteworthy feature is the $PM_{2.5}$ concentration not-near roadway is greater than the concentration near roadway for the low-income neighborhood. This result is likely because of local sources, a hypothesis supported by diurnal trends mentioned above and by the spatial contributions analysis below. The effect of local emission sources was similarly seen in low-income neighborhoods in Accra, Ghana, where biomass fuels are also extensively used (Dionisio et al., 2010).

A two-tailed unpaired t-test was performed on all data locations with the time-of-day data displayed in Figure 18 to determine the differences at the four locations are statistically significant ($p<0.05$). The p-values are displayed in Table 2.

Table 2 – Unpaired t-test p-values

	Loc 1A	Loc 1B	Loc 2A	Loc 2A
Loc 1A	--	0.0180	5.79E-09	8.40E-19
Loc 1B	--	--	5.29E-13	7.07E-22
Loc 2A	--	--	--	6.53E-4
Loc 2B	--	--	--	--

To display the statistical difference in monitoring location visually, the data from Figure 18 is plotted with the standard error as the shaded regions around each data series in Figure 19. Standard error was calculated from the data that was binned to create each time-of-day series. Again we see the most overlap during afternoon (12:00-16:00), while morning (7:00-9:00) and evening (19:00-23:00) see the most separation, particularly between neighborhoods.

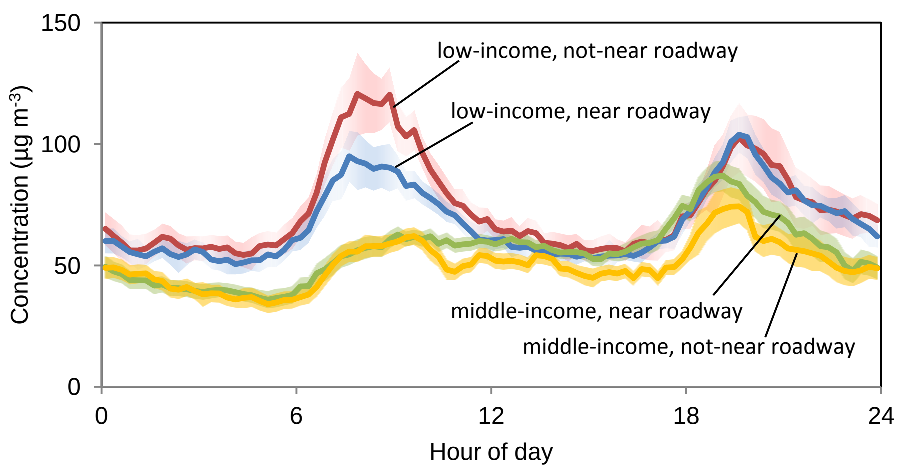

FIGURE 19 – Median $PM_{2.5}$ concentration by time of day for the four locations. Shaded regions show the standard error for each data series.

Median concentrations in the low-income neighborhood (68 and 74 µg m^{-3}, near and not-near the roadway respectively) are higher than in the middle-income neighborhood (56 and 50 µg m^{-3}, near and not-near the roadway), while all of these concentrations exceed long-term US EPA and WHO standards (15 and 10 µg m^{-3}, respectively). These daily means are of particular concern especially considering that it has been shown that each 10 µg m^{-3} increase in $PM_{2.5}$ mass concentration is associated with approximately an 8% increase in lung cancer mortality, a 6% increase in cardiopulmonary mortality, and a 4% increase in all-cause mortality (Pope et al., 2002).

5.4 Weekend/Weekday Effect

Analysis was done to evaluate how outdoor ambient concentrations varied by day of the week, most notably, to see if there was a weekend/weekday effect based on different weekly behaviors. The hypothesis is that there may be less commuting traffic thereby reducing or changing the diurnal daily patterns of pollution. Also, the emission sources within the neighborhoods, such as from cooking with solid fuels or burning trash, may increase on weekends, increasing the signal seen from inside the neighborhoods.

Figure 20 displays the mean (20a) and median (20b) $PM_{2.5}$ concentration of the four locations for each day of the week. In the middle-income neighborhood, mean and median concentrations show little variation by day of the week. In the low-income neighborhood, mean concentrations appear to peak mid-week (Wednesday) at the not-near roadway location (1B) and tend to decrease throughout the week in the near roadway (1A) location. The mid-week peak is not apparent for the median concentration values at the not-near roadway location suggesting the location may be subject to more extreme and variable concentrations.

Weekend/weekday plots by time-of-day are shown in Figure 21 for all four monitoring locations. Paired and unpaired t-tests (Table 3a-d) indicate modest weekend/weekday differences. In the middle-income neighborhood (near roadway [2A] and not-near roadway [2B]), mean concentrations are 6%-8% lower on weekends ($p<0.05$). In the low-income near roadway site (1A), concentrations are 10% higher on weekends ($p<0.01$). In the low-income not-near roadway site (1B), concentrations are not statistically significantly different between weekends and weekdays. Unpaired t-tests were also done for each hour of grouped data and significant differences ($p<0.05$) are indicated with and asterisk. From the hour by hour comparison we see the significant difference tend to occur least during midday.

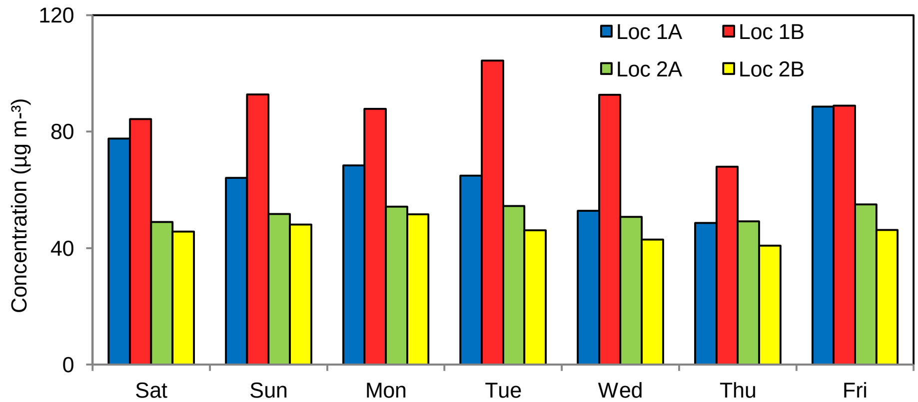

FIGURE 20a – Mean daily concentration for each location by day of the week..

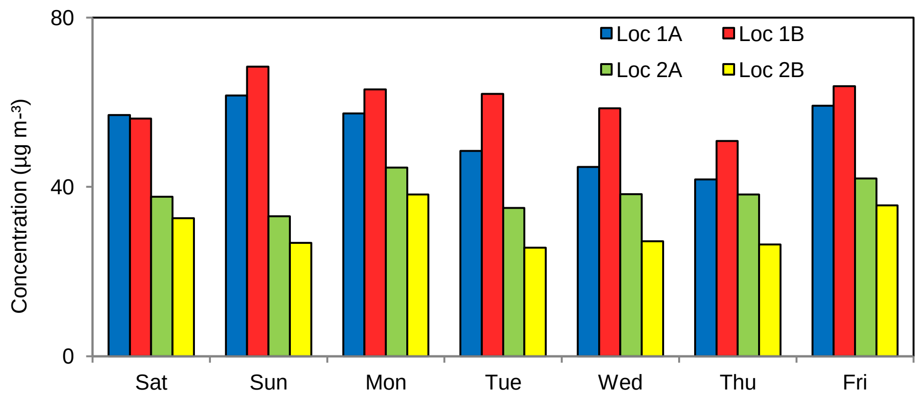

FIGURE 20b – Median daily concentration by day of the week..

Figure 22 shows the comparison for Sunday compared to Monday through Saturday with t-test results in Table 4. Similar results are seen with a bit more variability on Sundays, possibly the result of there being fewer data points. One noteworthy result is the peak seen on Sunday evenings in the middle-income neighborhood, which may be the result regular trash burning that was observed while on-site. Figure 23 shows the daily trends for Saturday/Sunday, Monday/Friday, and Tuesday-Thursday. Between the day groupings in Figure 23, no distinct patterns are seen that aren't exhibited in Figure 21 and 22, such as a larger traffic signal in the Monday/Friday group. Weekend effect for the spatial variability analysis is found in section 5.6.

As a result of the rotation schedule, some days of the week had a higher number of readings than others. To remove any weighting resulting from this, a second analysis was done where daily patterns were determined prior to combining, thereby weighting each day equally. Results are found in Figures 24, 25, 26 and Tables 5 and 6. Figures 24-26 are similar to Figures 21-23, with the difference that in Figures 21-23 all of the data are combined as they exist in the dataset whereas in Figures 24-26 the averages by day are generated prior to days being combined. For example, if the dataset contains more data for Tuesdays than for Wednesdays, then in the weekday average, Tuesday data would be weighted more heavily than Wednesday data in Figure 21; in contrast, the weekday average in Figure 24 will have equal weighting for Tuesday data and Wednesday data. While the equally weighted plots tend to have higher peaks, patterns remain the same.

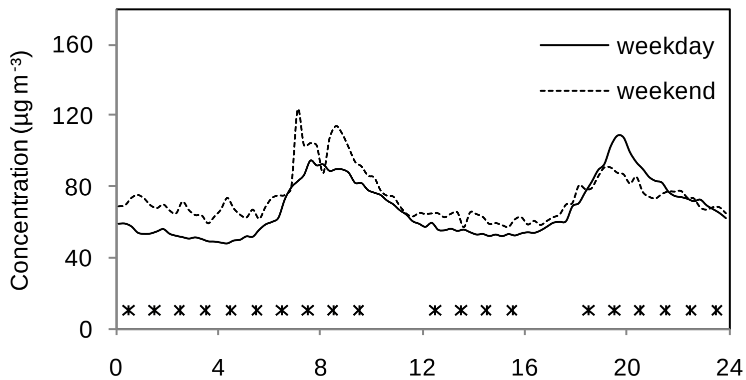

Table 3a. Loc 1A

	Weekday	Weekend
Mean	66.89	73.56
St. Dev.	15.92	13.77

paired t-test p(2-tail) = 1.98E-9
unpaired t-test p(2-tail) = 0.00221

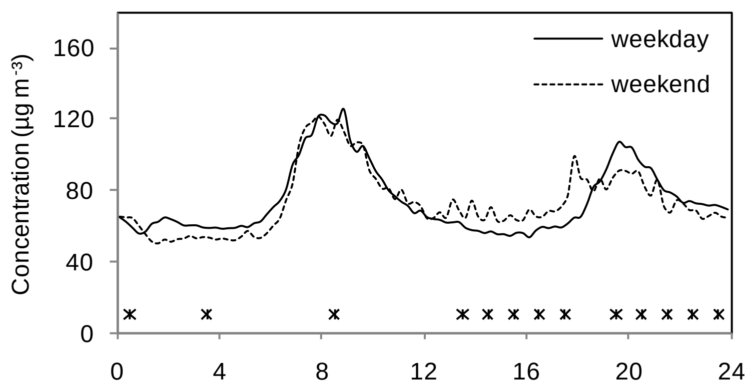

Table 3b. Loc 1B

	Weekday	Weekend
Mean	74.00	73.90
St. Dev.	19.17	18.11

paired t-test p(2-tail) = 0.919
unpaired t-test p(2-tail) = 0.972

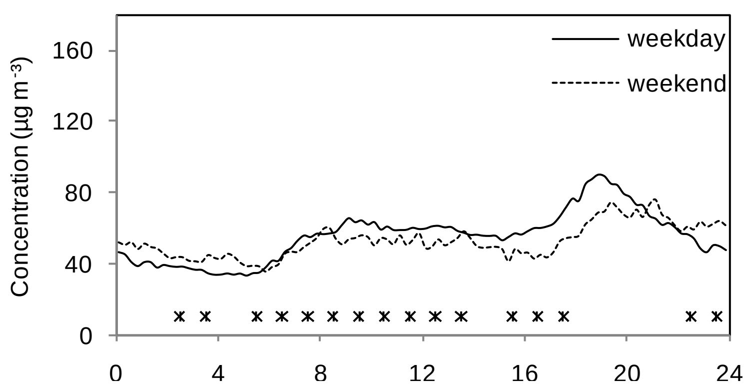

Table 3c. Loc 2A

	Weekday	Weekend
Mean	55.94	52.61
St. Dev.	13.99	9.08

paired t-test p(2-tail) = 0.00113
unpaired t-test p(2-tail) = 0.0519

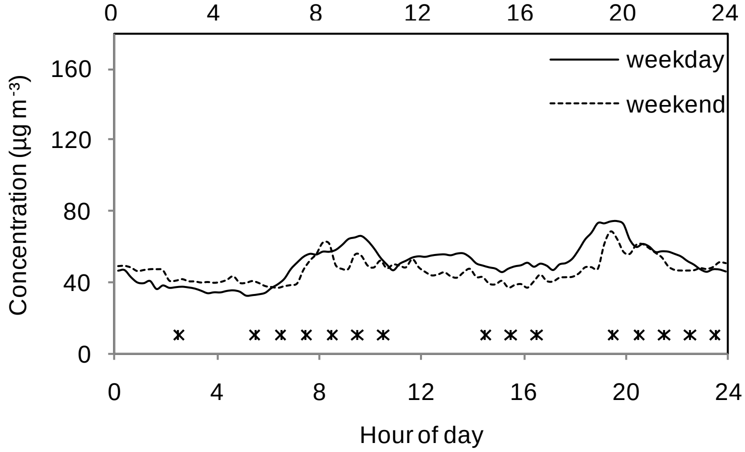

Table 3d. Loc 2B

	Weekday	Weekend
Mean	50.42	46.53
St. Dev.	10.68	6.98

paired t-test p(2-tail) =3.62E-6
unpaired t-test p(2-tail) = 0.00319

FIGURE 21 - Weekend/weekday effect at Locations 1A, 1B, 2A and 2B respectively. Asterisks (*) identify hours with a significant difference in an unpaired t-test (p<0.05).

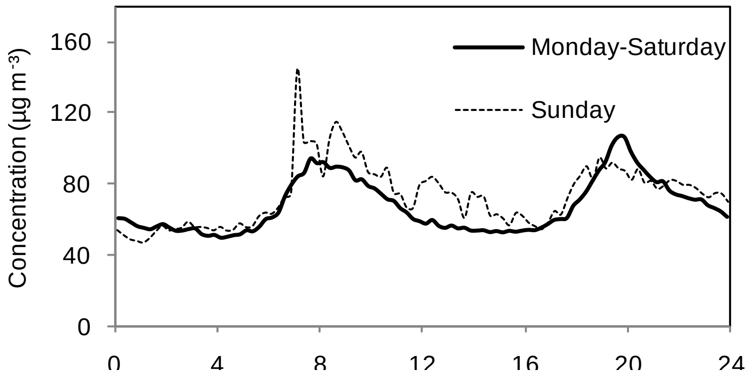

Table 4a. Loc 1A

	Mn-Sat	Sunday
Mean	67.37	73.59
St. Dev.	15.19	17.52

paired t-test p(2-tail) = 2.25E-6
unpaired t-test p(2-tail) = 0.0093

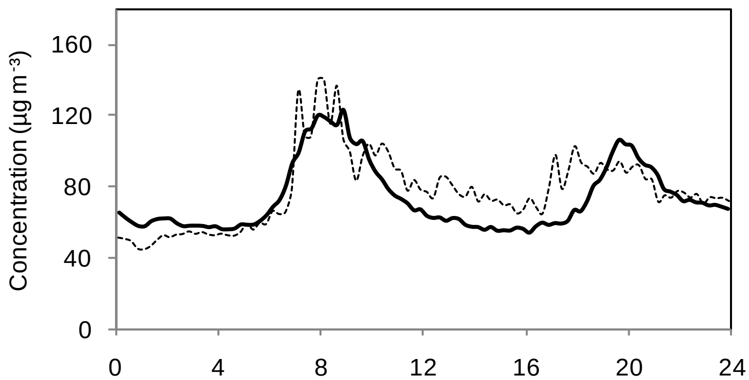

Table 4b. Loc 1B

	Mn-Sat	Sunday
Mean	73.61	77.62
St. Dev.	19.00	21.06

paired t-test p(2-tail) = 0.00476
unpaired t-test p(2-tail) = 0.1678

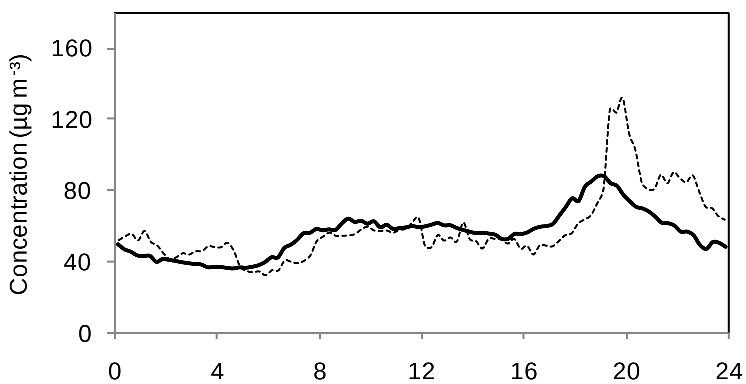

Table 4c. Loc 2A

	Mn-Sat	Sunday
Mean	55.60	58.70
St. Dev.	12.74	19.68

paired t-test p(2-tail) = 0.0500
unpaired t-test p(2-tail) = 0.1985

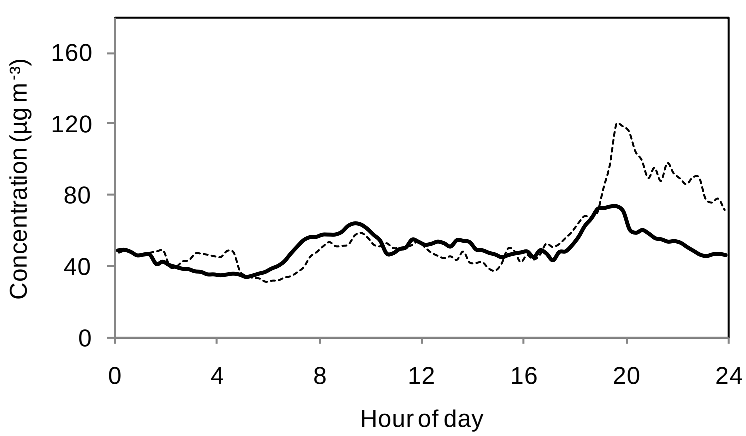

Table 4d. Loc 2B

	Mn-Sat	Sunday
Mean	50.23	56.55
St. Dev.	9.45	20.90

paired t-test p(2-tail) = 0.0005
unpaired t-test p(2-tail) = 0.008

FIGURE 22 - Sunday/Monday-Saturday effect at Locations 1A, 1B, 2A and 2B respectively**.**

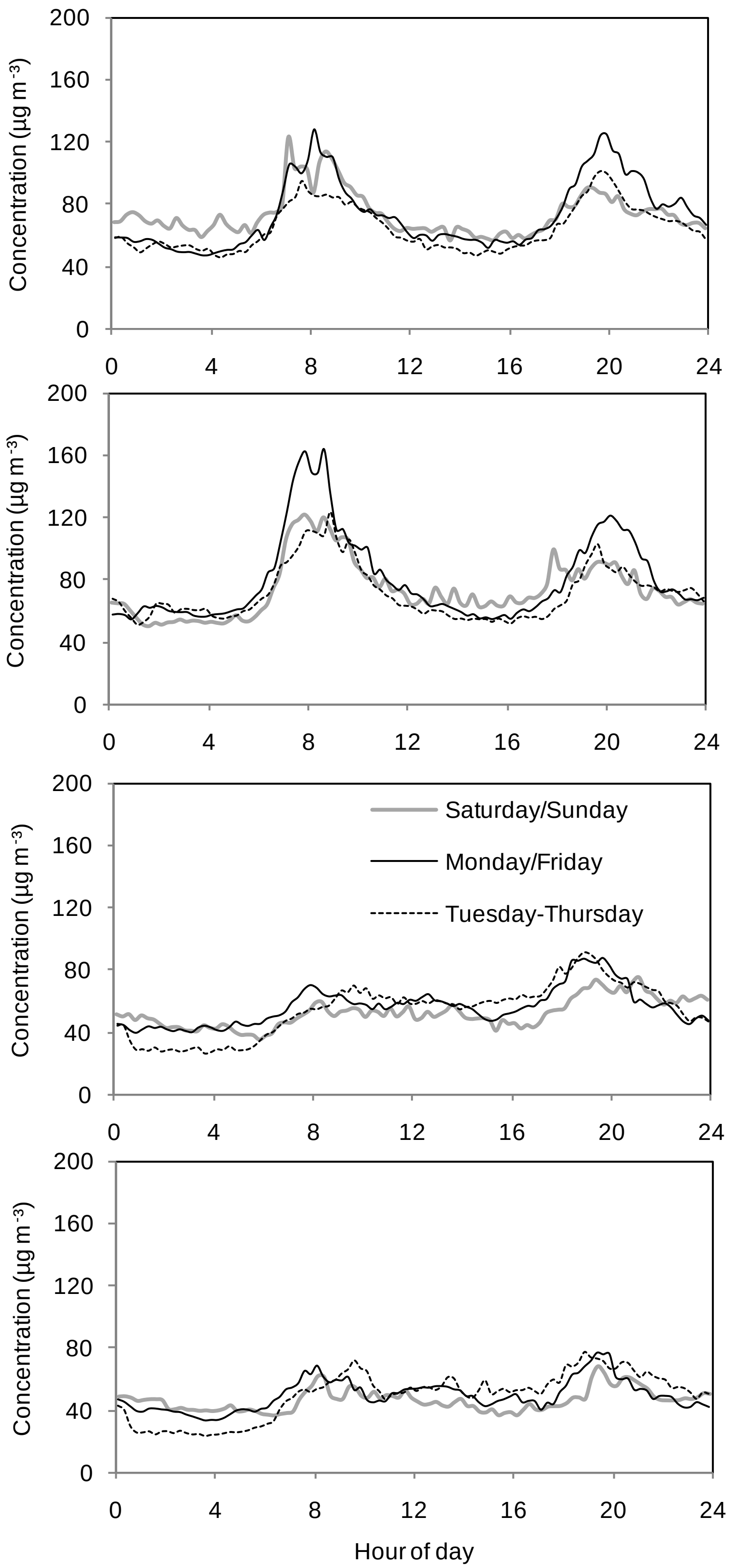

FIGURE 23 - Effect of different day groupings at Locations 1A, 1B, 2A and 2B respectively.

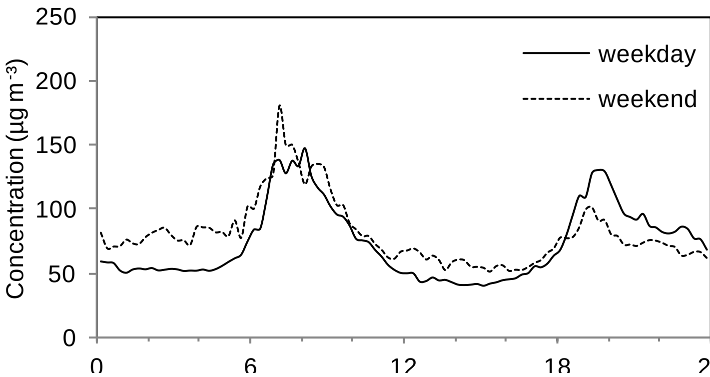

Table 5a. Loc 1A

	Weekday	Weekend
Mean	73.54	80.93
St. Dev.	29.20	24.80

paired t-test p(2-tail) = 0.000166
unpaired t-test p(2-tail) = 0.0603

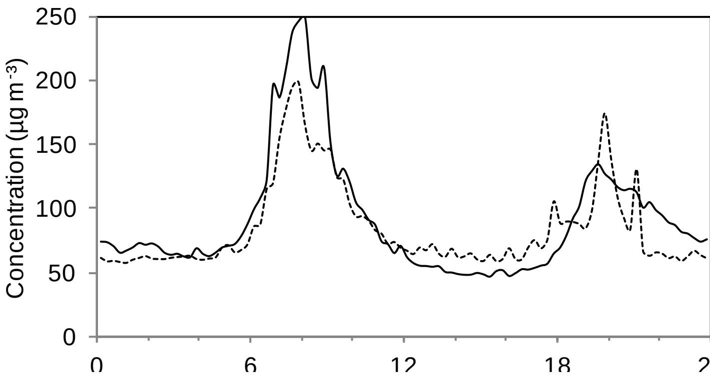

Table 5b. Loc 1B

	Weekday	Weekend
Mean	91.20	84.65
St. Dev.	47.32	33.84

paired t-test p(2-tail) = 0.00566
unpaired t-test p(2-tail) = 0.272

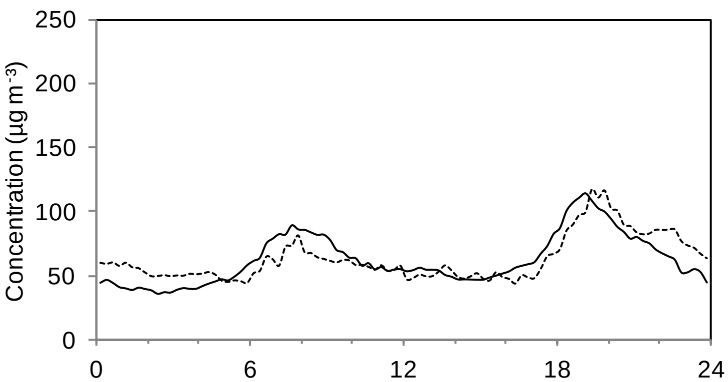

Table 5c. Loc 2A

	Weekday	Weekend
Mean	61.84	63.17
St. Dev.	19.28	17.28

paired t-test p(2-tail) = 0.277
unpaired t-test p(2-tail) = 0.617

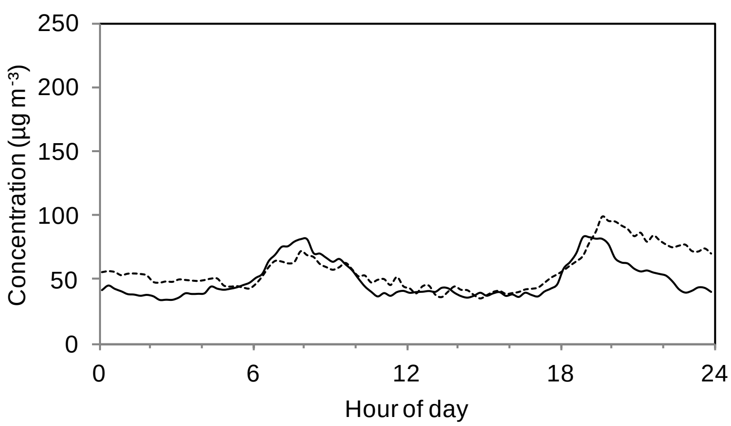

Table 5d. Loc 2B

	Weekday	Weekend
Mean	49.26	56.62
St. Dev.	14.53	15.62

paired t-test p(2-tail) =0.6.96E-8
unpaired t-test p(2-tail) = 0.000893

FIGURE 24 - Weekend/weekday effect at Locations 1A, 1B, 2A and 2B respectively. Analogous to Figure 21, with days equally weighted

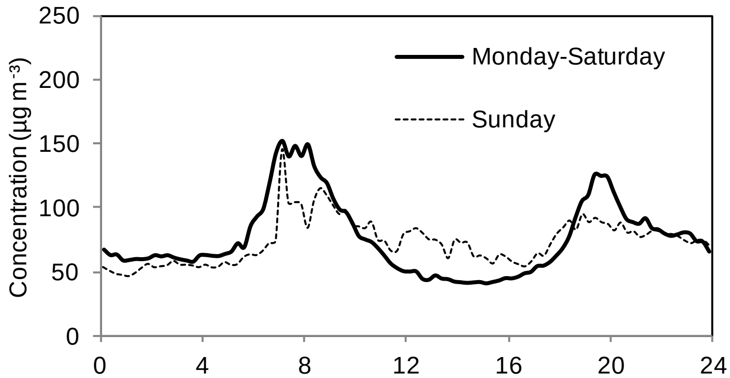

Table 6a. Loc 1A

	Mn-Sat	Sunday
Mean	75.99	73.59
St. Dev.	29.06	17.52

paired t-test p(2-tail) = 0.259
unpaired t-test p(2-tail) = 0.490

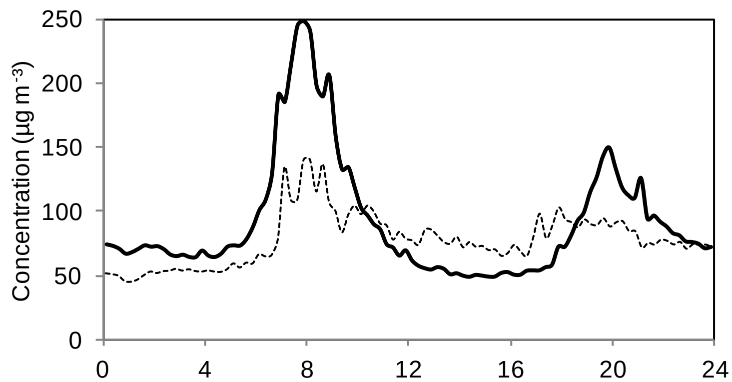

Table 6b. Loc 1B

	Mn-Sat	Sunday
Mean	91.28	77.61
St. Dev.	47.29	21.06

paired t-test p(2-tail) = 0.000326
unpaired t-test p(2-tail) = 0.0105

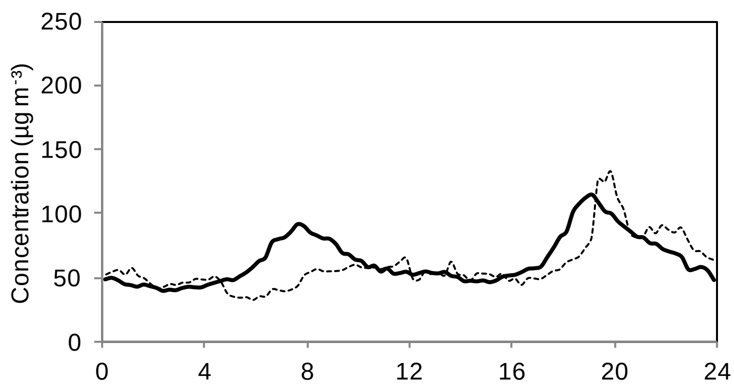

Table 6c. Loc 2A

	Mn-Sat	Sunday
Mean	62.81	58.70
St. Dev.	18.88	19.68

paired t-test p(2-tail) = 0.058
unpaired t-test p(2-tail) = 0.141

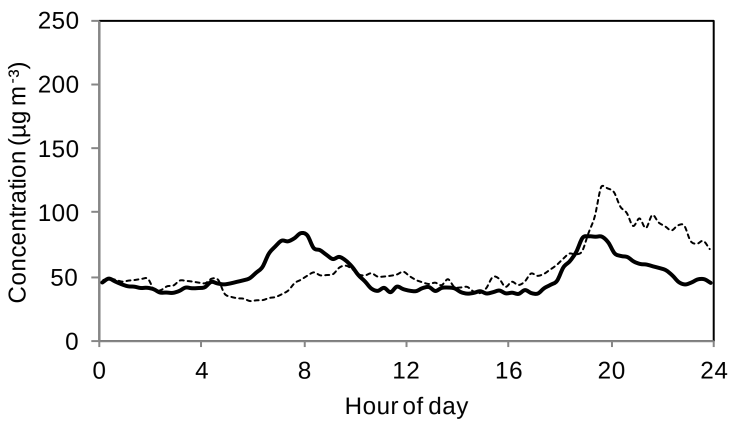

Table 6d. Loc 2B

	Mn-Sat	Sunday
Mean	50.50	56.55
St. Dev.	14.25	20.90

paired t-test p(2-tail) = 0.00315
unpaired t-test p(2-tail) = 0.0202

FIGURE 25 - Sunday/Monday-Saturday effect at Locations 1A, 1B, 2A and 2B respectively. Analogous to Figure 22, with days equally weighted.

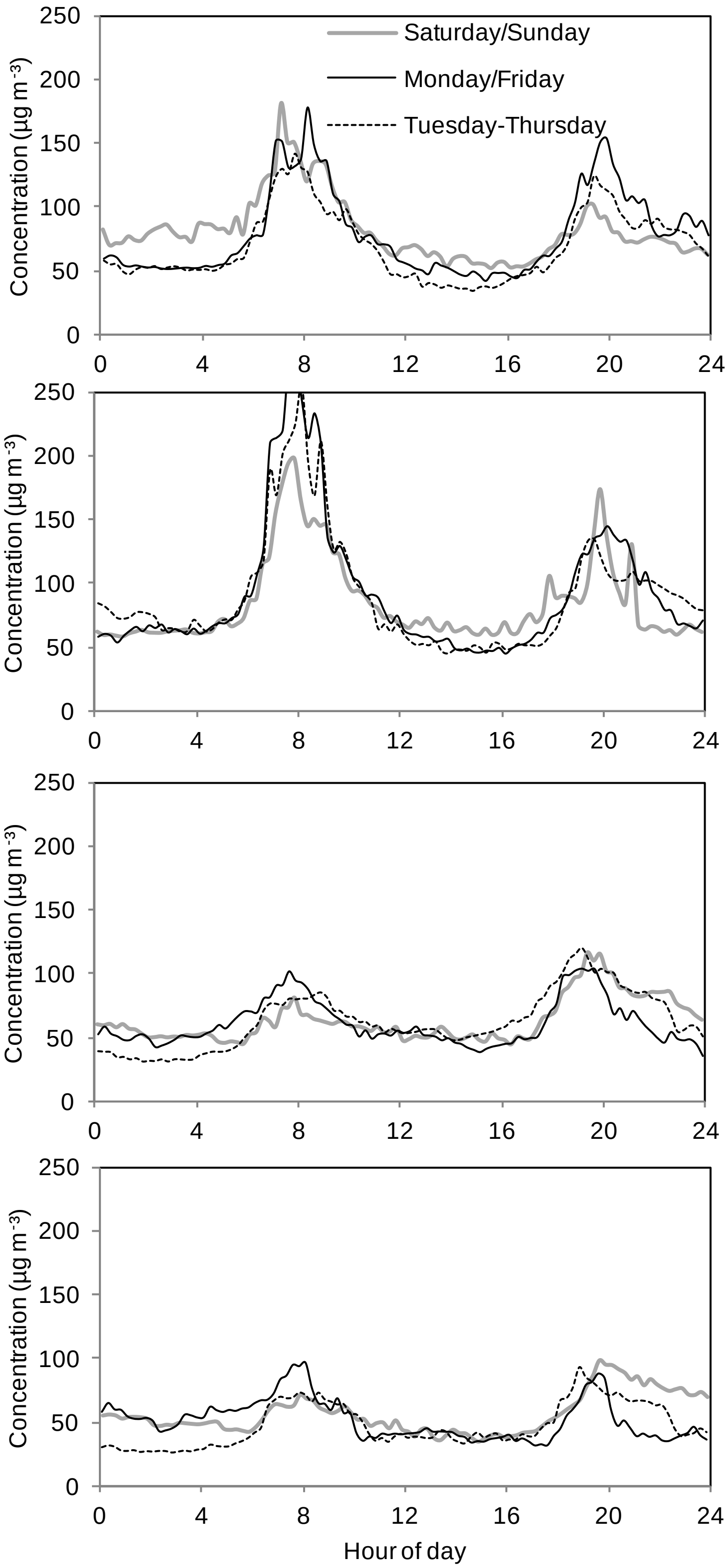

FIGURE 26 - Effect of different day groupings at Locations 1A, 1B, 2A and 2B respectively. Analogous to Figure 23, with days equally weighted

5.5 Wind Effect

The effect of weather on $PM_{2.5}$ concentration extends beyond the effect of RH on nephelometer readings, particularly because the substantial wind effects are highly variable by season. To analyze the effect the wind has on $PM_{2.5}$ concentration, data were separated into 5 different wind conditions described in section 5.1: (1) toward, (2) away, (3) perpendicular, (4) variable, and (5) calm. Box plots of the five conditions for each location (Figure 27) reveal the following. First, Calm conditions consistently have the highest concentrations, suggesting that any level of wind clears out pollution from the community. We also see that the Away wind condition consistently has the lowest concentrations except for the low-income, near roadway location (Figure 27a). This finding suggests that the roadway is a significant source of emissions that are attenuated when wind is blowing the emissions away from the monitors. The exception is the low-income, near roadway monitor (Figure 27a) where this wind condition doesn't attenuate the concentrations, potentially because there are addition significant sources within the neighborhood that are blown to the monitor.

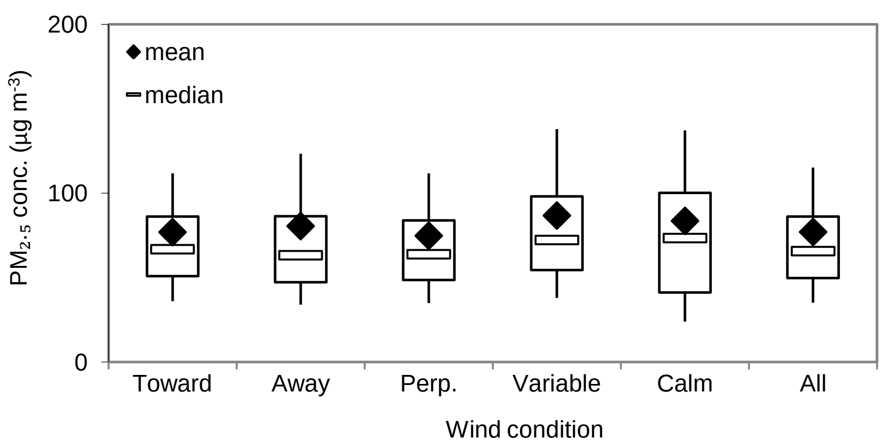

FIGURE 27a – Box plot of $PM_{2.5}$ concentrations at low-income, near roadway location. Box plot displays 10^{th}, 25^{th}, 75^{th}, and 90^{th} percentile as well as mean and median of data set.

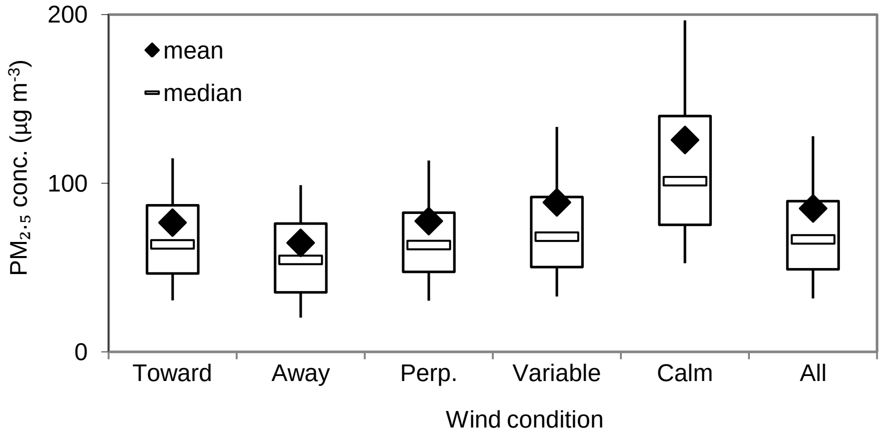

FIGURE 27b – Box plot of $PM_{2.5}$ concentrations at low-income, not-near roadway location.

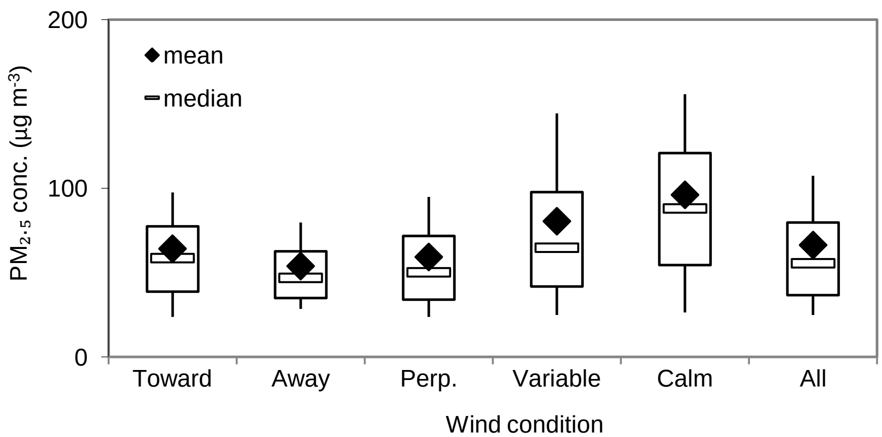

FIGURE 27c – Box plot of $PM_{2.5}$ concentrations at middle-income, near roadway location.

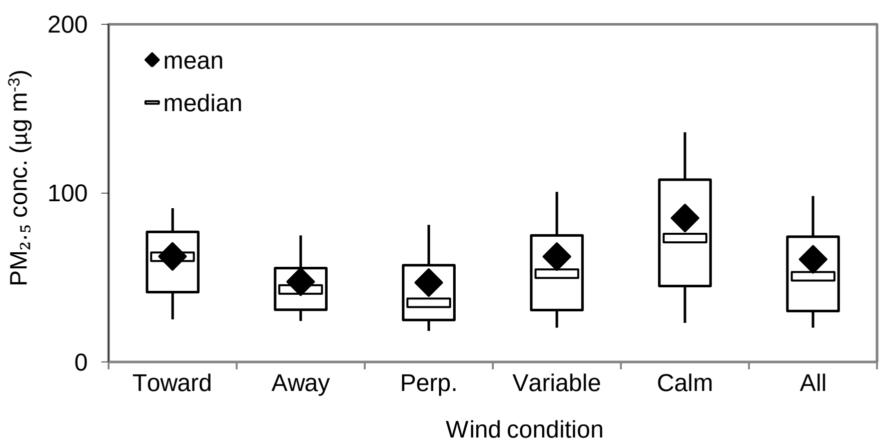

FIGURE 27d – Box plot of $PM_{2.5}$ concentrations at middle-income, not-near roadway location.

Additionally, wind split data was binned by the minute of the day as in Section 5.3; the 15-minute mean of the median from each minute (Figure 28a-d) displays the typical daily patterns of $PM_{2.5}$ by wind condition at each of the monitoring sites. Figure 28 displays similar trends as Figure 27; however, laying out the wind conditions by time-of-day reveals some additional information. During the morning peak at the low-income, near roadway location (Figure 28a), the highest concentrations occur when the wind is blowing away or variably, indicating a significant $PM_{2.5}$ source located within the neighborhood. At the low-income, not-near roadway location, the highest concentrations occur when the wind is blowing toward or variably, further suggesting a significant $PM_{2.5}$ source between the two monitoring sites.

Differences in concentration based on wind condition primarily happen during the diurnal peaks, when a higher amount of $PM_{2.5}$ sources are local (see 5.6). Not during the peaks, when a large amount of the $PM_{2.5}$ concentration is likely at urban background levels (see 5.6), the concentrations are similar near and not-near roadway. Taken together, these analyses highlight how exploration of spatiotemporal variability in concentrations can be used to reveal information about emission sources.

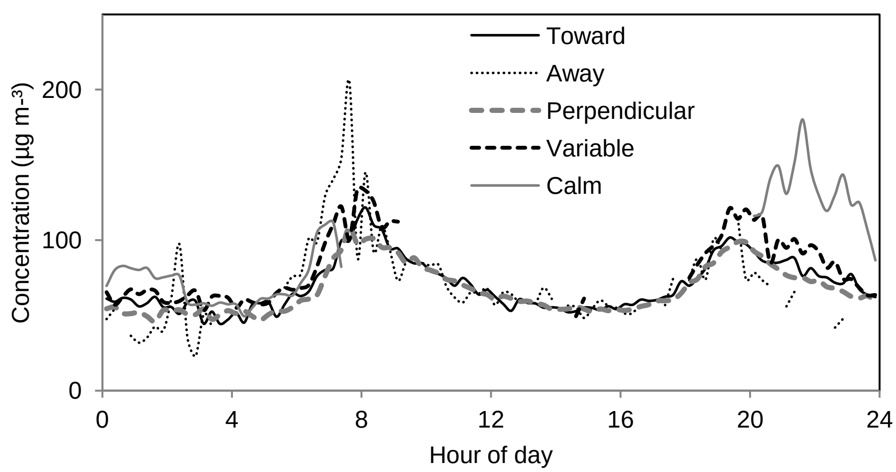

FIGURE 28a – 15 minute means of the median $PM_{2.5}$ concentration by time of day and wind condition for the low-income, near roadway location.

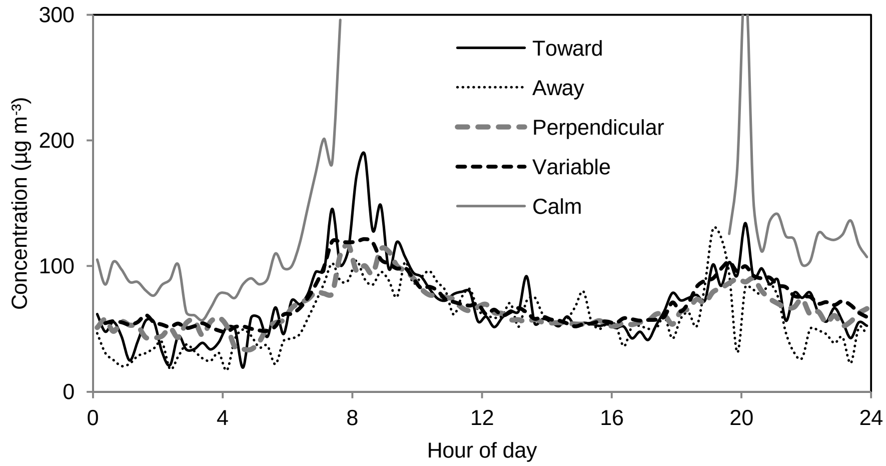

FIGURE 28b – 15 minute means of the median $PM_{2.5}$ concentration by time of day and wind condition for the low-income, not-near roadway location.

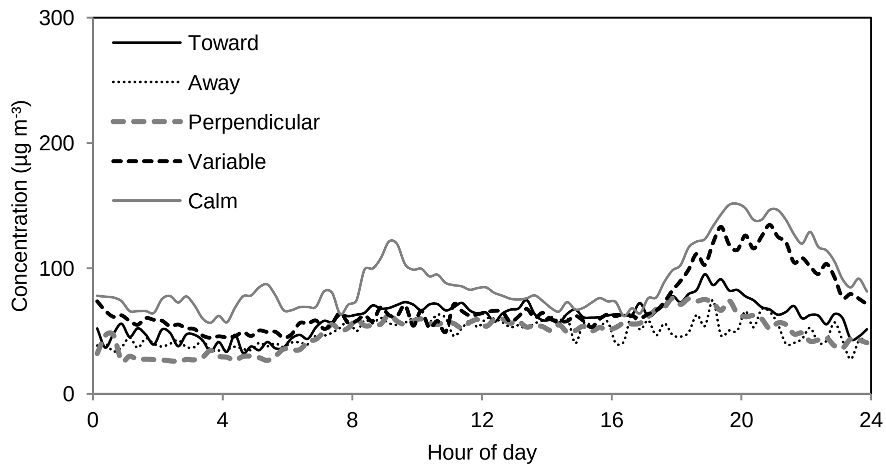

FIGURE 28c – 15 minute means of the median $PM_{2.5}$ concentration by time of day and wind condition for the middle-income, near roadway location.

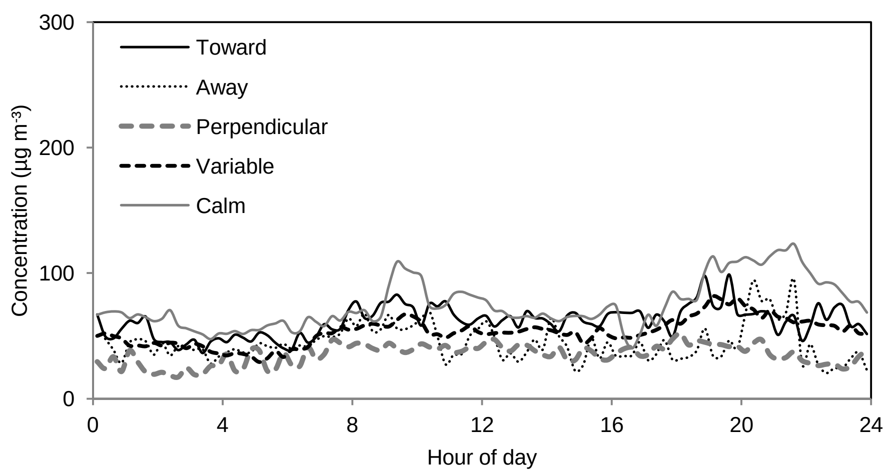

FIGURE 28d – 15 minute means of the median $PM_{2.5}$ concentration by time of day and wind condition for the middle-income, not-near roadway location.

5.6 Spatial Variability: Moving Average Subtraction

To discern a spatial signature from the temporal $PM_{2.5}$ mass concentrations, a moving-average subtraction method developed by Watson & Chow was applied to paired data in each neighborhood (Watson & Chow, 2001). In this approach, short-duration concentration pulses are hypothesized as attributable to local sources (<0.5 km). Concentrations after removing the short-term spikes (the "baseline") at the not-near roadway site are interpreted as the regional contribution (>5 km). The concentration difference between the baseline at the near roadway site and the baseline at the not-near roadway site is interpreted as attributable to neighborhood sources (~0.5-5 km). To generate the baseline for data sample, the hourly mean of the 60 values surrounding a 1 minute data point is calculated. If the hourly mean is less than the 1 minute value the hourly mean is kept in a new data set instead of the 1 minute data point, otherwise the 1 minute data point is kept. This process is repeated on the newly generated data set but with a 30 minute mean rather than an hourly mean to generate yet another new data set. Once again the process is repeated on the newly generated data set but with a 15 minute mean to finally obtain the baseline which has the short-duration concentration spikes imposed upon it. A raw data sample day with baselines is displayed in Figure 29a with a zoom-in showing the baseline in Figure 29b to illustrate the method.

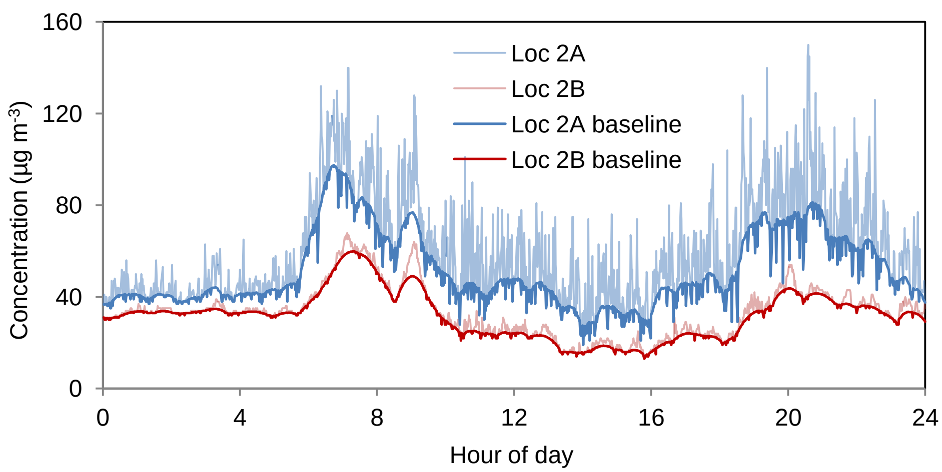

FIGURE 29a – Sample of raw data, plus moving-average subtraction method baselines, for one 24 hour period (October 16th, 2008) at the middle-income neighborhood.

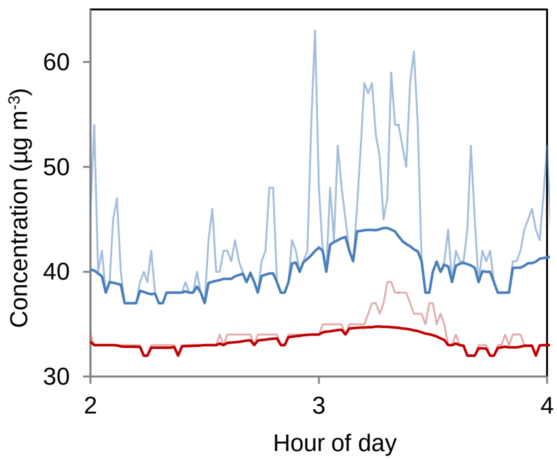

FIGURE 29b – A zoom-in from Figure 24a, displaying the raw data and baselines from the moving-average subtraction method.

Results from the moving-average subtraction method are shown in Figure 30. One modification to the moving-average subtraction method developed by Watson and Chow (2001) was implemented for this study since their method doesn't anticipate the not-near roadway data being higher than the near roadway data as seen in the low-income neighborhood. When this occurred, the Watson and Chow (2001) method assumed neighborhood emissions to be zero. Because this was such a common occurrence, the calculated neighborhood portion of emissions was underreported contributing only ~6% of the total emissions on average. For reference, Watson and Chow (2001) found neighborhood emissions contributing 23% of emissions in Mexico City. In this study, however, the higher baseline of the two locations is assumed attributable to neighborhood emissions, regardless of which location is higher. Neighborhood emissions were calculated as the absolute value of the difference between the two baselines. For display purposes in Figure 30, neighborhood and local emissions are grouped together.

Results indicate that two neighborhoods have similar relative contribution from local sources (5%-13%, on average), though they exhibit different absolute contributions and differing daily patterns. Mean absolute contributions were ~1.7 times higher in the low-income than in the high-income neighborhood (9.7 versus 5.8 μg m^{-3}). In the low-income neighborhood, local sources occurred throughout the day, but were ~1.7 times higher during morning and evening peaks than during other times of day. In the middle-income neighborhood, local sources occurred primarily during the evening peak: local contributions were ~1.8 times higher during evening peaks than during other times of day. The 2-h period with the overall highest contribution from local sources (~19%) occurred during 16:00–18:00 at the not-near roadway low-income location, which is consistent with a strong local non-roadway source such as cooking or trash burning.

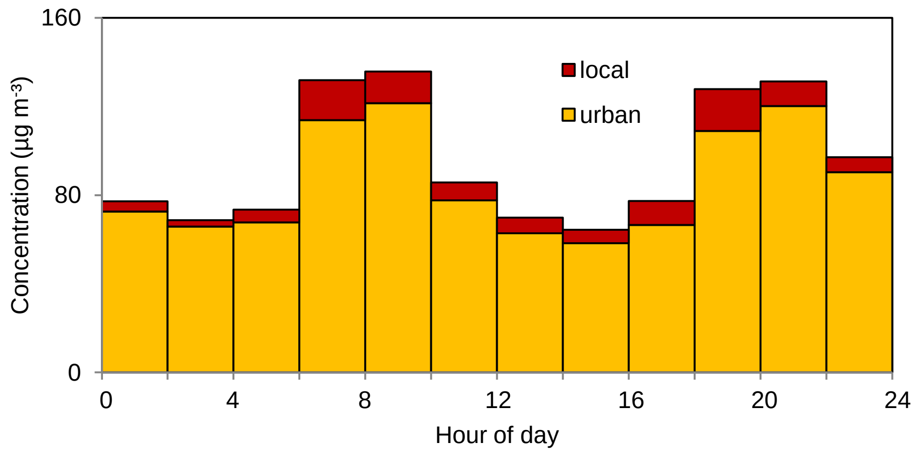

FIGURE 30a – Median $PM_{2.5}$ concentration by local- and urban-scale contributions by time of day for low-income, near roadway location in 2 hour bins.

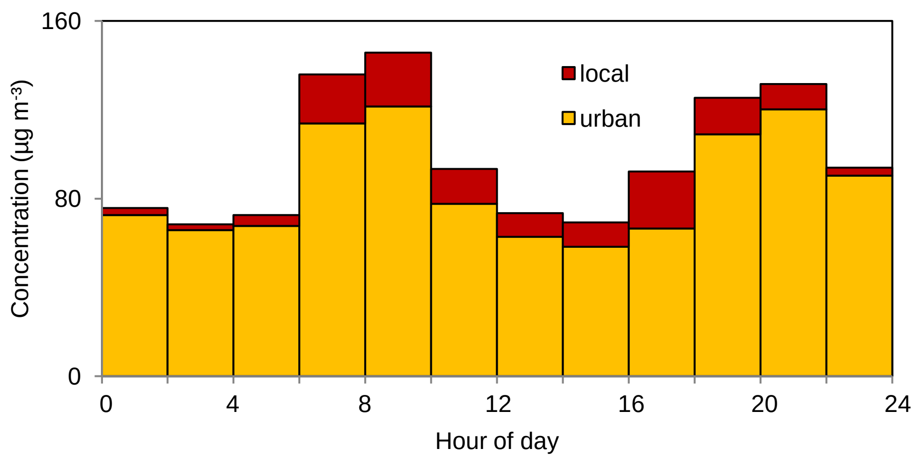

FIGURE 30b – Median $PM_{2.5}$ concentration by local- and urban-scale contributions by time of day for low-income, not-near roadway location in 2 hour bins.

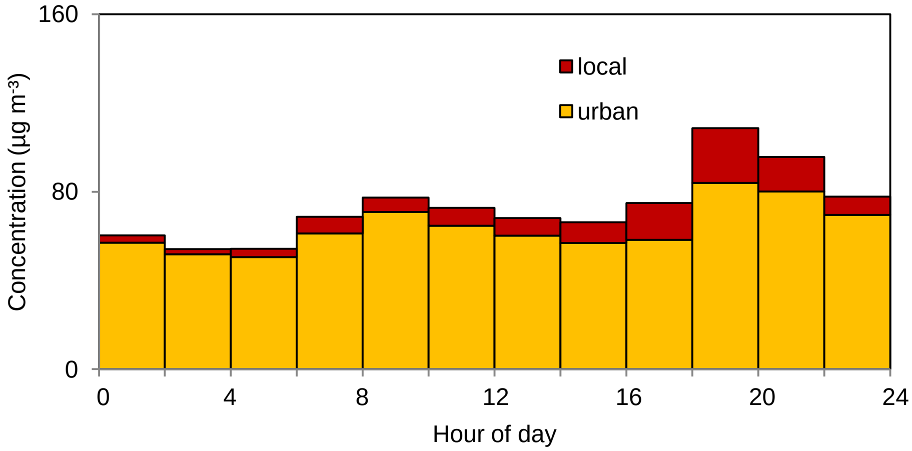

FIGURE 30c – Median $PM_{2.5}$ concentration by local- and urban-scale contributions by time of day for middle-income, near roadway location in 2 hour bins.

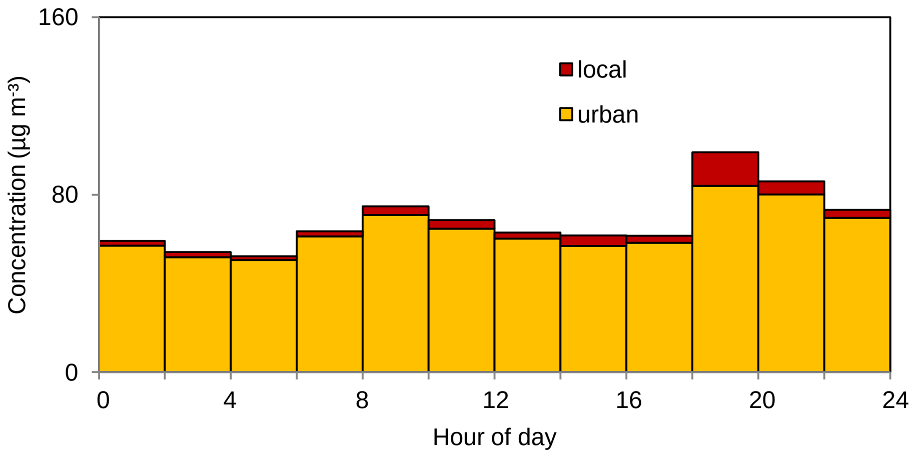

FIGURE 30d – Median $PM_{2.5}$ concentration by local- and urban-scale contributions by time of day for middle-income, not-near roadway location in 2 hour bins.

This analysis isn't suited for providing absolute resolution between spatial variability of emission sources, but rather to provide a relative comparison of the proportion of local emissions by time-of-day and between two co-located real-time monitors. For an alternative visual representation of the proportions in Figure 30, the spatial contributions are displayed as a percent of total concentration in Figure 31. Again we see the highest local contributions from the not-near roadway location in the low-income neighborhood and the near roadway location in the middle-income neighborhood. Additionally we see the highest local contribution for all locations comes in the evening hours.

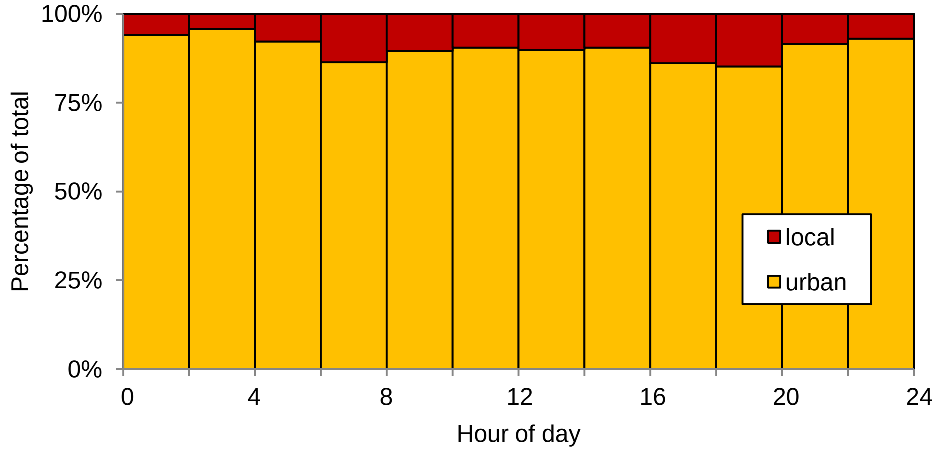

FIGURE 31a – Percentage of $PM_{2.5}$ concentration by local- and urban-scale contributions by time of day for low-income, near roadway location in 2 hour bins.

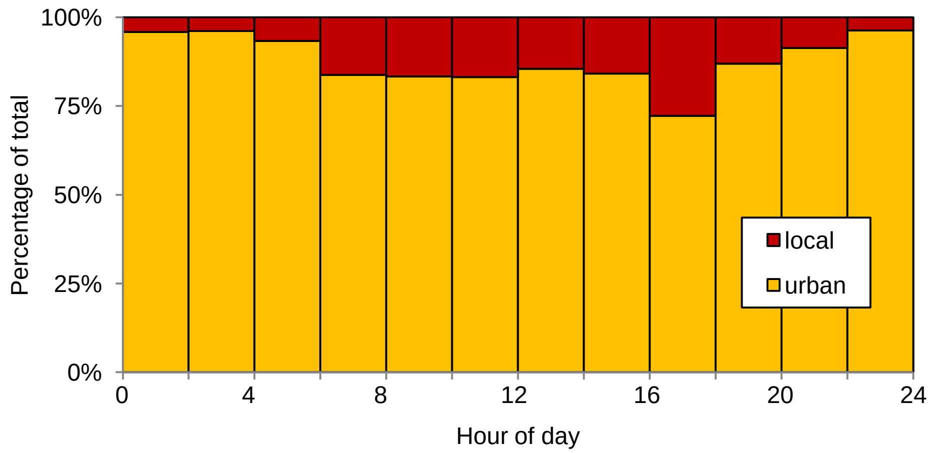

FIGURE 31b – Percentage of $PM_{2.5}$ concentration by local- and urban-scale contributions by time of day for low-income, not-near roadway location in 2 hour bins.

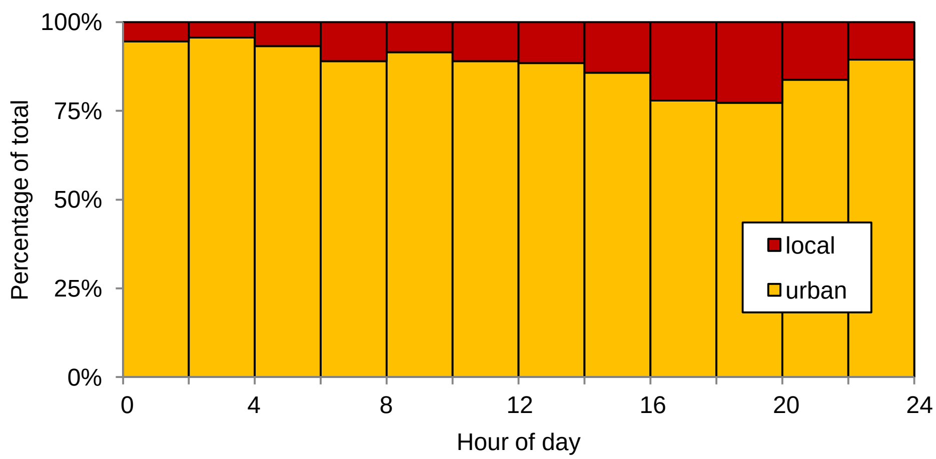

FIGURE 31c – Percentage of $PM_{2.5}$ concentration by local- and urban-scale contributions by time of day for middle-income, near roadway location in 2 hour bins.

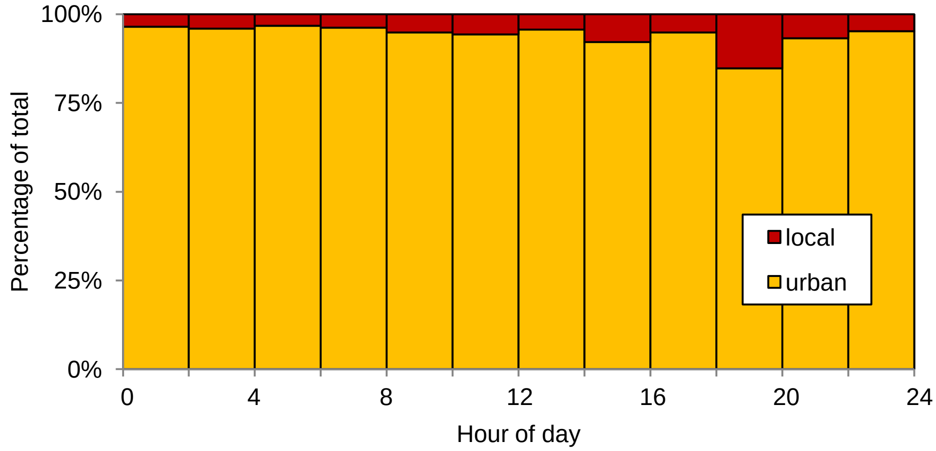

FIGURE 31d – Percentage of $PM_{2.5}$ concentration by local- and urban-scale contributions by time of day for middle-income, not-near roadway location in 2 hour bins.

Spatial variability was analyzed to see if there was a weekend effect as done in section 5.4. Results indicate that there isn't a strong weekend effect regarding the proportion of local emissions in the two neighborhoods. In the low-income neighborhood, local contributions saw little change on the weekend (decrease from 10% to 9% near roadway; increase from 12 to 16% not-near roadway). In the middle income neighborhood, local contributions decreased slightly (from 13% to 12% near roadway; 6% to 5% not-near roadway). Also of interest is the change in daily patterns of local contribution shown in Figure 32a & b. For the low-income not-near roadway location, we see an increase in local emission on the weekend at around 18:00, presumably when the largest meals of the week are being prepared.

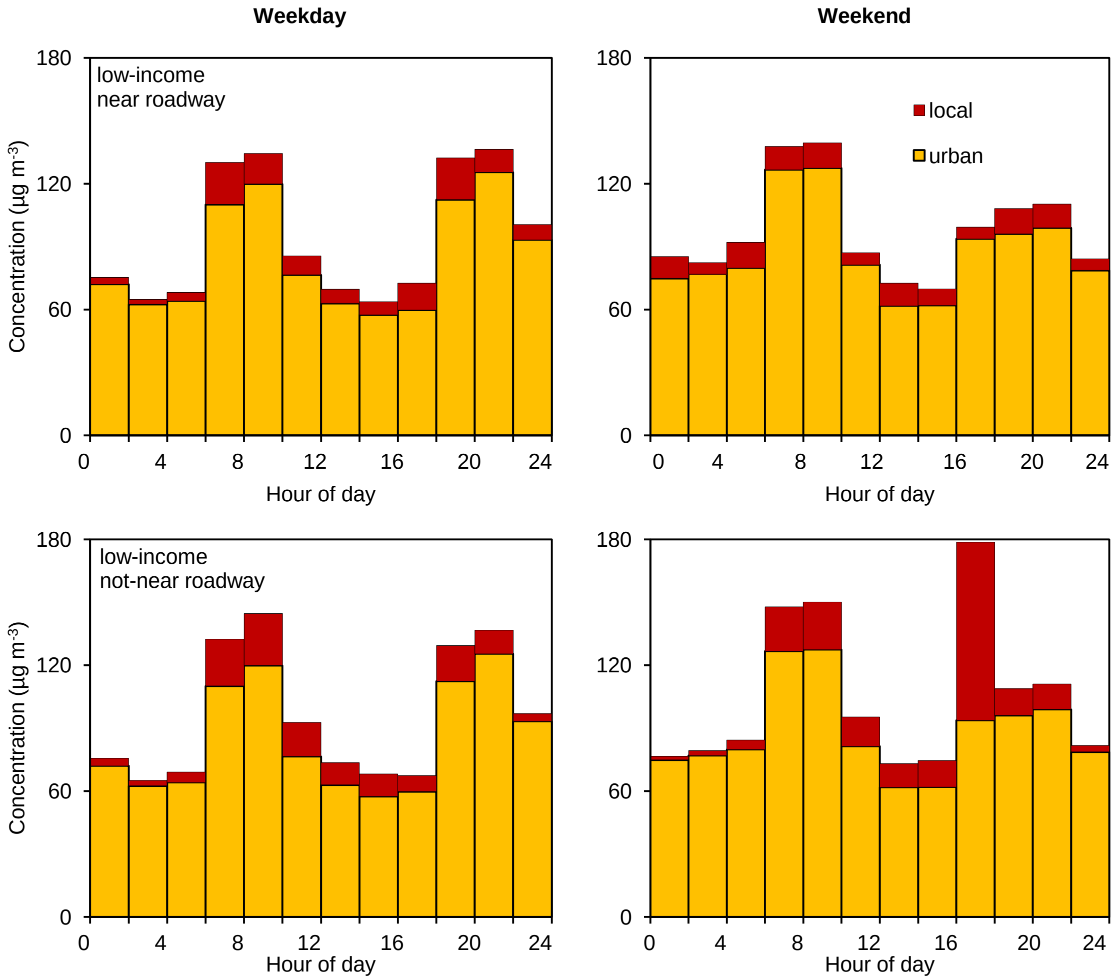

FIGURE 32a – Weekend and weekday median $PM_{2.5}$ concentration by local- and urban-scale contributions by time of day for low-income neighborhood in 2 hour bins.

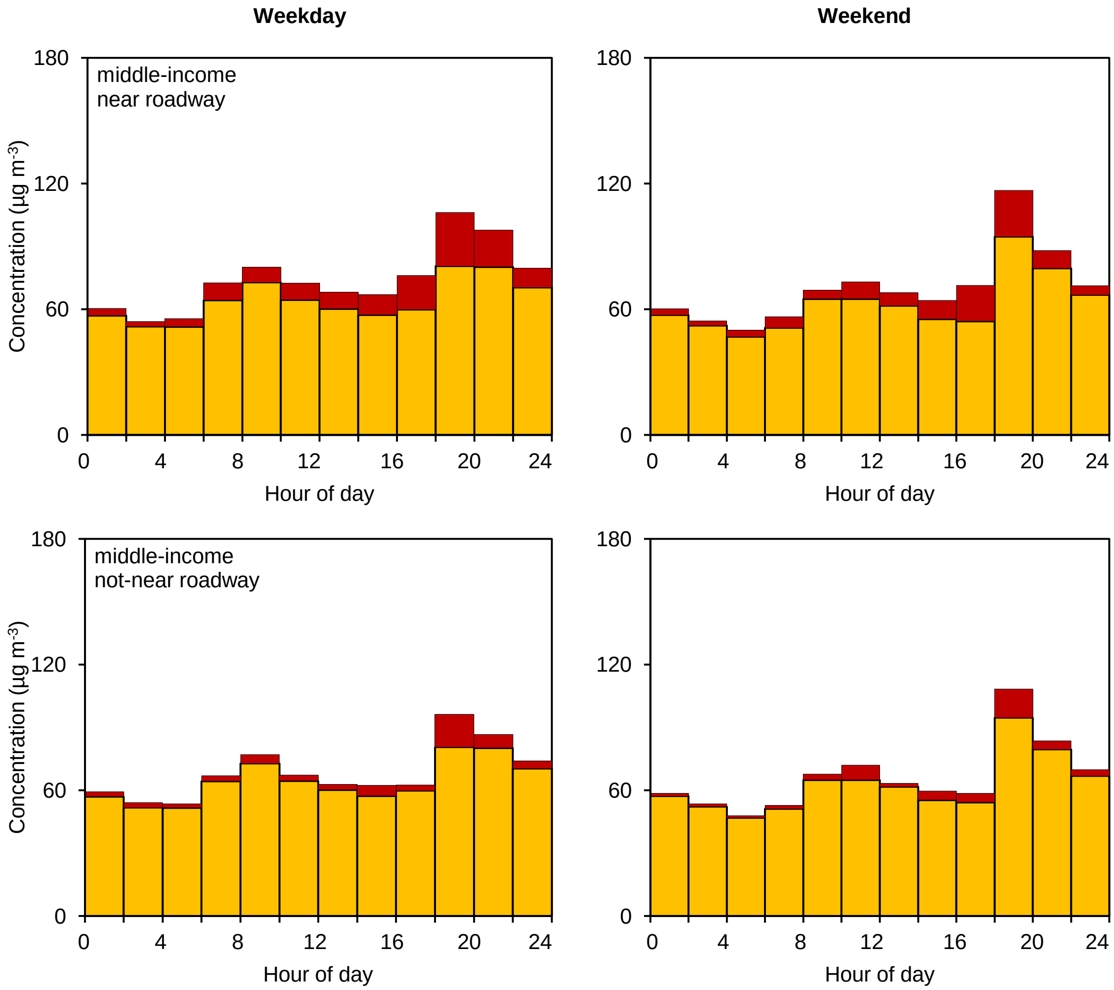

FIGURE 32b – Weekend and weekday median $PM_{2.5}$ concentration by local- and urban-scale contributions by time of day for middle-income neighborhood in 2 hour bins.

5.7 Transects

While the fixed placement of the monitors provided some spatial resolution of emissions, this study also aimed to examine the concentration of emissions as a function of distance from the roadway, similar to studies done in the developed world (Hu et al. 2009; Hitchins et al. 2000; Zhu et al. 2002a&b). A typical concentration decline based on distance from roadway is shown in Figure 33.

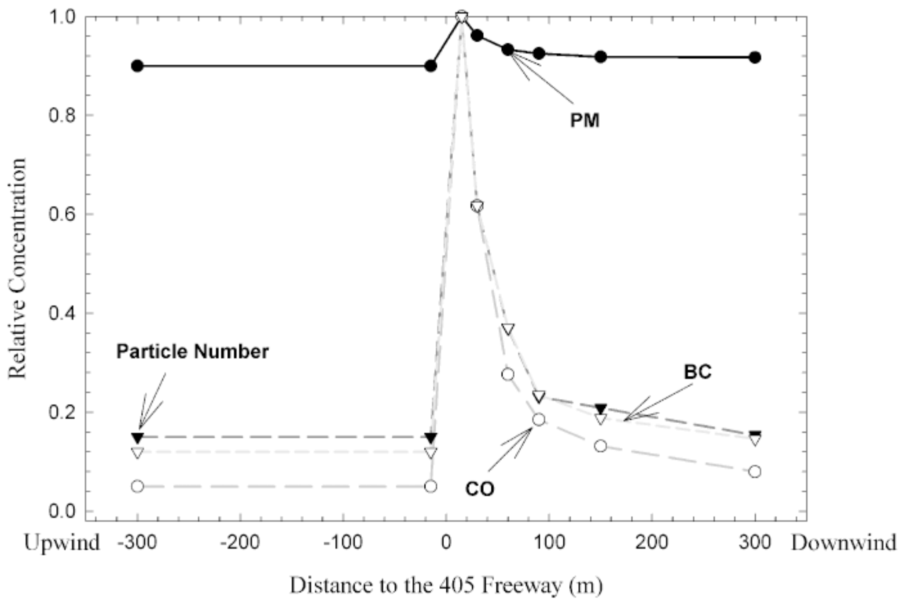

FIGURE 33 – Relative mass, number, BC, and CO concentrations vs. downwind distance measured by Zhu et.al. (2002) in Los Angeles, California.

To carry out these measurements, during each equipment rotation (approximately every two weeks), the monitors were walked in a transect from the roadway past both monitoring locations in as direct a path as could be walked, to the rear of the neighborhood and then back to the roadway. $PM_{2.5}$ concentrations were measured every second, and clock times were noted when measureable landmarks were passed. Distances for the data points between noted landmarks were interpolated assuming consistent walking speed between landmarks to produce concentrations as a function of distance from roadway instead of the raw data form of concentration by time. The data from the walked transects was first normalized by the median value for each transect walked and data from all 78 transects were combined by neighborhood (see Figure 34). Data was then compiled in 5-meter bins and the median normalized value for each 5m bin was plotted (Figure 35) to show the trend in mass concentration at each location.

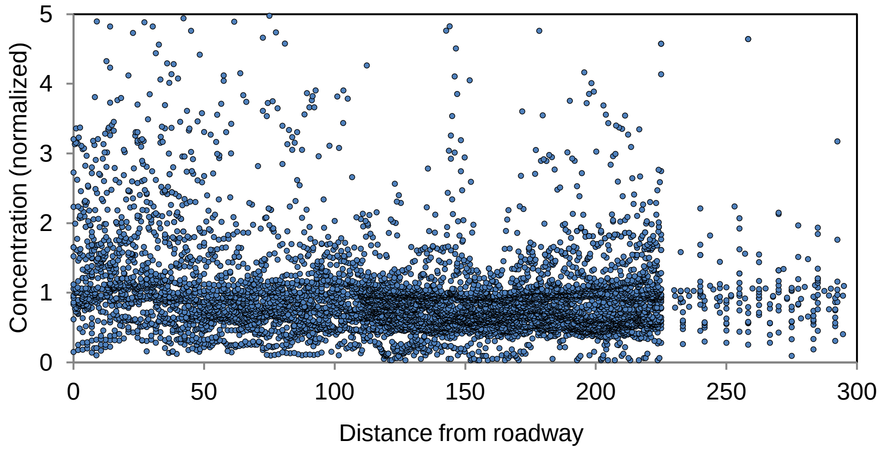

FIGURE 34a – All $PM_{2.5}$ concentrations normalized per transect as a function of distance from roadway in the low-income neighborhood.

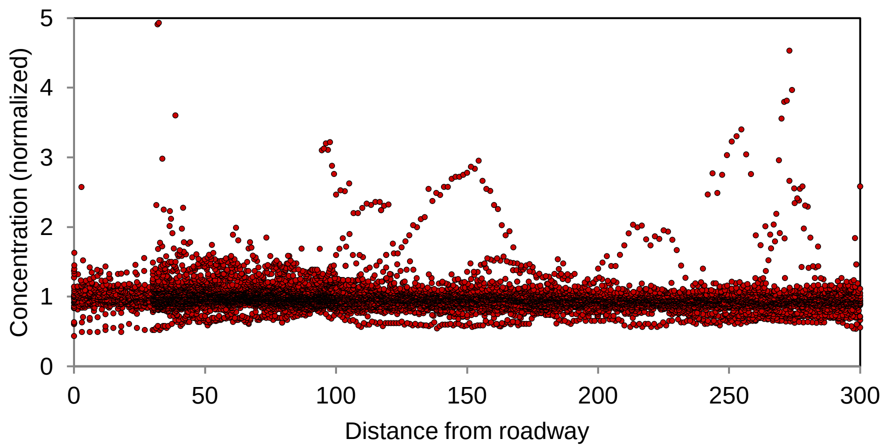

FIGURE 34b – All $PM_{2.5}$ concentrations normalized per transect as a function of distance from roadway in the middle-income neighborhood.

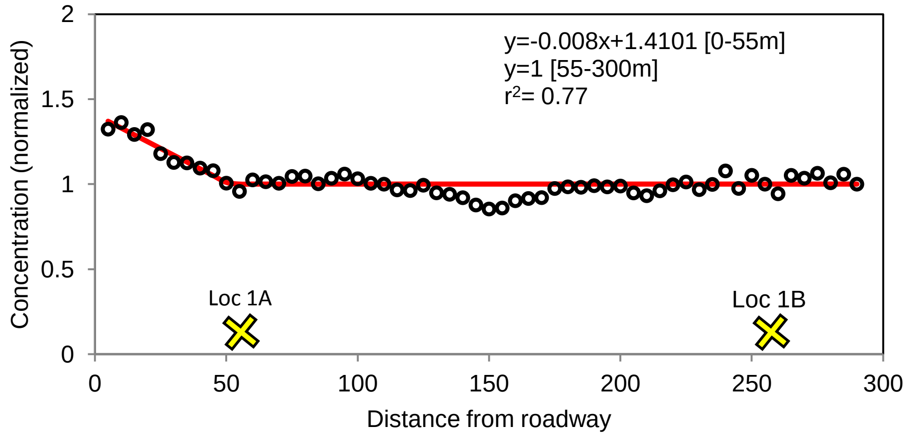

FIGURE 35a – Median $PM_{2.5}$ concentration normalized per transect as a function of distance from roadway in the low-income neighborhood.

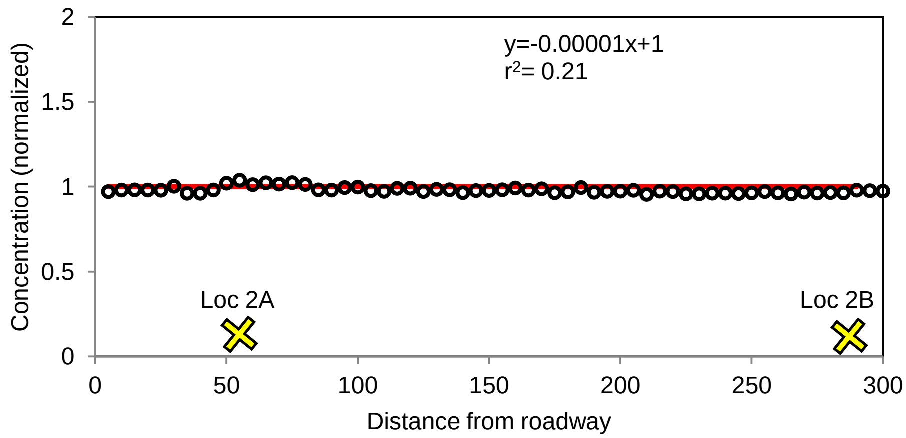

FIGURE 35b – Median $PM_{2.5}$ concentration normalized per transect as a function of distance from roadway in the middle-income neighborhood.

In the low-income neighborhood (Figure 35a), normalized concentrations increased to 1.4 times the normalized mean, but only within a distance of ~50 meters. Beyond 50 meters, there was minimal variation. Zhu et. al. (2002) measured similar trends near Interstate 405 in Los Angeles, seeing an increase in $PM_{2.5}$ of ~1.1 times the normalized concentration with an impact distance between 20 and 100 meters depending on wind conditions. A two-stage linear trend line was applied (y=-0.008x+1.4101 [0-55m]; y=1 [55-300m]) and shown to be a good fit (r^2= 0.77).

In the middle-income neighborhood, (Figure 35b), all distances are at or near the normalized concentration of 1, indicating near-zero spatial variability. A nearly flat trend line (y=-0.00001x+1) is shown but not a reasonable measure of goodness of fit because the correlation coefficient is a measure response between X and Y variables. Since we don't see any response in the concentrations from a change in distance, the correlation coefficient has little meaning. Sound barrier walls similar to the wall surrounding the middle-income neighborhood have been shown to reduce concentrations from nearby traffic emissions (Baldauf et al., 2008). Trees in the middle-income neighborhood might also remove local traffic emissions of $PM_{2.5}$ (Beckett, Freer-Smith, & Taylor, 2000).

Transects typically occurred between 11:00 and 18:00. As seen in Figure 18, concentrations are relatively spatially homogenous during that time. The impact of being near roadway is likely greater at other times of day when concentrations are showed to be more variable (Hu et al., 2009).

Increases in atmospheric instability and mixing height in the late morning cause increased vertical mixing in the airshed (Freiman, Hirshel, & Broday, 2006; Janhall, Olofson, Andersson, Pettersson, & Hallquist, 2006). This increased vertical mixing results in the comparatively low degree of spatial variability midday seen in the transects (Figure 35) and the midday homogeneous concentration trough (Figure 18).

Using data from the Modern Era Retrospective-analysis for Research Application (MERRA) provided by NASA's Global Modeling and Assimilation Office (GMAO), the annual average surface boundary layer is 6 times greater in early afternoon (1,120 m during 14:00-16:00) than in the morning (180 m during 5:00-9:00). This increased boundary layer increases airshed mixing and homogenizes pollution concentrations, as I observed in my data (Figure 18).

6.0 Conclusions

Stationary nephelometers placed in a low- and middle-income neighborhood at a location near and not-near a roadway show the varying affect that neighborhood and location within the neighborhood have on the ambient concentration of $PM_{2.5}$. On average, the ambient $PM_{2.5}$ concentration is 10-60% higher in the low-income neighborhood than in the high-income neighborhood, depending on time of day and wind condition. Monitoring data from the low-income neighborhood revealed significant $PM_{2.5}$ sources from within the neighborhood, such as cooking with solid fuels, reducing the relative importance of vehicle emissions from the major roadway. For this reason, steady declines in total concentration away from a roadway may not hold true in urban slums with significant in-neighborhood sources.

The moving-average subtraction method (Watson & Chow, 2001) provided important information regarding the spatial variability of $PM_{2.5}$ sources. Based on this method, my data suggest that the absolute contribution of local sources is higher in the low-income than in the middle-income neighborhood. Our analyses emphasize the importance of employing an RH correction factor that varies by time of day, rather than a daily mean correction factor, for working with real-time data.

While valuable, the findings from this study are limited in the fact that they are providing only ambient level resolution, representative of someone's breathing zone while on the roof of the monitoring location. Actual breathed concentrations for typical residents of Bangalore could be significantly different based on the particular micro-climates typically encountered. Also of note, the variability seen between the two neighborhoods was significant while only being ~1.5 km apart, indicating the high degree of spatial variability in concentrations within Bangalore. While ambient concentrations appear to vary by neighborhood income level, there are many other variables contributing to a neighborhood's ambient level of air pollution as well as within a neighborhood.

6.1 Next steps

In hindsight, collecting transect measurements at other times of day (e.g., early morning) would have provided a more complete picture of the concentrations as a function of time. Additionally, it would have been helpful to have a monitoring location closer to the major roadway (within 50 meters).

There are a couple logical next steps in this analysis. The data indicate significant within-neighborhood $PM_{2.5}$ emission sources (e.g., cooking with solid fuels). Of particular interest would be examining personal exposures in the same neighborhood for subjects cooking with solid fuels compared to subjects cooking with electricity or propane. Additionally, there are varying degrees of low-income or 'slum' even within Rajendra Nagar neighborhood. Within the slum, measurements for this study were in an area with more permanent housing, but there was a large population in a more temporary and poorer area that may have different environmental risks and air pollution. It would be interesting to examine patterns of concentration within the low-income neighborhood comparing 6-8 more monitoring sites within the neighborhood. After examining ambient concentration is the 'home' setting, more work needs to be done for time spent in commute and at work. Known for its congestions, both traffic concentrations as well as concentrations in some of the crowded market areas could reveal severe daily hazards for many people in Bangalore. Also of interest are some of the time periods with extremely high, short-term concentrations. Though expected to be less of a health risk as the chronic conditions, some of the short-term peaks were high enough to warrant investigation which may require video/CCTV support to determine the exact causes.

7.0 References

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Appendix - Literature Review of Outdoor Air Quality in the Developing World

Author	Journal (Year)	Title	Pollutant	Country/Location	Summary and Comments	Abstract
Afroz et al.	Environmental Research (2003)	Review of air pollution and health impacts in Malaysia	CO, Pb, SPM, NO_2, O_3 SO_2	Malaysia	Studies related to air pollution conducted in Malaysia have been few. The air pollution comes mainly from land transportation, industrial emissions, and open burning sources. Among them, land transportation contributes the most to air pollution. 82% of total air emissions come from traffic	In the early days of abundant resources and minimal development pressures, little attention was paid to growing environmental concerns in Malaysia. The haze episodes in Southeast Asia in 1983, 1984, 1991, 1994, and 1997 imposed threats to the environmental management of Malaysia and increased awareness of the environment. As a consequence, the government established Malaysian Air Quality Guidelines, the Air Pollution Index, and the Haze Action Plan to improve air quality. Air quality monitoring is part of the initial strategy in the pollution prevention program in Malaysia. Review of air pollution in Malaysia is based on the reports of the air quality monitoring in several large cities in Malaysia, which cover air pollutants such as Carbon monoxide (CO), Sulphur Dioxide (SO2), Nitrogen Dioxide (NO2), Ozone (O3), and Suspended Particulate Matter (SPM). The results of the monitoring indicate that Suspended Particulate Matter (SPM) and Nitrogen Dioxide (NO2) are the predominant pollutants. Other pollutants such as CO, Ox, SO2, and Pb are also observed in several big cities in Malaysia. The air pollution comes mainly from land transportation, industrial emissions, and open burning sources. Among them, land transportation contributes the most to air pollution. This paper reviews the results of the ambient air quality monitoring and studies related to air pollution and health impacts.
Akimoto, et al.	Science (2003)	Global Air Quality and Pollution	All	Global	Particularly in developing countries, continuing industrialization and migration toward urban centers, megacities are becoming more important sources of air pollution. International initiatives to mitigate global air pollution require participation from both developed and developing countries.	The impact of global air pollution on climate and the environment is a new focus in atmospheric science. Intercontinental transport and hemispheric air pollution by ozone jeopardize agricultural and natural ecosystems worldwide and have a strong effect on climate. Aerosols, which are spread globally but have a strong regional imbalance, change global climate through their direct and indirect effects on radiative forcing. In the 1990s, nitrogen oxide emissions from Asia surpassed those from North America and Europe and should continue to exceed them for decades. International initiatives to mitigate global air pollution require participation from both developed and developing countries.
Arku, et al.	Science of the Total Environment (2008)	Characterizing air pollution in two low-income neighborhoods in Accra, Ghana	PM_{10}, $PM_{2.5}$, NO_2, SO_2	Different neighborhoods in Accra, Ghana	The results show that PM10 at sites in these two neighborhoods ranged from 58 to 94 µg/m3 and PM2.5 from 22 to 40 µg/m3. There is evidence for the contributions from biomass and traffic sources, and from geological and marine non-combustion sources to particle pollution	Sub-Saharan Africa has the highest rate of urban population growth in the world, with a large number of urban residents living in low-income "slum" neighborhoods. We conducted a study for an initial assessment of the levels and spatial and/or temporal patterns of multiple pollutants in the ambient air in two low-income neighborhoods in Accra, Ghana. Over a 3-week period we measured (i) 24-hour integrated PM(10) and PM(2.5) mass at four roof-top fixed sites, also used for particle speciation; (ii) continuous PM(10) and PM(2.5) at one fixed site; and (iii) 96-hour integrated concentration of sulfur dioxide (SO(2)) and nitrogen dioxide (NO(2)) at 30 fixed sites. We also conducted seven consecutive days of mobile monitoring of PM(10) and PM(2.5) mass and submicron particle count. PM(10) ranged from 57.9 to 93.6 microg/m(3) at the four sites, with a weighted average of 71.8 microg/m(3) and PM(2.5) from 22.3 to 40.2 microg/m(3), with an average of 27.4 microg/m(3). PM(2.5)/PM(10) ratio at the four fixed sites ranged from 0.33 to 0.43. Elemental carbon (EC) was 10-11% of PM(2.5) mass at all four measurement sites; organic matter (OM) formed slightly less than 50% of PM(2.5) mass. Cl, K, and S had the largest elemental contributions to PM(2.5) mass, and Cl, Si, Ca, Fe, and Al to coarse particles. SO(2) and NO(2) concentrations were almost universally lower than the US-EPA National Ambient Air Quality Standards (NAAQS), with virtually no variation across sites. There is evidence for the contributions from biomass and traffic sources, and from geological and marine non-combustion sources to particle pollution. The implications of the results for future urban air pollution monitoring and measurement in developing countries are discussed.
Baldasano et al.	Science of the Total Environment (2003)	Air quality data from large cities	O_3, PM_{10}, NO_2, SO_2	Global	SO2 maintains a downward tendency throughout the world, with the exception of some Central American and Asian cities. NO2 maintains levels very close to the WHO guideline value throughout the world. However, in certain cities such as Kiev, Beijing and Guangzhou the figures are approximately three times higher than the WHO guideline value. Particulate matter is a major problem in almost all of Asia, exceeding 300 mg/m3 in many cities. Ozone is a problem for rich and poor. In poor countries and those with low average incomes, concentrations of air pollutants remain high and the tendency will be to increase their emission levels as they develop, making the problem worse.	This paper presents an assessment of the air quality for the principal cities in developed and developing countries. Part of the vast and widely dispersed information on air quality that is available at this time on the Internet was compiled, thus making possible a comprehensive evaluation of the tendencies that emerged at the end of the 20th century. Likewise, these values are compared to the air quality thresholds recommended by two international organizations: guideline levels of the World Health Organization (WHO) and limit values of the European Union (EU), in order to determine air quality concentration levels in large cities around the world. The current situation of air quality worldwide indicates that SO2 maintains a downward tendency throughout the world, with the exception of some Central American and Asian cities. NO2 maintains levels very close to the WHO guideline value around the world. For particulate matter, it is a major problem in almost all of Asia, exceeding 300 mg/m3 in many cities. Ozone shows average values that exceed the selected guideline values in all of the analyses demonstrating that it is a global problem. In general, the worldwide trend is to a reduction in the concentrations of pollutants because of the increasingly strong restrictions which local governments and international organizations impose. However, in poor countries and those with low average incomes, concentrations of air pollutants remain high and the trend will be the elevation of their ground levels as they develop, making the problem even worse.

Author	Journal (Year)	Title	Pollutant	Country/Location	Summary and Comments	Abstract
Cohen et al.	Journal of Toxicology and Environmental Health (2005)	The Global Burden of Disease Due to Outdoor Air Pollution	$PM_{2.5}$, general	Global	Fine particulate air pollution (PM2.5), causes about 3% of mortality from cardiopulmonary disease, about 5% of mortality from cancer of the trachea, bronchus, and lung, and about 1% of mortality from acute respiratory infections in children under 5 yr, worldwide. This amounts to about 0.8 million (1.2%) premature deaths and 6.4 million (0.5%) years of life lost (YLL). This burden occurs predominantly in developing countries; 65% in Asia alone. Only focused on PM, so the effect is likely underestimated. There is a critical need for better information on the health effects of air pollution in developing counties.	As part of the World Health Organization (WHO) Global Burden of Disease Comparative Risk Assessment, the burden of disease attributable to urban ambient air pollution was estimated in terms of deaths and disability-adjusted life years (DALYs). Air pollution is associated with a broad spectrum of acute and chronic health effects, the nature of which may vary with the pollutant constituents. Particulate air pollution is consistently and independently related to the most serious effects, including lung cancer and other cardiopulmonary mortality. The analyses on which this report is based estimate that ambient air pollution, in terms of fine particulate air pollution ($PM_{2.5}$), causes about 3% of mortality from cardiopulmonary disease, about 5% of mortality from cancer of the trachea, bronchus, and lung, and about 1% of mortality from acute respiratory infections in children under 5 yr, worldwide. This amounts to about 0.8 million (1.2%) premature deaths and 6.4 million (0.5%) years of life lost (YLL). This burden occurs predominantly in developing countries; 65% in Asia alone. These estimates consider only the impact of air pollution on mortality (i.e., years of life lost) and not morbidity (i.e., years lived with disability), due to limitations in the epidemiologic database. If air pollution multiplies both incidence and mortality to the same extent (i.e., the same relative risk), then the DALYs for cardiopulmonary disease increase by 20% worldwide.
Dionisio et al.	Environmental Science and Technology (2010)	Air Pollution in Accra Neighborhoods: Spatial, Socioeconomic, and Temporal Patterns	CO, $PM_{2.5}$	Accra, Ghana	PM in these four neighborhoods is substantially higher than the WHO Air Quality Guidelines. The highest pollution in the poorest neighborhood. In the poor neighborhood, higher concentrations were seen in the 'residential' location compared to the 'traffic' location. Concentrations saw peaks during specific times of day (typically mid-day and evening)	This study examined the spatial, socioeconomic status (SES), and temporal patterns of ambient air pollution in Accra, Ghana. Over 22 months, integrated and continuous rooftop particulate matter (PM) monitors were placed at a total of 11 residential or roadside monitoring sites in four neighborhoods of varying SES and biomass fuel use. PM concentrations were highest in late December and January, due to dust blown from the Sahara. Excluding this period, annual PM2.5 ranged from 39 to 53 μg/m3 at roadside sites and 30 to 70 μg/m3 at residential sites; mean annual PM10 ranged from 80 to 108 μg/m3 at roadside sites and 57 to 106 μg/m3 at residential sites. The low-income and densely populated neighborhood of Jamestown/Ushertown had the single highest residential PM concentration. There was less difference across traffic sites. Daily PM increased at all sites at daybreak, followed by a mid-day peak at some sites, and a more spread-out evening peak at all sites. Average carbon monoxide concentrations at different sites and seasons ranged from 7 to 55 ppm, and were generally lower at residential sites than at traffic sites. The results show that PM in these four neighborhoods is substantially higher than the WHO Air Quality Guidelines and in some cases even higher than the WHO Interim Target 1, with the highest pollution in the poorest neighborhood.
Engelbrecht et al.	Environmental Monitoring and Assessment (2001)	PM2.5 and PM10 concentrations from the Qalabotjha low-smoke fuels macro-scale experiment in South Africa	PM_{10}, $PM_{2.5}$	South Africa	Average PM2.5 and PM10 concentrations during the study period were 86 and 97 μg m−3, respectively, at the three Qalabotjha residential sites, and 50 to 60% lower at the Villiers gradient site. Residential coal combustion had a significant impact on air quality in the vicinity of the residential neighborhood. Domestic fuel switching demonstrated potential to improve air quality.	This article presents results from the particulate monitoring campaign conducted at Qalabotjha in South Africa during the winter of 1997. Combustion of D-grade domestic coal and lowsmoke fuels were compared in a residential neighborhood to evaluate the extent of air quality improvement by switching household cooking and heating fuels. Comparisons are drawn between the gravimetric results from the two types of filter substrates (Teflon-membrane and quartz-fiber) as well as between the integrated and continuous samplers. It is demonstrated that the quartz-fiber filters reported 5 to 10% greater particulate mass than the Teflon-membrane filters, mainly due to the adsorption of organic gases onto the quartz-fiber filters. Due to heating of sampling stream to 50 C in the TEOMcontinuous sampler and the high volatile content of the samples, approximately 15% of the particulate mass was lost during sampling. The USEPA 24-hr PM2:5 and PM10 National Ambient Air Quality Standards (NAAQS) of 65 g m−3 and 150 g m−3, respectively, were exceeded on several occasions during the 30-day field campaign. Average PM concentrations are highest when D-grade domestic coal was used, and lowest between day 11 and day 20 of the experiment when a majority of the low-smoke fuels were phased in. Source impacts from residential coal combustion are also found to be influenced by changes in meteorology, especially wind velocity. PM2:5 and PM10 mass, elements, water-soluble cations (sodium, potassium, and ammonium), anions (chloride, nitrate, and sulfate), as well as organic and elemental carbon were measured on 15 selected days during the field campaign. PM2:5 constituted more than 85% of PM10 at three Qalabotjha residential sites, and more than 70% of PM10 at the gradient site in the adjacent community of Villiers. Carbonaceous aerosol is by far the most abundant component, accounting for more than half of PM mass at the three Qalabotjha sites, and for more than a third of PM mass at the gradient site. Secondary aerosols such as sulfate, nitrate, and ammonium are also significant, constituting 8 to 12% of PM mass at the three Qalabotjha sites and 15 to 20% at the Villiers gradient site.

Author	Journal (Year)	Title	Pollutant	Country/Location	Summary and Comments	Abstract
Etyemezian et al.	Atmospheric Environment (2005)	Results from a pilot-scale air quality study in Addis Ababa, Ethiopia	PM_{10}, CO, O_3	Addis Ababa, Ethiopia	PM10 for urban and suburban sites were ~100 and 40 µg m−3 respectively. 34-60% of mass was from geologically derived material (from unpaved roads). Saw daily diurnal peaks associated with traffic, food preperation and heating.	Twenty-one samples were collected during the dry season (26 January–28 February 2004) at 12 sites in and around Addis Ababa, Ethiopia and analyzed for particulate matter with aerodynamic diameter o10 mm (PM10) mass and composition. Teflon-membrane filters were analyzed for PM10 mass and concentrations of 40 elements. Quartz-fiber filters were analyzed for chloride, sulfate, nitrate, and ammonium ions as well as elemental carbon (EC) and organic carbon (OC) content. Measured 24-h PM10 mass concentrations were o100 and 40 mgm 3 at urban and suburban sites, respectively. PM10 lead concentrations were o0.1 mgm 3 for all samples collected, an important finding because the government of Ethiopia had stopped the distribution of leaded gasoline a few months prior to this study. Mass concentrations reconstructed from chemical composition indicated that 34–66% of the PM10 mass was due to geologically derived material, probably owing to the widespread presence of unpaved roads and road shoulders. At urban sites, EC and OC compounds contributed between 31% and 60% of the measured PM10 while at suburban sites carbon compounds contributed between 24% and 26%. Secondary sulfate aerosols were responsible for o10% of the reconstructed mass in urban areas but as much as 15% in suburban sites, where PM10 mass concentrations were lower. Non-volatile particulate nitrate, a lower limit for atmospheric nitrate, constituted o5% and 7% of PM10 at the urban and suburban sites, respectively. At seven of the 12 sites, real-time PM10 mass, real-time carbon monoxide (CO), and instantaneous ozone (O3) concentrations were measured with portable nephelometers, electrochemical analyzers, and indicator test sticks, respectively. Both PM10 and CO concentrations exhibited daily maxima around 7:00 and secondary peaks in the late afternoon and evening, suggesting that those pollutants were emitted during periods associated with motor-vehicle traffic, food preparation, and heating of homes. The morning concentration maxima were likely accentuated by stable atmospheric conditions associated with overnight surface temperature inversions. Ozone concentrations were measured near mid-day on filter sample collection days and were in all cases <45 parts per billion.
Ghose et al.	Environmental Monitoring and Assessment (2005)	Assessment of the status of urban air pollution and its impact on human health in the city of Kolkata.	SPM, RPM, CO, SO_2, NO_X, Pb	Kolkata, India (Calcutta)	RPM concentration varied from 124.1 µg/m3 (at AQ2) to 192.5 µg/m3 (at AQ1) with an overall mean concentration of 152.2 µg/m3, always above national standard of 100. Highest concentrations were typically in the evening. NOx were almost always above national standard of 80 µg/m3. Much of the pollution is likely the result of poor infrastrucure, even for India (only 6% road area- should be 25-30%)	Air pollution has significant effects on exacerbation of asthma, allergy and other respiratory diseases. Like many other magacities in the world the ambient air quality of Kolkata is also being deteriorated day by day. Automobile exhausts and certain industrial pollutants produce O3 by photochemical reactions. The particulate matter, particularly less than 10 µ in size, can pass through the natural protective mechanism of human respiratory system and plays an important role in genesis and augmentation of allergic disorders. Sources of air pollution in the area and the unique problem arising out of the emission from the vehicles, industries, etc. have been described. Ambient air quality was monitored along with micrometeorological data and the results are discussed. The status of air pollution in the area has been evaluated and a questionnaire survey was conducted to estimate the allergic symptoms and exposure to assess the respiratory disorders. The data are analysed to evaluate the critical situation arising out of the emission of air pollutants and the impact on human health due to respirable diseases (RDs) to middle class sub-population (activity-wise) in the area are assessed. A strategic air quality management plan has been proposed. For the mitigation of air pollution problems in the city, the different measures to be adopted to maintain the balance between sustainable development and environmental management have been discussed.
Gupta et al.	Atmospheric Environment (2006)	Trends of particulate matter in four cities in India	PM	Delhi, Mumbai, Kolkata, Chennai - India	PM concentrations are all above national and WHO standards, but are showing decreasing (PM10) and steady (TSP) trends, while population and automobility are greatly increasing. Likely the result of stricter emission standards.	Particulate matter (PM) in all the four Metropolitan cities in India are higher than the prescribed standards of Central Pollution Control Board, India as well as WHO guidelines. Over last 10 years various changes in fuel quality, vehicle technologies, industrial fuel mix and domestic fuel mix have taken place resulting in changes in air quality in these cities. A set of time series analysis methods viz. t-test adjusted for seasonality, Seasonal Kendall test and Intervention analysis have been applied to identify and estimate the trend in PM10 and total suspended particles (TSP) levels monitored for about 10 years at three monitoring sites at each of the four cities in India. These tests have indicated that overall PM10 levels in all four metro cities have been decreasing or stationary. The distinct trends for the monthly averages of PM10 concentrations at Parel, Kalbadevi in Mumbai and Thiruvattiyar in Chennai for the period 1993–2003 were declining by 10%, 6% and 5% per annum, respectively. This is ascribed to a shift in the magnitude and spatial distribution of emissions in the city. However, the monthly averages of TSP do not have a clear trend over the period 1991–2003
Gurjar et al.	Atmospheric Environment (2008)	Evaluation of emissions and air quality in megacities	TSP, CO, SO_2, NO_X,	World megacities	Of 18 megacities considered here 5 classify as having ''fair'' air quality, and 13 as ''poor''. The megacities with the highest MPI, Dhaka, Beijing, Cairo, and Karachi, most urgently need reduction of air pollution. There seems to be a link between a knowledge index (KIR) and air quality.	Several concepts and indicators exist to measure and rank urban areas in terms of their socio-economic, infrastructural, and environment-related parameters. The World Bank regularly publishes the World Development Indicators (WDI), and the United Nations reports the City Development Index (CDI) and also ranks megacities on the basis of their population size. Here, we evaluate and rank megacities in terms of their trace gas and particle emissions and ambient air quality. Besides ranking the megacities according to their surface area and population density, we evaluate them based on carbon monoxide (CO) emissions per capita, per year, and per unit surface area. Further, we rank the megacities according to ambient atmospheric concentrations of criteria pollutants, notably total suspended particles (TSP), sulfur dioxide (SO2), and nitrogen dioxide (NO2). We propose a multi-pollutant index (MPI) considering the combined level of the three criteria pollutants (i.e., TSP, SO2, and NO2) in view of the World Health Organization (WHO) Guidelines for Air Quality. Of 18 megacities considered here 5 classify as having ''fair'' air quality, and 13 as ''poor''. The megacities with the highest MPI, Dhaka, Beijing, Cairo, and Karachi, most urgently need reduction of air pollution.

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Han and Naeher	Environmental International (2006)	A review of traffic-related air pollution exposure assessment studies in the developing world	PM, CO, NO_2, VOC, PAH	Multiple Cities	Airborne pollution is more serious in the developing world than in the developed countries, especially in those developing countries currently under rapid industrialization and changes in land use.	Exposure assessment studies in the developing world are important. Although recent years have seen an increasing number of trafficrelated pollution exposure studies, exposure assessment data on this topic are still limited. Differences among measuring methods and a lack of strict quality control in carrying out exposure assessment make it difficult to generalize and compare findings between studies. In this article, exposure assessment studies carried out in the developing world on several traffic-related air pollutants are reviewed. These pollutants include particulate matter (PM), carbon monoxide (CO), nitrogen dioxide (NO2), volatile organic compounds (VOCs), and polycyclic aromatic hydrocarbons (PAHs). In addition, it discusses advantages and disadvantages of various monitoring methods (ambient fixed-site monitoring, microenvironment monitoring, and personal exposure assessment using portable samplers) for these pollutants in exposure assessment studies. Also included in this paper is a brief introduction of standards for these pollutants in ambient air or in occupational settings established by the United States Environmental Protection Agency (USEPA), the United States Occupational Safety and Health Administration (OSHA) and the World Health Organization (WHO). The review ends with a summary of the limitations and gaps in recent studies and suggestions for future research in the developing world.
Harrison and Yin	Atmospheric Environment (2000)	Particulate matter in the atmosphere: which particle properties are important for its effects on health?	PM_{10}, $PM_{2.5}$	UK, Portugal, Pakistan	Strong similarities and consistancies in PM composition across the developed world and it matches the emission inventories fairly well. But lots of differences seen from developing countries because of higher pollutant loadings and much more natural wind-blown PM. Despite this, strong similarites in exposure-response from all cities, which is surprising... suggesting, the chemical composition isn't the driver. More work needs to be done to confirm it is particle size (phisical) properties causing effect.	Whilst epidemiological studies have consistently demonstrated adverse effects of particulate matter exposure on human health, the mechanism of effect is currently unclear. One of the major issues is whether the toxicity of the particles resides in some particular fraction of the particles as defined by chemical composition or size. This article reviews selected data on the major and minor component composition of PM2.5 and PM10 particulate matter showing quite major geographic variations in composition which are not reflected in the exposure-response coefficients determined from the epidemiology which show remarkably little spatial variation. The issue of particle size is more difficult to address due to the scarcity of data. Overall, the data presented provides little support for the idea that any single major or trace component of the particulate matter is responsible for the adverse effects. The issue of particle size is currently unclear and more research is warranted.
Health Effects Institute	Special Report (2004)	Health Effects of Outdoor Air Pollution in Developing Countries of Asia: A Literature Review	All	Asia	Urban air pollution contributes each year to approximately 800,000 deaths and 4.6 million lost life-years worldwide (WHO 2002). Two thirds of the deaths and lost life-years occur in the developing countries of Asia. Air pollution in Asian cities is closely tied to levels and trends in economic and social development. As well as rapidly increasing industrialization, urbanization, population growth, and demand for transportation, meteorologic conditions influence air pollution levels in most South and Southeast Asian cities. In western countries, generally indoor air pollution isn't considered for exposure, but in developing countries indoor air pollution can be significantly higher than outdoor.	For pollutant–outcome pairs for which four or more estimates were available, we calculated a summary measure of the percent change in mean number of daily events associated with a 10 μg/m3 increase in the pollutant. PM10, total suspended particles, and the gaseous pollutants SO2 and NO2 were each associated with all-cause mortality. Although the current studies are not representative of the full range of Asian settings, the summary estimates for PM10 and SO2 (an approximately 0.4%–0.5% increase in all-cause mortality for every 10 μg/m3 of exposure) resemble those previously reported by the large US and European multicity studies that used comparable statistical methods (Table 2). Statistical tests for publication bias suggested that this might be an issue for SO2 and all-cause mortality. Correcting for this possible bias resulted in a small reduction in the magnitude of the estimated increase in daily mortality. The size of the Asian air pollution epidemiology literature exceeded our expectations. We identified 138 studies published in the peer-reviewed literature between 1980 and 2003, most published over the past decade. This number may well be an underestimate because we may have failed to identify some papers published only in local peerreviewed literature. Asian investigators may also encounter difficulties in publishing their work in Western journals, so some research may simply go unreported. And although some countries are well represented in the literature, others are not. The majority of studies have been conducted in the more developed countries of East Asia with relatively few studies conducted in South and Southeast Asia, where rapid urban growth has been accompanied by extremely high levels of air pollution.
Kandlikar and Ramachandran	Annual Review of Energy and Environment (2000)	The Causes and Consequences of Particulate Air Pollution in Urban India: A Synthesis of the Science	PM_{10}	Indian Megacities (Delhi, Mumbai)	Indian cities are undergoing a risk transition from 'traditional' risks to 'modern' risks associated with air pollution. The urban poor are bearing the brunt of the risk overlap resulting mostly from the use of biomass as a fuel, while more modern sources (traffic, industry) are experienced similiarly by both the poor and rich. There is a striking imbalance between the knowledge of the issue of urban air pollution and its importance to public health.	Indian megacities are among the most polluted in the world. Air concentrations of a number of air pollutants are much higher than levels recommended by the World Health Organization. In this paper, we focus on Mumbai and Delhi to characterize salient issues in health risks from particulate air (PM10) pollution in Indian cities. We perform a synthesis of the literature for all elements of the causal chain of health risks—sources, exposure, and health effects—and provide estimates of source strengths, exposure levels, and health risks from air pollution in Indian cities. We also analyze the factors that lead to uncertainty in these quantities and provide an overall assessment of the state of scientific knowledge on air pollution in urban India.

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Kaushik et al.	Environmental Monitoring and Assessment (2006)	Assessment of ambient air quality in urban centres of Haryana (India) in relation to different anthropogenic activities and health risks.	TSPM. PM_{10}, SO_2, NO_2	Haryana, India	Particulates exceeded standards for all areas, while NO2 and SO2 were within limits. SO2 increased during winter months with an increase in combustion for space heating and relatively stable atmospheric conditions. Likely corresponds to an increase in hospital visits for acute respiratory diseases during the winter. Monsoon rains also seemed to 'scrub off' concentrations.	Considering the mounting evidences of the effects of air pollution on health, the present study was undertaken to assess the ambient air quality status in the fast growing urban centres of Haryana state, India. The samples were collected for total suspended particulate matter (TSPM), respirable suspended particulate matter (PM10), sulfur dioxide (SO2), and oxides of nitrogen (NO2) during different seasons from 8 districts of Haryana during January, 1999 to September, 2000. The four types of sampling sites with different anthropogenic activities i.e. residential, sensitive, commercial and industrial were identified in each city. The ambient air concentration of TSPM and PM10 observed was well above the prescribed standards at almost all the sites. The average ambient air concentrations of SO2 and NO2 were found below the permissible limits at all the centres. Comparatively higher concentration ofSO2 was observed during winter seasons, which seems to be related with the enhanced combustion of fuel for space heating and relatively stable atmospheric conditions. Air Quality Index (AQI) prepared for these cities shows that residential, sensitive and commercial areas were moderately to severely polluted which is a cause of concern for the residents of these cities. The high levels of TSPM and SO2 especially in winter are of major health concern because of their synergistic action. The data from Hisar city reveals a significant increase in the total number of hospital visits/admissions of the patients with acute respiratory diseases during winter season when the level of air pollutants was high.
Kulkarni and Patil	Environmental Monitoring and Assessment (1999)	Monitoring of daily integrated exposure of outdoor workers to respirable particulate matter in an urban region of India	RPM (PM_5)	Mumbai, India	The average 24-hour integrated exposure to RPM was 322 µg/m3 and exceeded the corresponding PM10 level observed at the nearest Ambient Air Quality Monitoring Station by a factor of 2.25. The daily integrated exposure and therefore the health risk of outdoor workers in an urban area is significantly more serious than that indicated by ambient air quality data. The residential and occupational components of daily exposure were nearly equal (3.62 mgh/m3 and 3.58 mg h/m3, respectively). There was no correlation between person RPM and ambient RPM.	It is more and more recognised that an estimation of the exposure of the population to air pollutants is more relevant than the ambient air quality, since it gives a better indication of health risk. Outdoor workers in an urban region are generally of low income status and are exposed to higher levels of both indoor and outdoor air pollution. Hence respondents from this population subgroup have been selected for this study. Outdoor workers are divided into two categories, viz. traffic constables and casual outdoor workers like watchmen, roadside shopkeepers etc. Most of the respondents are from the lower income group. Each respondent is monitored for a continuous 48-hour period. The sampling frequency is once a week. The study region is situated in the north-west part of the Greater Mumbai Municipal Corporation. It can be classified as industrial cum residential area. The daily integrated exposure of the outdoor workers consists of two major micro-environments, viz. occupational and indoor residential. A personal air sampler was used along with a cyclone to measure levels of Respirable Particulate Matter (RPM). The cyclone has a 50% removal efficiency for particle diameter of 5 m. Paired samples of PM10 (ambient) and RPM (personal) were collected to establish the correlation between them. The average 24-hour integrated exposure to RPM was 322 g/m3 and exceeded the corresponding PM10 level observed at the nearest Ambient Air Quality Monitoring Station by a factor of 2.25. The 90% confidence interval for this exposure is 283–368 g/m3. This study clearly demonstrates that the daily integrated exposure and therefore the health risk of outdoor workers in an urban area is significantly more serious than that indicated by ambient air quality data.
Mage et al.	Atmospheric Environment (1996)	Urban air pollution in megacities of the world	SPM, CO, SO_2, NO_2, Pb, O_3	World megacities (>10 million people)	While the specific air quality issues from each megacity and different, all of those in the developing world have a serious concern about SPM. There is an immediate need for improved monitoring and emissions inventory as a prerequisite for sound management strategies.	Urban air pollution is a major environmental problem in the developing countries of the world. WHO and UNEP created an air pollution monitoring network as part of the Global Environment Monitoring System. This network now covers over 50 cities in 35 developing and developed countries throughout the world. The analyses of the data reported by the network over the past 15-20 yr indicate that the lessons of the prior experiences in the developed countries (U.S.A., U.K.) have not been learned. A study of air pollution in 20 of the 24 megacities of the world (over 10 million people by year 2000) shows that ambient air pollution concentrations are at levels where serious health effects are reported. The expected rise of population in the next century, mainly in the developing countries with a lack of capital for air pollution control, means that there is a great potential that conditions will worsen in many more cities that will reach megacity status. This paper maps the potential for air pollution that cities will experience in the future unless control strategies are developed and implemented during the next several decades.
Nagendra et al.	Transportation Research Part D (2007)	Assessment of air quality near traffic intersections in Bangalore city using air quality indices	SPM, RSPM, CO, SO_2, NO_X	Bangalore, India	At all locations all AQI values developed from data are improving and categorized as 'good' to 'moderate'. Descriptors may be poorly chosen. Ex- Good for PM10 is 0-100 µg m−3 (up to the national standard)	Air quality indices are used for local and regional air quality management in many metro cities of the world. In the present study, air quality indices have been calculated using the US Environmental Protection Agency procedure to assess the status of ambient air quality near busy traffic intersections in Bangalore, India. The measured 24 h average criteria pollutants such as sulfur dioxide, oxides of nitrogen, respirable suspended particulate matter and suspended particulate matter for the period from 1997 to 2005 at three air quality monitoring stations are used for the development of AQIs. The result indicated that the air pollution at all the three air quality monitoring stations can be characterized as 'good' and 'moderate' for SO2 and NOx concentrations for all days from 1997 to 2004. Analysis of air quality indices values for both forms of suspended matter concentrations during 1999–2005 indicates 91% and 94% of the times days are in category 'good' and 'moderate'. The yearly average air quality indices values of respirable suspended particulate matter and suspended particulate matter concentrations indicated decreasing trend and are coming under the category of 'good' and 'moderate' form the category of 'poor' and 'very poor'.

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Padhi and Padhy	Inhalation Toxicology (2008)	Assessment of intra-urban variability in outdoor air quality and its health risks.	SPM, CO, SO_2, NO_2	Suburban India	Residential exposure to highly trafficked roads is associated with respiratory illness. Being within 1 km of a major road had a significant effect of respiratory illness while being within 5km did not.	Ambient air quality along with micrometeorological data was measured in a suburban area of India, from March 2006 to February 2007 in order to assess the intra-urban variability of air pollutants in different parts of the city. The prevalences of asthma and respiratory disorders were determined using a questionnaire survey of 750 adults. The association between intra-urban variability of air pollution and respiratory diseases were evaluated with logistic regression analyses. Compared with subjects staying 5.0 km away from a main road to those subjects living within 0.5 km and 1.0 km had odds ratios of 1.00 (95% CI, 0.85 to 1.50), 3.57 (95% CI, 3.00 to 3.95), and 3.00 (95% CI, 2.85 to 3.50), respectively for doctor-diagnosed asthma. A reduction of measured pollutant concentration with increase in distance from the main road was observed. The study demonstrated that residential exposure to highly trafficked roads is associated with respiratory diseases. Considering the continuing rise in motorized vehicle use and the paramount role of inhalation toxicology, these findings have high public health relevance and should be corroborated in prospective studies.
Shendall and Naeher	Environment International (2002)	A pilot study to assess ground-level ambient air concentrations of fine particles and carbon monoxide in urban Guatemala	$PM_{2.5}$, CO	Guatemala City, Quetzaltenango, Antigua, Guatemala	Street level fine particulates significantly exceed the ambient monitor concentrations. Ground-level PM2.5 concentrations were between 40-90 µg m-3. CO were between 3.5-7 ppm. Both varied by site and city.	Ambient concentrations and the elemental composition of particles less than 2.5 Am in diameter (PM2.5), as well as carbon monoxide (CO) concentrations, were measured at ground-level in three Guatemalan cities in summer 1997: Guatemala City, Quetzaltenango, and Antigua. This pilot study also included quantitative and qualitative characterizations of microenvironment conditions, e.g., local meteorology, reported elsewhere. The nondestructive X-ray fluorescence elemental analysis (XRF) of Teflon filters was conducted. The highest integrated average PM2.5 concentrations in an area (zona) of Guatemala City and Quetzaltenango were 150 Ag m 3 (zona 12) and 120 Ag m 3 (zona 2), respectively. The reported integrated average PM2.5 concentration for Antigua was 5 Ag m 3. The highest observed half-hour and monitoring period average CO concentrations in Guatemala City were 10.9 ppm (zona 8) and 7.2 ppm (zonas 8 and 10), respectively. The average monitoring period CO concentration in Antigua was 2.6 ppm. Lead and bromin experience in the future unless control strategies are developed and implemented during the next several decades.sidential, sensitive and commercial areas were moderately to severely polluted which is a cause of concern for the residents of these cities. The high levels of TSPM and SO2 especially in winter are of major health concern because of their synergistic action. The data from Hisar city reveals a significant increase
Smith et al.	Annual Review of Energy and Environment (1993)	Fuel combustion, air pollution exposure, and health: the situation in developing countries	All	Developing areas	Advantages for LDC: 1- Cheaper to intro clean fuels at the beginning of development rather than to retrofit. 2- Benefit from advances in technology and monitoring from more developed coutries... including exposure modeling. Disadvantages - They are dealing with risk overlap from "new" emission risks as well as "old" risks	As described in the Appendix, there are a number of recent studies of air pollution in developing-country cities (2-5, 1 7 , 99, 100), each of necessity relying heavily on the one available source of comparative international ambient monitoring data, Global Environment Monitoring System (GEMS) (6ab-IO).! In this review , therefore, rather than simply reprqduce the GEMS data, I have chosen to examine developing-country air pollution from the standpoint of a useful analysis technique that has been under development in recent years: "Total Exposure Assessment." Basically the review is composed of four parts: 1 . A brief description of the historical and current relationship between energy use and air pollution. 2. An explanation of the idea of exposure assessment and the power that it can bring to analyses of the health impacts of air pollution. 3. Focusing on developing countries, a global exposure assessment, combining demographic data with GEMS outdoor data and less-developed country (LDC) indoor air-monitoring studies. 4. A review of the health effects literature relevant to the micro-environments found to harbor the largest human exposures .
Smith et al.	Energy (1994)	Air pollution and the energy ladder in asian cities	PM_{10}, CO, NO_2	Pune, India; Beijing, China; Bangkok, Thailand	Improvement for one house alone switching to clean fuel may not be great if no one else nearby joins in, i.e. neighborhood outdoor levels may remain high. It has shown that household fuel choice seems to have the most impact on air pollution exposures at the lowest level of development (Pune), intermediate at middle stages even with use of coal (Beijing), and least in the more economically advanced developing country, where fuel choice seems to have little or no impact (Bangkok). Finally, the results in each city would seem to indicate that true human exposures may be substantially higher than indicated by ambient monitoring stations.	Household fuel switching from lower to higher quality fuels, i.e. movement up the “energy ladder,” generally leads to substantially lower emissions of health-damaging pollutants. The extent to which human exposures are reduced is difficult to predict, however, because of interactions due to penetration of outdoor pollutants into homes and vice versa. In order to help answer the question of how much exposures might be reduced by movement up the energy ladder, a three-city household air pollution study covering particulates (PM10), nitrogen dioxide (NO2), and carbon monoxide (CO) was conducted in and near households spanning the most important current steps in each city's energy ladder. Steps examined were biomass-kerosene-gas in Pune, India; coal-gas in Beijing, China; and charcoal-gas in Bangkok, Thailand. In most instances, 24-hour sampling was conducted and some personal monitoring was undertaken during cooking periods. Preliminary calculations of the exposure and health implications of fuel switching are presented.

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Smith and Ezzati	Annual Review of Environment and Resources (2005)	How environmental health risks change with development: The epidemiologic and environmental risk transitions revisited	General	Developing areas	Risks transition from household to community to global and development proceeds. There is not an increase in chronic diseases with development. All 'disease' decrease with development. Though the proportion of total that are chronic do increase with development. The world illness burden is dominated by category I (infection disease) which is dominated by the developing world and often by children.	Transition frameworks are used to envision the important changes that occur during economic development from poor to middle-income or rich countries. We explain the derivation of and use data from the Global Burden of Disease (GBD) and Comparative Risk Assessment (CRA) projects of the World Health Organization (WHO) to explore the classic epidemiologic transition framework, which describes the changes in causes of illness and death during economic development. We provide the first full empirical test of the environmental risk transition framework, which describes the shift in environmental risks during development from household, community, and global risk factors.We find that the simplistic conclusions commonly drawn about the epidemiologic transition, in particular the increase in chronic diseases with development, are not supported by current data; in contrast, the conceptual framework of the environmental risk transition is broadly supported in a cross-sectional analysis. We also describe important kinds of environmental health risks and diseases that are not well estimated using current methods
Tri-Tugaswati	Environmental Research (1993)	Review of air pollution and health impacts in Indonesia	SPM, SO_2, NO_X, CO, O_X, and NH_3	Indonesia	The air pollution mainly comes from land transportation, industrial emissions, and a densely populated residential area where most people perform their activities. SPM and NOx are the predominant pollutants.	Air quality monitoring is part of the initial strategy in the pollution prevention program in Indonesia. Since 1978, the government of Indonesia has had a commitment to the World Health Organization (WHO) to provide air quality data for the Global Environmental Monitoring System (GEMS Programme)—The WHO/UNEP Project, in which certain cities from all over the world have been selected. Air quality as part of the WHO/UNEP project is monitored with respect to pollutants like SPM, SO2 and NOx. The result of the monitoring indicates that SPM and NOx are the predominant pollutants. Other pollutants such as Ox, H2S, NH3, and CO are also monitored in several big cities in Indonesia. The air pollution mainly comes from land transportation, industrial emissions, and a densely populated residential area where most people perform their activities. Review of the air pollution in Indonesia was based on the reports of the air quality monitoring in several large cities in Indonesia which covered air pollutants such as SPM, SO2, NOx, CO, Ox, and NH3 from 1978 until the latest available data in 1989. This review also discusses health impact investigations conducted in the community, especially from the exposure to SPM, CO, and lead from motor vehicle exhaust.
van Donkelaar et al.	Environmental Health Perspectives (2010)	Global Estimates of Ambient Fine Particulate Matter Concentrations from Satellite-based Aerosol Optical Depth: Development and Application	$PM_{2.5}$	Global	The global population-weighted geometric mean PM2.5 concentration of 20 µg/m3. The WHO interim standard is exceeded over 50% of the population in eastern Asia. Satellite-based monitoring has shown to have good spatial agreement with ground-based monitoring.	**Background:** Epidemiologic and health impact studies of fine particulate matter (PM2.5) are limited by the lack of monitoring data, especially in developing countries. Satelliteobservations offer valuable global information about PM2.5 concentrations. Methods: Global ground-level PM2.5 concentrations were mapped using total column aerosol optical depth (AOD) from the MODIS and MISR satellite instruments and coincident aerosol vertical profiles from the GEOS-Chem global chemical transport model. **Results:** Global estimates of long-term average (2001-2006) PM2.5 concentrations at ~10 km × 10 km resolution indicate a global population-weighted geometric mean PM2.5 concentration of 20 µg/m3. The World Health Organization Air Quality PM2.5 Interim Target-1 (35 µg/m3 annual average) is exceeded over central and eastern Asia for 38% and 50% of the population, respectively. Annual mean PM2.5 concentrations exceed 80 µg/m3 over Eastern China. Evaluation of the satellite-derived estimate with ground-based in-situ measurements indicates significant spatial agreement with North American measurements (r = 0.77, slope = 1.07, n = 1057) and with non-coincident measurements elsewhere (r = 0.83, slope = 0.86, n = 244). The one standard deviation uncertainty in the satellite-derived PM2.5 is 25%, inferred from the AOD retrieval and aerosol vertical profiles errors and sampling. The global population-weighted mean uncertainty is 6.7 µg/m3. **Conclusions:** Satellite-derived total-column AOD, when combined with an aerosol transport model, provides estimates of global long-term average PM2.5 concentrations.
Vichit-Vadakan et al.	Environmental Health Perspectives (2001)	Air pollution and respiratory symptoms: results from three panel studies in Bangkok, Thailand.	PM_{10}, $PM_{2.5}$	Bangkok, Thailand	Associations were found between these pollution metrics and the daily occurrence of both upper and lower respiratory symptoms in each of the panels. The estimated odds ratios are generally consistent with and slightly higher than the findings of previous studies conducted in the United States.	Several studies in North American cities have reported associations between air pollution and respiratory symptoms. Replicating these studies in cities with very different population and weather characteristics is a useful way of addressing uncertainties and strengthening inferences of causality. To this end we examined the responses of three different panels to particulate matter (PM) air pollution in Bangkok, Thailand, a tropical city characterized by a very warm and humid climate. Panels of schoolchildren, nurses, and adults were asked to report daily upper and lower respiratory symptoms for 3 months. Concentrations of daily PM10 (PM with a mass median aerodynamic diameter less than 10 µm) and PM2.5 (airborne particles with aerodynamic diameters less than 2.5 µm) were collected at two sites. Generally, associations were found between these pollution metrics and the daily occurrence of both upper and lower respiratory symptoms in each of the panels. For example, an interquartile increase of 45 µg/m3 in PM10 was associated with about a 50% increase in lower respiratory symptoms in the panel of highly exposed adults, about 30% in the children, and about 15% in the nurses. These estimates were not appreciably altered by changes in the specification of weather variables, stratification by temperature, or inclusion of individual characteristics in the models; however, time trends in the data cause some uncertainty about the magnitude of the effect of PM on respiratory symptoms. These pollutants were also associated with the first day of a symptom episode in both adult panels but not in children. The estimated odds ratios are generally consistent with and slightly higher than the findings of previous studies conducted in the United States. Key words: air pollution, Bangkok, daily diary, particulate matter, respiratory symptoms.