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Characterization of Particulate Matter Concentrations (PM10, PM10-2.5, and PM2.5) at High-Altitude School and Residential Mircroenvironments in Quito, Ecuador

Teresa Montoya
University of Texas at El Paso, teremont20@yahoo.com

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CHARACTERIZATION OF PARTICULATE MATTER CONCENTRATIONS (PM_{10}, $PM_{10\text{-}2.5}$, AND $PM_{2.5}$) AT HIGH-ALTITUDE SCHOOL AND RESIDENTIAL MICROENVIRONMENTS IN QUITO, ECUADOR

TERESA MONTOYA

Environmental Science and Engineering

APPROVED:

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Wen-Whai Li, Ph.D., Chair

____
Rodrigo X. Armijos, M.D., ScD, Co-Chair

____
John Walton, Ph.D.

____
Norris J. Parks, Ph.D.

____
Benjamin C. Flores, Ph.D.
Dean of the Graduate School

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by

Teresa Montoya

2013

Dedication

To God, Who has given me strength every step of the way, and to my daughter, who is my inspiration

CHARACTERIZATION OF PARTICULATE MATTER CONCENTRATIONS (PM_{10}, $PM_{10-2.5}$, AND $PM_{2.5}$) AT HIGH-ALTITUDE SCHOOL AND RESIDENTIAL MICROENVIRONMENTS IN QUITO, ECUADOR

by

TERESA MONTOYA, B.S., M.S.

DISSERTATION

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Abstract

Air quality issues in Latin American countries are especially challenging because of the limited availability of resources to address them, lack of stringent standards and the rapid and uncontrolled growth of their cities increasing the number of vehicles on the road and the expansion of the industry. In particular, the city of Quito, Ecuador exacerbates its environmental issues by its high-altitude (2800 m above sea level) coupled by its location around a mountain valley and frequent temperature inversions.

This study focused on evaluating the spatial variation of the PM concentrations and the effectiveness of a central monitoring network in representing exposure. To accomplish this, a study was conducted in Quito (Ecuador) to evaluate the effect of transient and long-term ambient PM exposure on systemic inflammation, oxidative stress, and atherogenesis in a group of 300 children. Environmental PM data ($PM_{2.5}$, $PM_{10-2.5}$, and $PM_{2.5}$) were collected to evaluate the association of exposure with inflammation and arterial thickening. Weekly averages were collected at schools and residential sites every month, over a 12-month period at three exposure sites (high, medium, and low). Particulate matter sources in Quito, based on size fraction, can be attributed to quarries, unpaved roads, and soil erosion coming especially from the north (for PM_{10}), while the majority of $PM_{2.5}$ can be attributed to traffic emissions and industrial sources (CORPAIRE, 2007).

Spatial and temporal variations of outdoor coarse PM ($PM_{10-2.5}$) concentrations were associated with meteorological data observed at a central monitoring network. Indoor concentrations for all PM fractions showed weaker association with meteorological or co-pollutant data collected at a central monitoring station. However, outdoor school and residential measurements showed stronger associations with indoor measurements, making them good indicators for indoor exposures, especially at places with no significant indoor PM sources and good ventilation, such as schools in Quito. Indoor residential levels were the highest levels from all the microenvironments studied, making them a priority for evaluation in future studies.

Patterns of PM exposure across the three zones varied depending on PM size fraction, with Zone 2 resulting in higher exposure of $PM_{2.5}$ because of its location in the urban center of Quito and high traffic emissions, while the northern and southern zones (1 and 3 respectively) yielded higher exposures

for $PM_{10-2.5}$. In the case of PM_{10}, exposure classification could be misinterpreted because it contains both fine and coarse fractions of particulate matter. It is important to separate exposure by each size fraction because size influences patterns of deposition within the respiratory tract as well as source of emission. Coarse particles come primarily from mechanical grinding, windblown dust, agricultural activities, while $PM_{2.5}$ is more likely to come from combustion processes, therefore their chemical composition is different and health effects would differ also. Future studies should focus on isolating $PM_{10-2.5}$ levels with health effects, to evaluate the importance of establishing regulatory standards.

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Chapter 1: Introduction

Available resources in developing countries for dealing with urban environmental problems, such as air quality, are quite limited. Therefore, close attention must be paid to choose control measures and policies that will be both practical and effective (Jurado and Southgate, 1999). In particular, the rapid growth experienced in Latin American urban centers has brought with it an increase in vehicle numbers and the expansion of industry without environmental controls (Faiz et al, 1995; Jurado and Southgate, 1999). The air quality issues in these countries are compounded by high altitude, uncontrolled combustion, aged vehicle fleet, and dust emissions from unprotected surfaces. A literature review published in 2003 by Baldasano and co-workers points that, for developed countries, strong restrictions imposed by government and international organizations will eventually lead to a reduction in pollutant concentrations. However, for developing countries, concentrations of air pollutants remain high and the trend will be the elevation of their ground levels as they become rapidly urbanized increasing traffic congestion, but lacking the necessary guidelines or infrastructure to support this development. Such is the case for several cities in Latin America. Specific characteristics contributing to the deterioration of air quality in Latin America include (Faiz et al, 1995):

- The use of aging and poorly-maintained diesel-powered vehicles.
- Higher average age of the vehicle fleet.
- Production of obsolete vehicle models, with fuel efficiencies half as those practiced in America or Japan, having emission characteristics of US models of the 1960s and 1970s.
- Poor fuel quality including high lead content of gasoline and the high sulfur content of diesel
- Insufficient road space (ratio of local streets to arterials), ineffective traffic management, and poor public transportation systems have contributed to traffic congestion, declining travel speeds, and increasing pollutant emissions in all major metropolitan centers in Latin America.
- Poor quality in the road network leading to multiple unpaved roads.
- Industry emissions from combustion sources.

- Lack of strong environmental standards.

Shendell and Naeher (2002) measured $PM_{2.5}$ and CO in Guatemala in 1997. Data collected suggested that street-level fine particle concentrations ($PM_{2.5}$) exceeded the levels measured in the ambient network. Characterization of the $PM_{2.5}$ levels suggested sources of air pollution including fossil fuel combustion emitting hydrocarbons, combustion of conventional sulfurous fuels, soil/roadway dust, farm/agricultural dust, and vehicle emissions.

A study by Gee and Sollars (1997) measured VOCs at Caracas (Venezuela), Quito (Ecuador), Santiago (Chile), and Sao Paulo (Brazil), and two cities in Asia Bangkok (Thailand) and Manila (Philippines). Levels in Quito were the lowest of all the cities studied and this may reflect its high altitude, allowing for the use of fuels with low aromatic content. The similarity in the VOC distribution across the Latin American cities implies a similar set of emission sources and they concluded that vehicles are the predominant source for air pollution.

Bogo et al. (2003) measured daily concentration levels of PM_{10} and $PM_{2.5}$ levels in Buenos Aires (Argentina) from December (1998)- September (1999). Levels of $PM_{2.5}$ correlated with CO during the winter, an indication of traffic emissions contributing to the $PM_{2.5}$ levels. Levels of PM_{10} did not correlate well with CO, an indication that the sources of the coarse fraction are not solely traffic emissions. The $PM_{2.5}$ levels measured in the study were near or larger than the U.S. EPA standard. Hence, the levels of $PM_{2.5}$ are dangerous and may have a significant health impact, although in this study, health impacts were not assessed. This work is considered as the first attempt to monitor PM in Buenos Aires. Buenos Aires has a flat topology and high wind speeds, which allow for the dispersion of pollutants (no accumulation), the opposite of Quito, Ecuador.

The implications of elevated levels of particulate matter in Latin America can have a significant impact in the population. A study done in Temuco, Chile by Sanhueza, et al (2009) found that PM_{10} had a significant association with daily mortality and morbidity. There is evidence of positive relationships between ambient PM levels and mortality, hospital admissions, and acute respiratory infections (ARI) for cardiovascular and respiratory disease. In particular, the study results show that for an increase of

100 μg/m^3 in PM_{10} the RR (relative risk) for mortality was 1.164 (CI 1.094-1.239), 1.121 (CI 1.082-1.161) for hospital admissions, and 1.105 (CI 1.088-1.123) for ARI in adults older than 65 years.

Overall, the limited number of air quality studies that have been conducted in Latin America indicate that levels of particulate matter is a major problem in the region. Resources to solve the problem are limited therefore effective and practical measures must be proposed in order to protect the population.

1.1 Air Quality in Quito, Ecuador

Quito is located approximately at 0º13'23" S and 78º30'45" W with an average elevation of 2,800 meters above the sea level, making combustion possible with 27 percent less oxygen than at sea level. Thus, combustion is less efficient and has greater emission of pollutants. It is located in north-central Ecuador in the Guayllabamba river basin on the eastern slopes of Pichincha, an active stratovolcano in the Andes Mountains. The city is surrounded by mountains, minimizing wind transport of pollutants out of the valley. In addition, the city gets around 2,000 hours of sunlight per year due to its location (15 miles from the Equator). Population according to the 2010 census is at 2,239,191.

Quito has a fairly constant cool climate, with spring-like weather year round. Maximum and minimum average temperatures during the day range from 65.7°F to 48.7°F at night. Rather than experiencing four-seasons, Quito has a wet period known as Winter (October-May) and a dry period known as Summer (June-September). Temperature inversions are common in July thru September and November thru December (when the sky has no clouds and lets heat radiate into space)

Vehicle ownership has increased exponentially, increasing at the same time the exposure to traffic emissions. In 1992, it went from 61 vehicles per 1000 people, to 181 vehicles per 1000 people in 2007. By the end of the year 2011, the motor vehicle fleet was at 410,000 and the number of industries regarded as having a "significant environmental impact" were 1,302 (Secretaría de Ambiente, 2011). At the same time, the abundance of fossil fuels (subsidization of energy in Quito) have significantly increased motor vehicle usage and encouraged the establishment of energy-intensive industry (Jurado and Southgate, 1999). Although the increase in motor vehicle usage has coincided with the deterioration

of air quality, Jurado and Southgate suggested that vehicular exhaust does not make up most of the city's pollution when focusing on certain pollutants. Previous analysis revealed that 44% of the sulfur dioxide (SO_2) and 40% of nitrogen oxides (NOx) come from textile and leather-working factories and the food and beverage industry emits 37% of the SO_2 and 35% of the NOx.

Quito's geographical location sets itself to have air quality issues similar to other Latin American cities such as Mexico City, with its high-altitude (2800 m) coupled by its location around a mountain valley and its frequent experience of temperature inversions (Harris et al, 2011). Brachtl et al. (2009) observed that morning rush-hour traffic and temperature inversions caused daily maxima for polycyclic aromatic hydrocarbons (PAH), sulfur dioxide (SO_2), nitrogen dioxide (NO_2), carbon monoxide (CO), and $PM_{2.5}$. Quito's air quality problems have resulted in respiratory illnesses (e.g. pneumonia) costing its residents several millions of dollars annually in lost earnings and medical expenditures (Jurado and Southgate, 1999). Carbon monoxide (CO) levels in Quito from vehicle emissions have resulted in 92% of children, going to school in a high-traffic area, having carboxyhemoglobin (COHb) levels above the safe level. The same group of children are 3.25 times more likely to have an acute respiratory infection, ARI (Estrella et al, 2005). Harris et al, (2011) associated higher ambient air pollution levels ($PM_{2.5}$ and NO_2) as measured at El Camal, with pneumonia hospitalizations, respiratory illness, stunting and anemia.

1.2 Air Quality Standards in Quito, Ecuador

Quito has not remained dormant in its air quality issues and it currently has the Metropolitan Network of Air Monitoring (REMMAQ in Spanish) in place, divided into five components to measure air quality and meteorological data. The five components along with their measured parameters are as follows:

1. Automatic Network of Air Quality (*Red Automática de Calidad del Aire, RAUTO*). Composed of 8 stations located in the 8 administrative zones of Quito (Carapungo, Cotocollao, Belisario, Centro, El Camal, Guamaní, Los Chillos, and Tumbaco) plus one backup station, measure SO_2 (Carapungo, Cotocollao, Belisario, Centro, El Camal, and Tumbaco), CO (Carapungo,

Cotocollao, Belisario, Centro, El Camal, and Guamaní), O_3 (at all eight stations), NO_x (Carapungo, Cotocollao, Belisario, Centro, El Camal, and Guamaní), $PM_{2.5}$ (Carapungo, Cotocollao, Belisario, Centro, and El Camal) and PM_{10} (Carapungo, Guamaní, and Tumbaco).

2. Passive Monitoring Network (*Red de Monitoreo Pasivo, REMPA*). Operational since December, 2005. Monitors at 35 locations with high population and vehicle traffic along the QMD, measuring NO_2, SO_2, and BTX 30-days per month, and O_3, and aldehydes for 10-days twice a month.
3. Deposit Network (*Red de Depósito, REDEP*). Operational since May 2005 with 35 monitoring locations along the QMD, to measure 30-day monthly concentrations of particulate matter by gravimetric analysis.
4. Active Network of Particulate Matter (Red Activa de Material Particulado, RAPAR). Operational since May 2003 and composed of nine high volume samplers for PM_{10}, and two for $PM_{2.5}$, with 24-hr measurements taken every six days.
5. Meteorological Network (*Red Meteorológica, REMET*). Meteorological parameters such as temperature, wind speed and direction, solar radiation, relative humidity, atmospheric pressure, and precipitation are measured at six out of the nine automatic stations (under bullet no. 1). Meteorological stations are included at Carapungo, Cotocollao, Belisario, el Camal, Tumbaco, and Los Chillos.
6. Network to Monitor Environmental Noise (*Red de Monitoreo de Ruido Ambiente, REMRA).* Fully operational from August 2010 with three stations along the North-Center-South length of Quito at Jipijapa, Centro, and Camal.

The monitors were overlooked by CORPAIRE (Corporación para el Mejoramiento de la Calidad del Aire) from 2004-2010. At the end of the year 2010, the monitoring network became part of the Municipal Environmental Department of the Quito Metropolitan District (*Secretaría de Ambiente del Municipio del Distrito Metropolitano de Quito)*. The monitoring network was established since 2003 and validated by the US EPA in 2004. Information acquired by the monitoring network is available in the Internet at www.quitoambiente.gob.ec

Quito's air quality standards are known as Norma de Calidad del Aire Ambiente (NCAA) and are followed in all of Ecuador to protect the health and well-being of the community, air quality, ecosystems and the environment as a whole. These guidelines were revised between 2010 and 2011 and officially established June 7, 2011. The norms show standards for seven pollutants that include PM_{10}, $PM_{2.5}$, NO_2, SO_2, CO, O_3, and benzene and are given in Table 1.1. Table 1.2 shows guidelines established by the World Health Organization (WHO) and Table 1.3 shows the National Ambient Air Quality Standards (NAAQS) established by the US Environmental Protection Agency (EPA) for comparison purposes. The NAAQS introduce the secondary standard, which is followed to protect public welfare, including protection against decreased visibility, damage to animals, crops, vegetation, and buildings. The WHO or NCAA guidelines only provide a primary standard to protect health. Overall, Quito's NCAA exceed WHO guidelines for PM_{10}, $PM_{2.5}$, (both annual and 24-hr) and for SO_2 (24-hr).

Table 1.1: NCAA (Normas de Calidad del Aire Ambiente) Standards for Ecuador

Pollutant	Level	Averaging Time	Allowed Exceedances
[1]Total Suspended Particles	1 mg/cm^3	Accumulated over 30 days	Not allowed
[1]PM_{10}	50 µg/m^3	1-yr average	Not allowed
	100 µg/m^3	24-hr average	Not allowed
[1]$PM_{2.5}$	15 µg/m^3	1-yr average	Not allowed
	50 µg/m^3	24-hr average	Not allowed
SO_2	60 µg/m^3	1-yr average	Not allowed
	125 µg/m^3	24-hr concentration	Not allowed
	500 µg/m^3	10-min concentration	Not allowed
CO	10 µg/m^3	8-hr concentration	1-per year
	30 µg/m^3	1-hr maximum concentration	1-per year
O_3	100 µg/m^3	8-hr maximum concentration	1-per year
NO_2	40 µg/m^3	1-yr average	Not allowed
	200 µg/m^3	1-hr maximum concentration	Not allowed
Benzene	5 µg/m^3	1-yr average	Not allowed

[1] Concentration levels should be evaluated under standard conditions at 25ºC and 760mmHg

Table 1.2: Air Quality Guideline Values (WHO)

Pollutant	Level	Averaging Time
PM_{10}	20 μg/m^3	1-yr
	50 μg/m^3	24-hr (99th percentile)
$PM_{2.5}$	10 μg/m^3	1-yr
	25 μg/m^3	24-hr (99th percentile)
SO_2	20 μg/m^3	24-hr
	500 μg/m^3	10-minute
O_3	100 μg/m^3	8-hr maximum concentration
NO_2	40 μg/m^3	1-yr
	200 μg/m^3	1-hr

Table 1.3: USEPA National Ambient Air Quality Standards (NAAQS)

Pollutant	Primary/ Secondary	Level	Averaging Time	Description
PM_{10}	Both	150 μg/m^3	24-hr	Not to be exceeded more than once per yr over 3 yrs
$PM_{2.5}$	Primary	12 μg/m^3	Annual	Annual mean, averaged over 3 yrs
	Secondary	15 μg/m^3	Annual	Annual mean, averaged over 3 yrs
	Both	35 μg/m^3	24-hr	98th percentile, averaged over 3 yrs
SO_2	Primary	75 ppb	1-hr	99th percentile of 1-hr daily maximum concentrations, averaged over 3 yrs
	Secondary	0.5 ppm	3-hr	Not to be exceeded more than once per yr
CO	Primary	9 ppm	8-hr	Not to be exceeded more than once per yr
		35 ppm	1-hr	
O_3	Both	0.075 ppm	8-hr	Annual fourth-highest daily maximum 8-hr concentration, averaged over 3 yrs.
NO_2	Primary	100 ppb	1-hr	98th percentile, averaged over 3 yrs.
	Both	53 ppb	Annual	Annual mean
Lead	Both	0.15 μg/m^3	Rolling 3 month average	Not to be exceeded

From 1994 to 1997, the United States Agency for International Development (USAID) with the support of the United States Environmental Protection Agency (USEPA) sponsored the project E2P3 (Ecuador Environmental Pollution Prevention Project) (Sarmineto, 2004). The tasks undertaken by the E2P3 were summarized in two main concepts: 1) cleaner production assistance to industrial facilities, and 2) promotion of cleaner production (pollution prevention or waste minimization) (Sarmiento, 2004). Pollution prevention diagnostic assessments were carried out in companies previously selected from the most representative and waste-intensive industry sectors (Sarmiento, 2004). The effects of this project were analyzed in a document prepared by Sarmiento (2004) in which he concluded that most of the companies selected sustained the pollution prevention efforts, although there was no evidence of specific policy recommendations influenced by the results of the company demonstrations. Moreover, the project was very limited in providing dissemination mechanisms and policy advice to promote its implementation.

Other efforts to improve Quito's air quality and reduce traffic congestion are reflected in many of their programs. The Metropolitan District of Quito (DMQ) established an inspection and maintenance (I/M) program for their motor vehicle fleet known as *Revisión Técnica Vehicular*, as well as the "*Pico y Placa"* program. *Pico y Placa* consists of prohibiting the usage of vehicles, according to the last digit in their license plate, for a 6-hour period each day (from 7:00-9:30 and 16:00-19:30 hrs), in the main avenues of the city including, Morán Valverde (south), Diego de Vásquez (north), Mariscal Sucre (west), and Simon Bolívar (east), (http://www.eluniverso.com/2010/05/03/1/1447/desde-hoy-rige-pico-placa-vias-quitenas.html?p=1447A&m=256). The program was continued in 2011 and it significantly reduced CO emissions, especially during rush hours. In September 2011 the Week of Sustainable Mobility (*Semana de la Movilidad Sustentable)* was established and it aimed at promoting transportation alternatives that would diminish pollution and traffic. That week registered lower levels of CO and $PM_{2.5}$ when compared to readings during other typical weeks, when the program was not in place. (Secretaría de Ambiente, 2011).

In addition, CORPAIRE has released emission inventories for 2003, 2005, and 2007 and the now *Secretaría de Ambiente del Municipio del Distrito Metropolitano de Quito* continued to release emission

inventories for 2011 and 2012. The emission inventory corresponds solely to the area of the Metropolitan District of Quito (QMD) with an area of 12,323 square kilometers. Evaluated pollutants in the inventory include ozone precursors (NO_x, methane volatile organic compounds COVNM), PM_{10}, $PM_{2.5}$, ammonia (NH_3), CO, SO_2, and greenhouse gases CO_2, CH_4, and N_2O. Although, it is important to note that in the 2007 inventory, the authors talked about shortcomings to the document due to missing or incomplete information.

1.3 Air Quality and School Children

It is well known that children are most affected by air pollution than adults due to their still-developing lungs, higher level of physical activity, and higher metabolic rate (Fromme et al 2007, Branis et al. 2009, and Raysoni et al. 2011). Children spend from 5-8 hrs. of their day at school and the school year ranges from 175-220 days. Because many schools are so close to high-traffic roads and because there is a growing trend in the number of children that travel to and from school by vehicle (Mejia et al. 2011), children attending schools are continually exposed to vehicle emissions and it is imperative that we understand their level of exposure. Numerous studies have been done in the US and throughout the world to understand the exposure of children to particulate matter. Results suggest that children are exposed to levels above those recommended by the World Health Organization (WHO).

Janssen, et al. (2001) conducted measurements for $PM_{2.5}$, NO_2, and benzene inside and outside of 24 schools located within 400 m of motorways in the Netherlands. Results show that concentrations of air pollutants (indoor and outdoor) are significantly associated with distance, traffic density and composition, and percentage time downwind. Spatial variation within the schools was not reported. Specifically, $PM_{2.5}$ (indoor and outdoor) concentrations were reported to significantly increase with increasing truck traffic density and decrease significantly with increasing distance.

Branis, et al. (2009) measured indoor PM concentrations in a naturally ventilated elementary school gym in the central part of Prague (Czech Republic). The indoor $PM_{2.5}$ concentration levels exceeded the WHO recommended 24-hour limit of 25 $\mu g/m^3$ in 50 percent of the days measured. Meteorological factors had important associations with $PM_{2.5}$ levels: the lower the wind speed, the

higher the outdoor and indoor PM concentrations, temperature effect was significant and negative in the winter, positive in the summer, corresponding with the well-known fact that, in the winter, low temperatures facilitate the formation and extend the residence time of airborne PM, while higher temperatures in the summer favor the formation of oxidative smog, of which particulate matter is an important compound.

A study by Fromme, et al. (2007) measured PM_{10} and $PM_{2.5}$ along with temperature, relative humidity, and carbon dioxide (CO_2) starting in the winter of 2004-2005 and continuing in the summer of 2005 at 64 classrooms and a district outside the city boundary of Munich. The results found higher particulate matter median concentrations during the winter than the summer. A significant negative correlation between humidity and real-time monitored $PM_{2.5}$ was observed in winter and a significant positive correlation during the summer; no correlation between humidity and PM_{10} or $PM_{2.5}$ gravimetrically measured was observed. PM concentrations within schools were strongly correlated and this correlation was particularly high for small PM fractions. A significant positive correlation between temperature and gravimetrically measured $PM_{2.5}$ was observed in the summer. The study found that in primary schools, having class levels of 1-4, higher PM values were measured as compared to those in secondary schools, suggesting more intense physical activity of younger children. Higher PM levels were recorded with increased levels of CO_2, indicating insufficient ventilation for transport and removal of PM.

A study conducted by Raysoni, et al. (2011) monitored indoor and outdoor concentrations of fine and coarse particulate matter, black carbon (BC), and nitrogen dioxide (NO_2) at four schools in the El Paso, TX (US)- Ciudad Juarez (Mexico) border. Two schools were located in the US and two in Mexico. One school in each country was located near a high-traffic road and the other one near a low traffic zone. Results revealed that concentrations of all pollutants, except coarse PM were higher in high traffic zones that in low traffic zones. Substantial spatial variability of all pollutants in the region was observed, suggesting that children's exposure will greatly depend on their school location. In another study, by Raysoni et al. (2013), the authors examined children's exposure to traffic related air pollutants (PM, BC, NO_2, and VOCs) at four elementary schools in El Paso, Texas, three schools located near high traffic

zones and one located near a low traffic zone. Results show similarity in concentration levels amongst the three schools located near high traffic zones as compared to the low traffic zone-school, and the authors re-emphasize the importance of micro-scale monitoring because central monitors may not adequately quantify the exposure to air pollutants.

Mejia et al. (2011) conducted a literature review regarding the methodologies employed to assess the exposure of children to air pollutants at school and how these methodologies influence the assessment of the impact of this exposure on the children's health. Although the review focused on assessing the different methodologies employed to measure children's exposure to air pollutants at school, some important conclusions could be extracted from their review: (1) exposure in the classroom results from the contribution of the emissions of indoor materials and indoor activities and their depletion caused by ventilation surface sinks; (2) at schools, children are exposed to emissions from sources within and outside the school, sources such as industry emissions have been shown to contribute to higher prevalence of illness. However, around most schools, traffic is the most important source. Other sources of exposure at school include new furniture, musical instruments, and children's daily activities; (3) studies have shown that exposures at home differ from exposures at school due to different sources. Therefore, it is imperative to differentiate between both exposures in order to identify effects and activity patterns more closely associated with exposure at each type of environment; (4) results published so far have shown that socioeconomic level is a strong determinant of school location in relation to major pollution sources. To this respect, existing data indicates that children from lower income families are exposed to higher levels of air pollution at school than those from more privileged families.

1.4 Dissertation Hypothesis

In order to characterize particulate matter exposure at a high-altitude city, a study was conducted in Quito (Ecuador) to evaluate the effect of transient and long-term ambient PM exposure on systemic inflammation, oxidative stress, and atherogenesis in a group of 300 children. The data was collected over a 12-month period in two sessions 6-months apart, in three exposure zones, (high, medium, and

low) of varying traffic and PM levels, to investigate the association of $PM_{2.5}$ and PM_{10} exposure with inflammation and arterial thickening. Portable monitors were used to collect seven-day indoor and outdoor PM levels (PM_{10}, $PM_{10-2.5}$, and $PM_{2.5}$) at three selected schools and a random subsample of subject homes in each selected zone. Continuous PM data as well as meteorological factors were collected from central air quality monitors to understand the spatio-temporal variation in the city.

The hypotheses in this dissertation are examined by analysis of the environmental data collected in the study to characterize and evaluate PM (PM_{10}, $PM_{10-2.5}$, and $PM_{2.5}$) concentration gradients for a high altitude city across school and residential indoor and outdoor microenvironments. It evaluates the spatial variation across the PM concentration gradients and the effectiveness of a central monitoring network in representing exposure. The most important factors (meteorological, co-pollutant, or local sources) in determining exposure were assessed. Particularly, two hypothesis were tested,

1. Spatial and temporal variations of outdoor PM concentrations can be associated with meteorological and co-pollutant data observed at a central monitoring station.
2. Indoor PM exposure for children both at school and home is associated with PM, co-pollutants, and other meteorological factors collected outdoors and from a monitoring network.

1.5 Dissertation Research Tasks

This research assessed the exposure of children aged 7-12 years by measuring PM levels at central monitoring stations, at school, and at home, in three different regions of Quito, to PM_{10}, $PM_{10-2.5}$, and $PM_{2.5}$. The specific tasks were as follows,

1. Conduct a conceptual model of PM in Quito using data obtained from central monitors. The conceptual model will serve as a basis to understand PM trends as modeled by the current monitoring network, as well as factors (co-pollutants and meteorology) influencing PM levels in Quito.
2. Describe and quantify exposure levels at three different exposure zones in Quito utilizing data collected from the environmental monitoring phase of the study.

3. Compare PM levels obtained from central monitoring stations with those obtained outdoors and indoors to evaluate the strength of the association and concentration gradients across the city.

Chapter 2: Background Knowledge

Particulate matter pollution is currently one of the most pressing air quality problems attributed to a variety of sources including vehicle emissions, industrial combustion processes, resuspension from unpaved roads, quarries, and other unprotected surfaces. Moreover, as technology advances, it develops the capability to produce emissions and monitor the exposure to smaller and smaller particles. Long-term and short-term exposure to particulate matter has been associated with a myriad of health effects in several epidemiological studies, including, but not limited to, increased of respiratory infections and symptoms, decreased lung function, hospital admissions due to cardiovascular disease and acute respiratory infections (ARI), and increased mortality from respiratory and cardiovascular disease (Hoek et al, 2002; Estrella et al, 2005; Chang et al, 2005; Barraza-Villarreal et al, 2008; Gill et al, 2011; Sanhueza et al, 2012). Adverse health effects will vary depending on the level of PM concentration, size, and chemical composition (Polichetti et al. 2009), therefore understanding its chemical characterization and ways to quantify exposure is of utmost importance. The first section in chapter 2 gives a description of the chemical composition, size classification, and common sources of particulate matter. The second section describes methods that have been used to quantify exposure to particulate matter and their effectiveness.

2.1 Particulate Matter

Particulate matter is defined as particles in the atmosphere of varied chemical composition (depending on their source) that includes inorganic ions, metallic compounds, elemental carbon, organic compounds and crustal compounds. Regarding origin, particles can be classified as either primary or secondary, where primary particles are emitted directly from the source whereas secondary particles are formed from gases through chemical reactions in the atmosphere. In terms of their size, particulate matter can be classified based on their diameter. Since particles are hardly ever spherical, particle diameter is determined by other means. Diffusion and gravitational settling are two important physical properties of particulate matter that will determine their sizing property: smaller particles will exhibit diffusion, while larger particles gravitational settling. In smaller particles, Stokes diameter (D_p) will be

the property more commonly used to describe particle size based on the aerodynamic drag force imparted on a particle when its velocity differs from that of the surrounding fluid. It is independent of particle density. For "larger" particles, such as the ones covered in this thesis, aerodynamic diameter is the adequate term to classify them on their size. Aerodynamic diameter (D_a) is dependent on particle's density and it is defined as the diameter of a spherical property with an equal gravitational settling velocity but a density of 1 g/cm^3.

Currently, the Environmental Protection Agency (EPA) regulates particulate matter in two classifications: coarse particle (PM_{10}) having an aerodynamic diameter between 10 micro-meters (μm) and 2.5 μm and as fine particle ($PM_{2.5}$) having an aerodynamic diameter of 2.5 μm or less. The standards are based in part on epidemiologic relationships between health effects and PM concentrations as measured with existing monitoring methods (USEPA, 2004). Figure 2.1 provided by the EPA gives a general definition of the size of the particle in terms of objects we encounter every day and a brief description for sources and composition. Standards for particulate matter and other criteria pollutant, established by the EPA, are shown in Chapter 1 (Table 1.3).

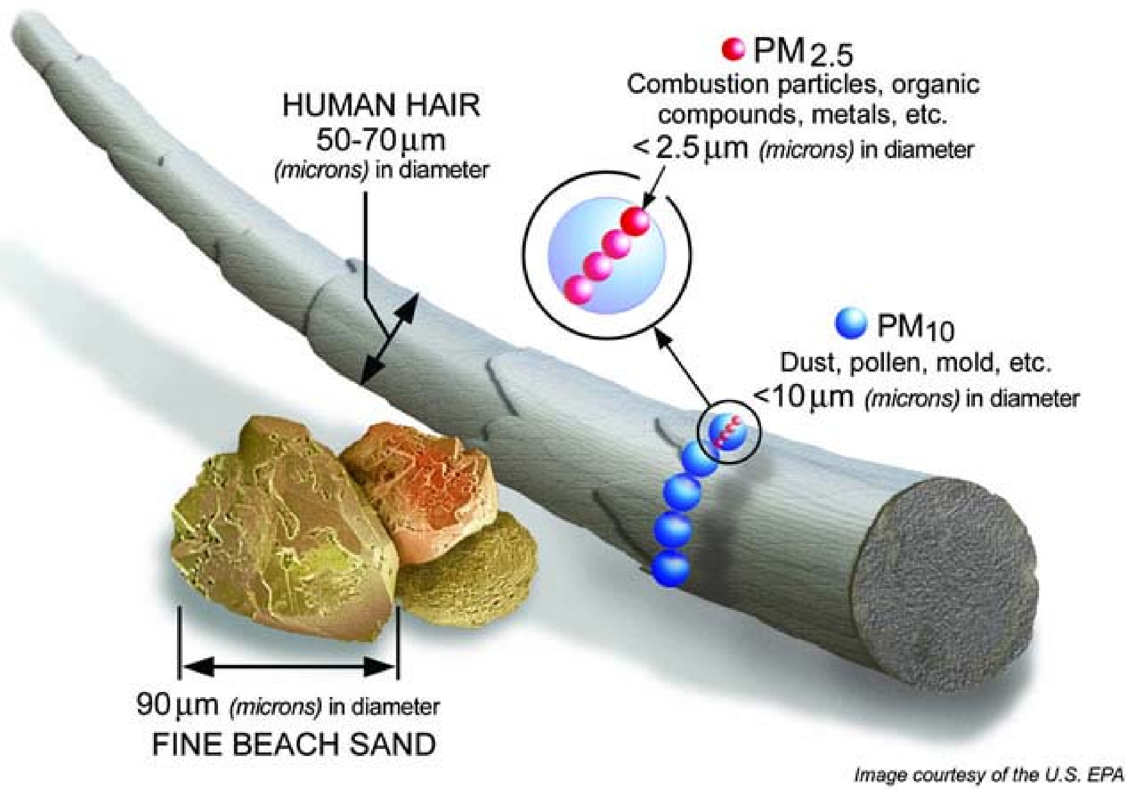


Figure 2.1: Particulate matter sizing

Sources for primary particulate matter encompass traffic emissions, dust, and industrial emissions. Secondary particulate matter is a result of chemical reactions in the atmosphere.

Particulate matter can be collected in terms of number (no/volume) or mass (mass/volume). It can be measured continuously and measurements recorded after a pre-defined period of time or it can be measured over several days. Examples of common measurement instruments include, tapered element oscillating microbalance (TEOM), Harvard cascade impactors, among others. When we say a particle matter sampling device collects $PM_{2.5}$, we refer to the size fraction specified by the 50% cut point size. Meaning, the $PM_{2.5}$ sampling device will collect 50% of 2.5 µm particle and reject 50% of 2.5 µm particles. Figure 1.2 provides size-cut curves through an ideal (no-particle-loss) inlet for five different size samples. IPM refers to inhalable particulate matter, TPM to thoracic particulate matter and RPM to respirable particulate matter and this classification scheme is followed by the American Conference of

Governmental Industrial Hygienists in terms of their entrance into the different portions of the respiratory system. Inhalable particles enter the respiratory tract, thoracic particles reach the lung airways and the gas-exchange regions of the lung, and respirable particles are part of the thoracic particles that are more likely to reach the gas-exchange region of the lung (USEPA, 2004).

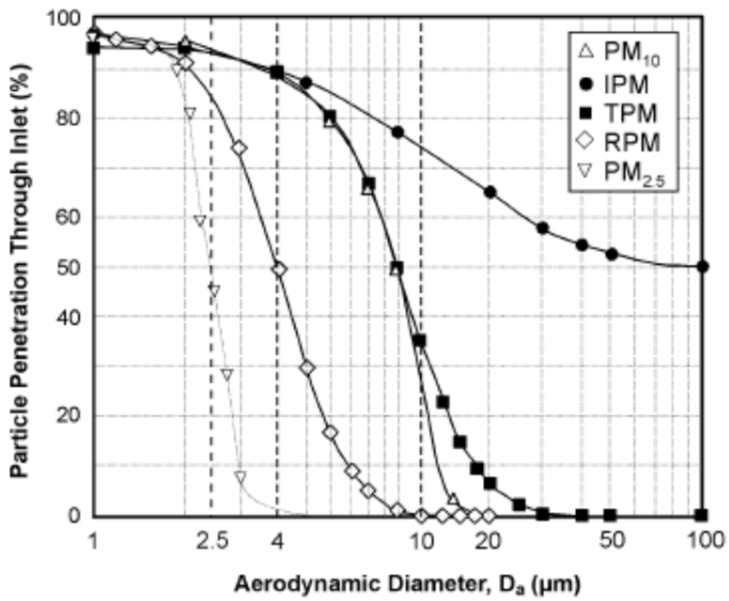


Figure 2.2: Particulate matter size-cut curves Source: US EPA 2004.

Several studies have shown associations of particulate matter levels and all kind of health problems ranging from respiratory to cardiovascular. Air pollutants are respiratory irritants and increase susceptibility to acute respiratory infections, ARI (Harris, et al. 2011).

In addition to health problems, Menz (2011) has compiled a list that includes damage to the environment and infrastructure, including:

1. Impact on building materials includes loss of mechanical strength, leakage, and failure of protective coating due to degradation of materials.
2. Atmospheric haze depresses crop yield for wheat, barley, potato, and other species.
3. And foremost, high concentrations have been linked to cause an increase in human morbidity and mortality rates, exacerbation of pre-existing respiratory diseases and

symptoms, increased hospital admissions for respiratory and cardiac ailments, and a cause for respiratory ailments such as chronic bronchitis or lung cancer.

2.2 Central, Site, and Personal Monitoring

In an effort to characterize the community's exposure to elevated pollution levels (specifically particulate matter) numerous studies have been conducted evaluating the effectiveness of established monitoring networks and comparing them to site and personal monitoring. This section reviews studies that have been conducted to evaluate the accuracy of central monitors in characterizing site (indoor/outdoor) and personal exposures. Mixed reviews demonstrate that the effectiveness of ambient monitoring networks will depend on geographical location, seasonal variations, and local sources.

Sarnat, et al. (2000, 2005, and 2010) examined the relationships between ambient (central) PM levels and personal or in site levels in three different studies. The first study (2000) was conducted in Baltimore, MD to examine the level of association between ambient PM measurements and personal concentrations measured from a cohort of older adult subjects. The results demonstrated that the strength of the associations varied by particle cut-size and by season. The strength of the association increased with decreasing particle size and with warmer weather: in the summer, associations were stronger than in the winter. During the summer, indoor ventilation increased, so there was more mixing of the air outside and inside as compared to the mixing during the winter. In 2005, Sarnat, et al. published another study that included a cohort of older subjects and school children. Personal as well as ambient measurements were collected for $PM_{2.5}$, O_3, NO_2, and SO_2. As in the past study (2000), the results from the 2005 study found significant correlation between ambient $PM_{2.5}$ concentrations and personal exposures with stronger correlations during the summer than winter. Concentrations for gaseous pollutants were better surrogates of personal $PM_{2.5}$ exposures than of personal exposure to the gases themselves. Finally, in the 2010 study, Sarnat et al. published a study analyzing spatial and temporal relationships for $PM_{2.5}$ in Israeli, Jordania, and Palestine. The results from this study indicated homogeneity between the sites, but differences in absolute concentrations, demonstrating the importance of local sources. Although no personal measurements were conducted in this study, the results are

indicative of the importance of in-site monitoring due to the presence of spatial variability in PM. Moreover, the authors stress the importance of regulatory strategies targeting regional and local control strategies to reduce $PM_{2.5}$ levels.

Janssen, et al. (2000) analyzed correlations between ambient levels, indoor levels, and personal exposure to $PM_{2.5}$ in a cohort of elderly subjects with cardiovascular disease at the Netherlands and Finland. Statistical analysis gave high correlations between personal, indoor, and outdoor (ambient) $PM_{2.5}$ concentrations. The article stresses that the findings provide support for using fixed-site measurements (central monitors) as a measure of exposure to PM.

Williams, et al. (2003) published the results of a 1-year investigation conducted in North Carolina for personal, residential, and ambient PM levels. The goal of the research was to estimate ambient $PM_{2.5}$ contributions to personal and indoor PM concentrations. Participants of the study were older than 50 (years) and having controlled hypertension. High correlations were observed and little error was introduced into the model when a single ambient PM measurement was used to represent exposure. However, the authors point that the reason behind this was that the North Carolina area where they performed the study had few major sources and a moderate climate. The results may not be the same if the study is performed somewhere with several local major sources or proximity to roadways.

Poupard, et al. (2005) attempts to define if a dependable assessment of the indoor pollution level can be obtained by measuring the outdoor pollution level and other parameters. In addition to particulate matter, indoor and outdoor concentrations for O_3, NO, and NO_2 were also collected at eight schools in La Rochelle (France). In regards to the particulate matter measurements, the authors concluded that (1) the influence of room occupancy in indoor particulate matter concentrations will vary with particle size and (2) indoor ozone and particles concentrations are negatively correlated, which may be the results of complex homogeneous/heterogeneous processes.

Brown, et al. (2009) also analyzed exposure factors responsible for inter-subject variability in personal exposures, while controlling for ambient concentrations, for $PM_{2.5}$, O_3, NO_2, and SO_2. Data for this analysis was taken from the study by Sarnat, et al. (2005). The findings of this study revealed that personal exposures were strongly influenced by ambient levels under well-ventilated conditions,

including open windows, the absence of central air conditioning (CAC), and older homes, which may be less tightly constructed. Again, as it was reported by Sarnat, et al. (2005), ambient concentrations accounted for a greater proportion of the variability in the summertime when windows were open. However, for pollutants with indoor sources, such as EC and NO_2, it may not be sufficient to estimate exposures using ambient concentrations under well-ventilated conditions.

Rodes, et al. (2010) published part of the results from the Detroit Exposure and Aerosol Research Study (DEARS) analyzing $PM_{2.5}$ relationships from several microenvironments for all seasons and participants. Results from this analysis show that the personal exposure collections indoors were typically, at least, 13 times greater than those contributed outdoors. Measurements in six enumeration monitoring areas (EMA) in Detroit were conducted and compared to a fixed monitoring station, revealing that $PM_{2.5}$ concentrations at three sites were statistically different from the central site, while $PM_{2.5}$ concentrations at the other three sites were the same as that from the central site. A modeling approach is suggested to calibrate personal and indoor exposures against central site data in order for central site monitoring to be representative of the outdoor environment.

Raysoni, et al. (2011) favors an in-site monitoring approach. Results from the study indicated substantial spatial variability of pollutants in the region. Children's exposure varied based on the location of their school (high vs. low traffic conditions). The study states that central monitoring alone may not "mirror the representative pollutant concentrations in urban areas that experience varying levels of traffic and other fugitive emission sources."

Mejia et al. (2011) in their literature review regarding the methodologies employed to assess children's exposure to air pollutants at schools state that data from central monitors provide only a "general idea of the pollution in the schools, but because of the small-area variations in pollution levels, they have very low accuracy." They suggested ground-level monitors (monitors installed at schools) to show actual pollution levels, however, it is important to specify the exact location of the monitors, which many publications fail to do. Few publications have shown different concentrations within a school at the yards, classrooms, and other facilities (e.g. gymnasiums). Therefore, even within a school,

as children move around throughout the day, they experience different exposures and few studies, according to Mejia et al. (2011), have shown that.

The literature review presented above discussed advantages and disadvantages of central monitoring data to measure exposure. Several studies found significant correlations between central monitoring data and personal concentrations (Sarnat et al., 2000; Sarnat, et al., 2005; Janssen, et al., 2000; Williams, et al., 2003; Brown, et al., 2009; Rodes, et al., 2010). Others agree that central monitoring is not enough to convey exposure and additional monitoring should be conducted, especially near sensitive populations, such as children (Raysoni, et al., 2011; Mejia, et al., 2011). In general, the validity of central monitors in portraying personal exposure will greatly depend on the region, its geographical location, meteorology, season, particle cut-size, and local sources.

2.3 Conclusion

The numerous studies reviewed throughout Chapters 1 and 2 revealed that:

- Air quality in Latin America has been affected due to the rapid motorization and lack of environmental controls. Air pollutant levels are often above the recommended WHO guidelines. Effective and practical control measures must be proposed in order to use effectively the limited resources.
- Specifically in Quito, Ecuador, air quality has been affected by both vehicle emissions and industrial emissions as well as by its geographical location and tendency for temperature inversions. Air quality studies conducted in the region reveal that populations living near a roadway are at greater risk for experiencing elevated levels of air pollutants. Although efforts have been made to ameliorate the effects from air pollution, much work still remains.
- Children spend a considerable amount of their time at school and because of the development of their lungs, they are considered a sensitive population to air pollution even before being diagnosed with any respiratory illness. Studies reveal that schools near high traffic zones experience elevated levels of particulate matter (Janssen, et al., 2001; Raysoni, et al., 2011). Beside outdoor sources, (e.g. industry or traffic emissions), weather, occupancy level,

ventilation, and activities inside the classroom are all factors that will have an effect on indoor concentrations. A study by Branis, et al. (2009) found indoor concentrations at a school in Prague above the WHO recommended guideline, so it is important to characterize the level of exposure for children at schools.

- Regarding what is the best methodology to characterize exposure, the general consensus is that central monitoring will work to characterize the community's exposure depending on the region, its geographical location, meteorology, season, particle cut-size, and local sources.

Chapter 3: Experimental Design and Methodologies

This study was conducted in 2010 in the Quito Metropolitan District (DMQ), capital city of Ecuador, to evaluate the effect of transient and long-term ambient PM exposure on systemic inflammation, oxidative stress, and atherogenesis in a group of 300 children living in high altitude cities (such as Quito). Environmental data was collected over a 12-month period, while health data was collected in two sessions (6-months apart). The data was collected from three exposure zones (high, medium, and low) in Quito, to investigate the association of transient $PM_{2.5}$ and PM_{10} exposure with inflammation as measured by several blood markers (hpCRP, IL-6, ICAM, VCAM, and E-selectin cell adhesion molecules). Environmental measurements were collected for fine and coarse particulate matter ($PM_{10\text{-}2.5}$ and $PM_{2.5}$) over a 12 month period. Health data consisting of laboratory analysis, health questionnaires, physical activity history, medical history, physical exam, and blood pressure were collected twice in the 12-month period. In addition, during the first session, subjects also underwent an ultrasound study to examine the relationship of long-term $PM_{2.5}$ and PM_{10} exposure with arterial thickening. The PM exposure models were constructed from continuous data obtained from central air quality monitors to understand the spatio-temporal variation in the city. Portable monitors were used to collect seven-day indoor and outdoor PM levels at three selected schools in each exposure zone and from a random subsample of subject homes to maximize the representativeness of the data. This chapter describes the experimental design and methodologies used in this research. Site selection and characteristics are first discussed in Sections 3.1 and 3.2. The experimental design including sampling plan, laboratory analysis, and central monitoring data are described in Sections 3.4, 3.5, and 3.6. The last section (3.7) provides the methodology for the health analysis.

3.1 Site Selection

Each of the three selected exposure zones for this study encompassed a 5-mile radius from its central monitor location and is classified as either a high, medium, or low exposure zone according to historical PM levels (Ecogestion, 2005; Corpaire, 2006; Corpaire, 2007). Historical PM levels for the three exposure zones were based on 5-year (2003-2007) PM records collected from ambient monitors.

Accordingly, the 24-hour $PM_{2.5}$ and PM_{10} averages were reported as 26.7 μg/m^3 and 77 μg/m^3 respectively for the central-high exposure zone (El Camal), 20 μg/m^3 and 34.1 μg/m^3 respectively for the north-medium exposure zone (Cotocollao), and 13.1 μg/m^3 and 24.4 μg/m^3 respectively for the south-low exposure zone (Los Chillos). Neighborhood density, traffic patterns, population characteristics, and consultation with the Quito Environmental Department Director (Dr. Eschanique) were also considered for site selection and classification. Traffic and demographic data for the city (DMQ, 2007) were seen to correlate positively with the PM air quality data.

Figure 3.1 shows the locations of the three selected zones in Quito along with the sites where environmental data was collected and information on the bus routes crossing each zone. Figure 3.2 shows the vehicle flow of main avenues. The blue line represents main avenues with high vehicle flow, the yellow line represents medium vehicle flow, and the green line low vehicle flow. It can be seen that high and medium traffic levels are concentrated just north and going into El Camal. Blue lines representing high traffic also surround the El Camal area. In the Cotocollao area, to the north, traffic flow can be described medium-to-low with a few segments displaying high traffic. The southeast area (Los Chillos) is mostly surrounded by low traffic (green) roads with one main, high traffic avenue.

Based on traffic and ambient monitoring data, the north location is selected as the medium exposure zone (Cotocollao), the central location as the high exposure zone (El Camal), and the south location as the low exposure zone (Los Chillos). For the purpose of this study, the zones were labeled in order from North-to-South as Zone 1 (Cotocollao), Zone 2 (El Camal), and Zone 3 (Los Chillos) as shown in Figure 3.1. In each zone, one public primary school was selected to participate in the study based on central monitor proximity ($\leq$ 5 miles apart) and size ($\geq$ 150 students). Meetings with parents and children from each of the selected schools were held in order to recruit study participants. Parents who expressed an interest in having their children participate filled out a brief questionnaire to evaluate certain criteria and determine if their child qualified to be part of this study. A computerized random numbers program was used to select the requisite number of subjects. Residential sites (about 40 sites per zone) were then selected at random from the pool of subjects in each zone. In Figure 3.1, school locations are depicted by a blue pin with a star, residential sites are depicted by a yellow pin, and central

monitors are in green. In the upper right hand corner of the figure we can see an image of the city (Quito).

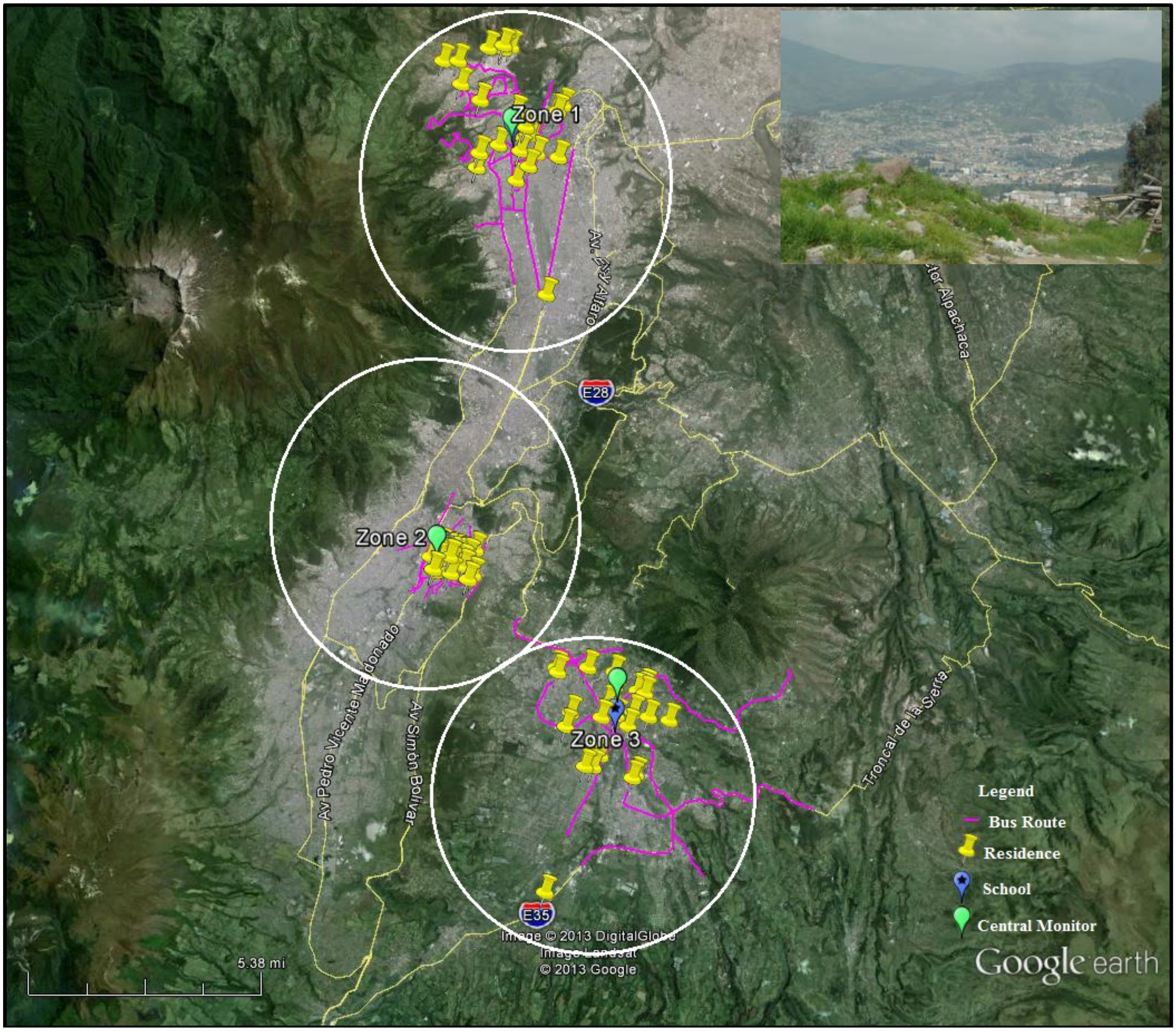


Figure 3.1: Sampled zones in Quito, Ecuador showing the sampling locations as well as a photograph from the view in Quito in January, 2010 *(Image from Google Earth)*

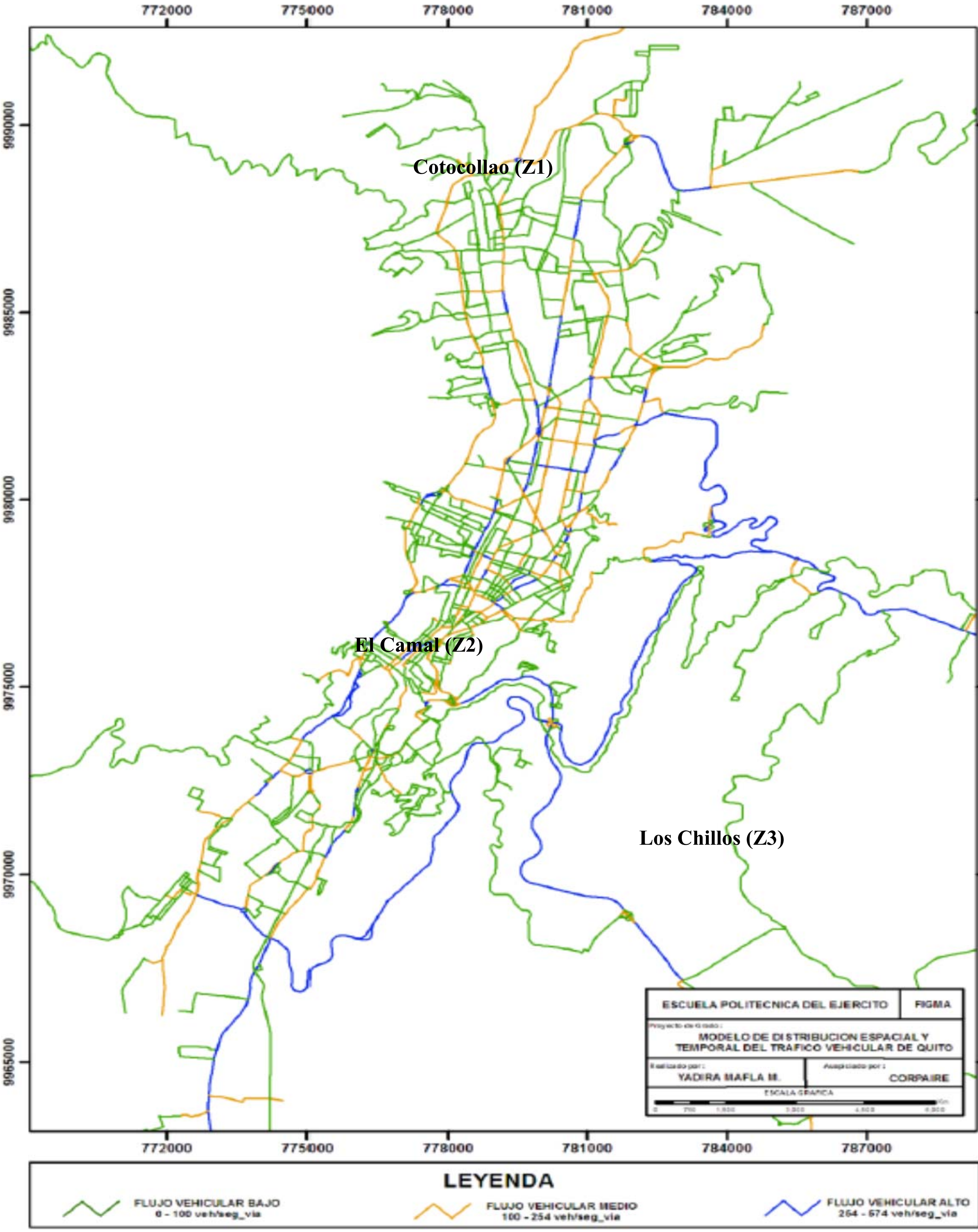


Figure 3.2: Model for traffic flows at main roads in the Metropolitan District of Quito: green line (low), yellow line (medium), blue line (high) (Source: Mafla, 2004).

3.2 Site Characteristics

The public primary schools (elementary schools) with more than 150 students and within a 5-mile radius from the central monitor were considered for selection in this study. One school was selected in each zone. The selected schools shared common characteristics in terms of their layout, each one having classrooms distributed in two or three levels surrounding the outdoor play area. The outdoor play area usually consisted of a cement basketball court and limited playground equipment in a dirt area, with little to no landscape. Each classroom had direct access to an outdoor hallway. Due to the nature of the weather in Quito, the schools did not have central heating or air conditioning, but relied on natural ventilation for thermal comfort.

The homes in each zone were selected on three criteria: (1) the location of the residence fell within a 5-mile radius of the central monitor of any of the exposure zones included in this study, (2) the selected residence belonged to a child (subject) participating in the study, and (3) the selected homes did not have any smokers. The selected homes in each zone shared similar characteristics of a typical Ecuadorian home. Again, because of the nature of the weather in Quito, residences do not have central heater or cooler systems, but rely on natural ventilation for thermal comfort. On average, houses had three windows opened for 2-hours per day. A typical house is made of cement block, concrete, and steel. It consisted of four rooms: kitchen/dining room, living room, and two bedrooms. Liquefied petroleum (LP) is the fuel of choice for cooking and for the water heater.

Neighborhoods are a combination of residential houses and commercial businesses including grocery stores, restaurants, bakeries, domestic gas vendors, tire-repair shops, carpentries, shoe-repair shops, and various ambulant food vendors. Food vendors are usually operating during late afternoon and at night. Many of the monitored residences had a shop on the lower level and the living-area (home) was located on the upper level. Although it is not a common practice, the field staff noted that some of the residences burned trash once or twice a week (3%). Others burn candles (veladoras). Most of the roads are paved, although the field staff noted that about 3% of the residences had some street sections that were not paved. Also, field staff noted about 8% of the residences undergoing renovation or the house

next to it undergoing some other construction related activity (such as painting walls, adding rooms, among others).

3.2.1 Zone 1

Zone 1 is known as Cotocollao and it is located to the north of Quito. It is regarded as the medium exposure zone because of its particulate matter levels averaging 34.1 $\mu g/m^3$ for $PM_{2.5}$ and 20 $\mu g/m^3$ for PM_{10} (2004-2007 data). Figure 3.3 shows the location of the school and the residences that were sampled. A wind rose generated with wind data from the central monitor (2010) is also included in the figure. Although it is not at the center of Quito, Zone 1 still is exposed to exhaust from private vehicles and public transportation as depicted by the number of main roads in the region (Figure 3.2). Particulate matter emissions from quarries are also close to the region.

School- The elementary school in Zone 1 had classrooms distributed throughout three floors as shown in Figure 3.4. Both Figures 3.4 and 3.5 show outdoor play areas for the children. Figure 3.4 shows a basketball court where children practice physical education and Figure 3.5 shows a play area with swing sets over dirt. Figure 3.6 shows the inside of a classroom and Figure 3.7 shows the outdoor area where the samplers were mounted.

Residences- A total of 47 homes were monitored in Zone 1 throughout the study. The residences were located all throughout the zone, surrounding the central monitor and the school.

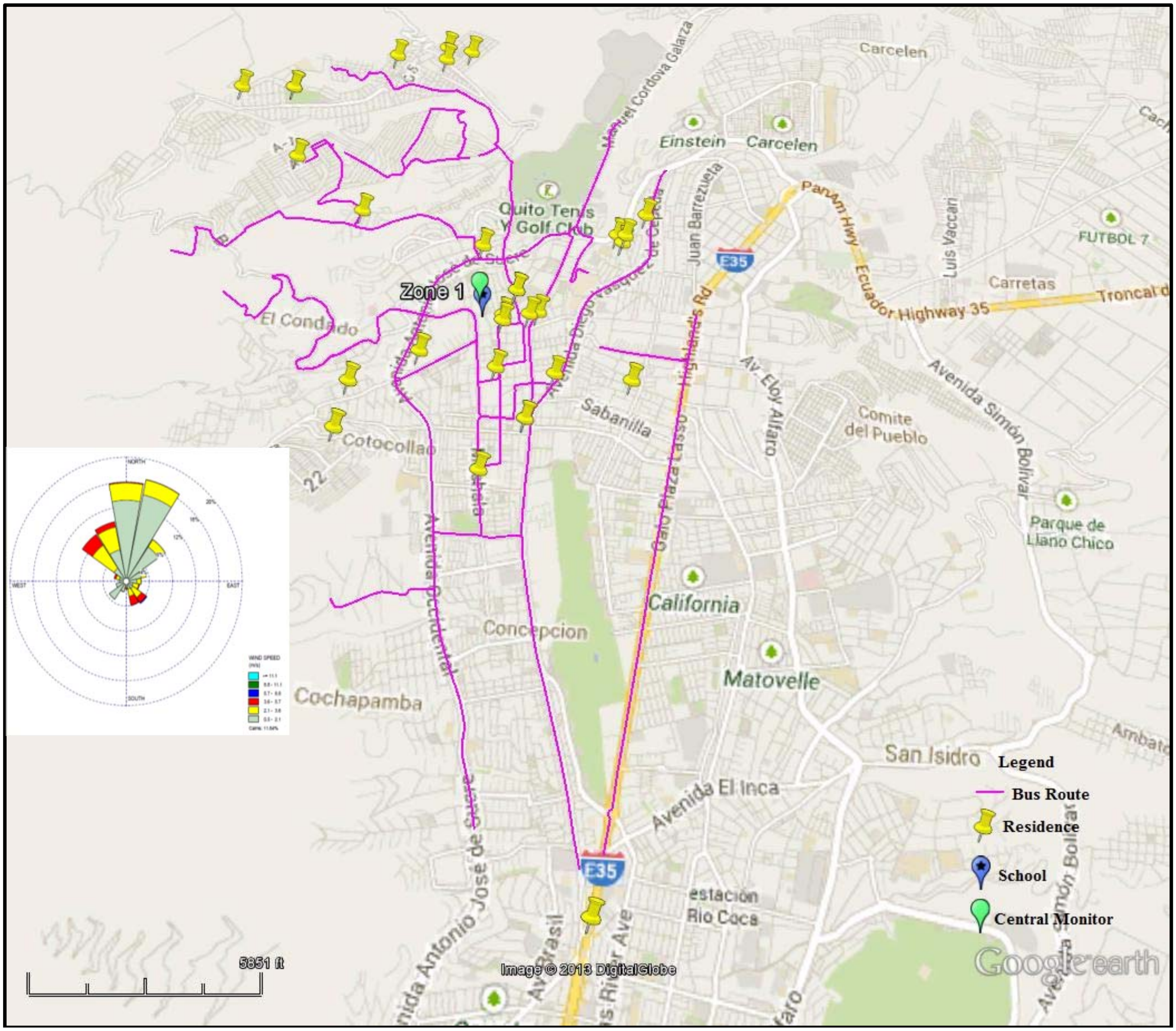


Figure 3.3: Location of school and residences sampled for Zone 1 *(Image from: Google Earth)*

Figure 3.4: Children's play area for Zone 1 school

Figure 3.5: Children's play area for Zone 1 school

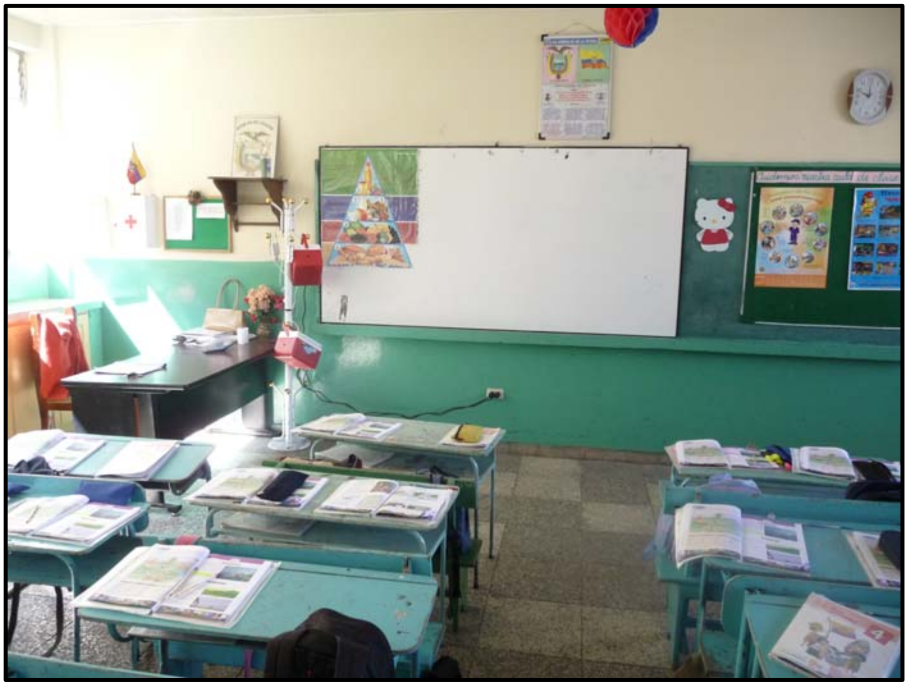


Figure 3.6: School classroom for Zone 1

Figure 3.7: School outdoor monitor setup location for Zone 1

3.2.2 Zone 2

Zone 2 is known as El Camal and it is located right in the center of Quito, as can be seen in Figure 3.1. Several main avenues (Figure 3.2) and bus routes cut across El Camal, and particulate matter levels recorded from central monitors classify it as the high exposure zone with 24-hour average levels for $PM_{2.5}$ at 26.7 µg/m^3 and for PM_{10} at 77 µg/m^3 (2004-2007 data). Figure 3.8 shows the location of the school and residences that were sampled as well as the wind rose for 2010. Since Zone 2 is located in the central part of Quito, traffic exhaust from both private and public vehicles is significant in this area.

School- The school in Zone 2 is only 2 stories high. Figure 3.9 shows the basketball court where children take physical education and play during recess time.

Residences- A total of 45 residences were monitored in Zone 2 throughout the study period. The residences were closer together (as opposed to the other zones) right in the center of the zone, south of the central monitor and the school.

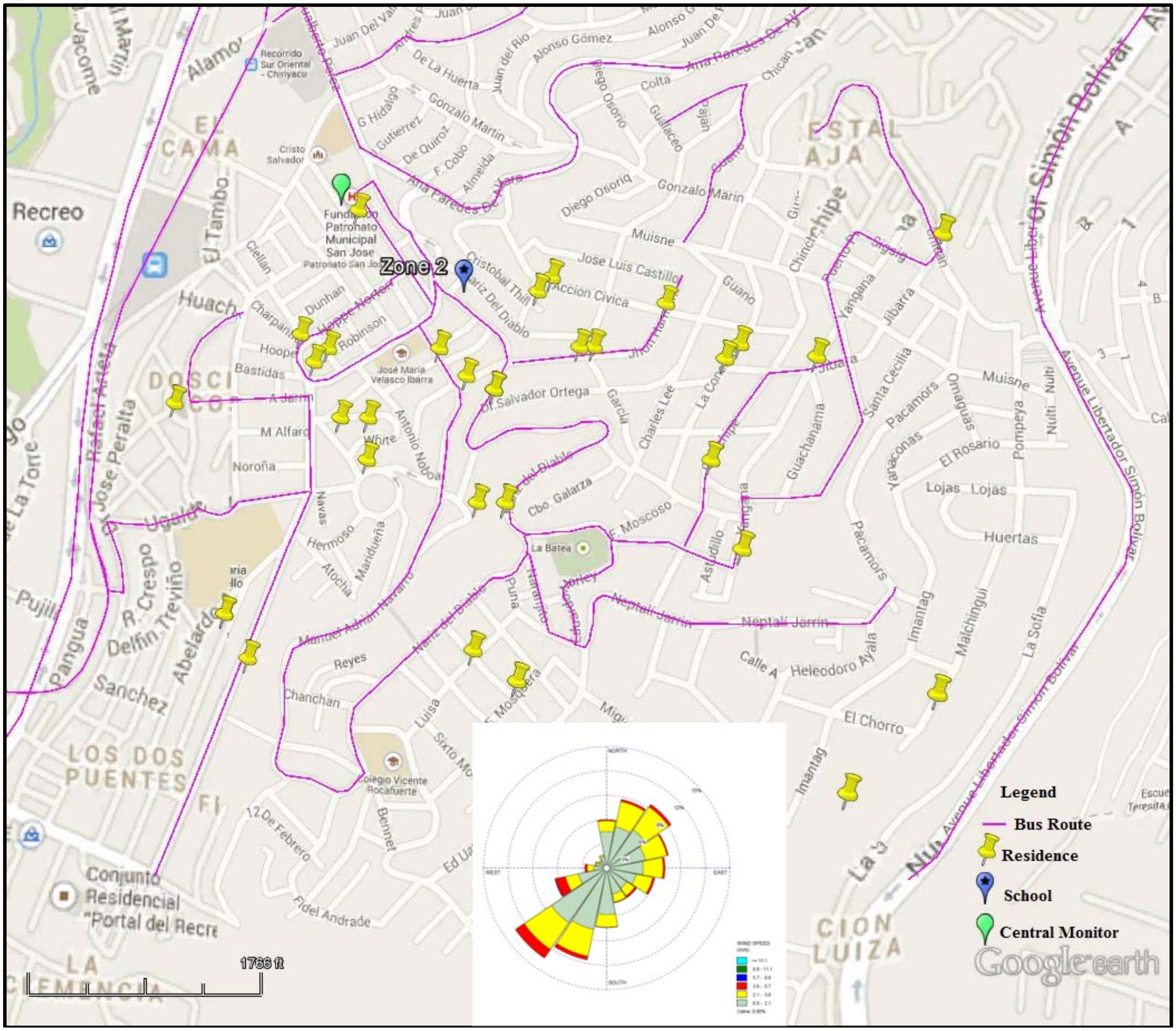


Figure 3.8: Location of school and residences sampled for Zone 2 *(Image from: Google Earth)*

Figure 3.9: Outdoor play area for the school in Zone 2

3.2.3 Zone 3

Zone 3 is known as Los Chillos and it is located to the southeast of Quito. It is considered the low exposure zone having 24-hour $PM_{2.5}$ average of 13.1 µg/m^3 and PM_{10} average of 24.4 µg/m^3. Figure 3.10 shows the location of the school and residences that were monitored as well as a 2010 wind rose for the area. Private and public transportation is not as heavy as in Zones 1 and 2 as can be seen by the amount of bus routes in Figure 3.10 and the traffic flow from Figure 3.2. However, there is a textile industry located east of the zone that has been reported by Quito's Environmental Department to emit nitrogen oxides (NOx), particulate matter (PM), sulfur dioxide (SO_2), and carbon monoxide (CO).

School- The elementary school in Zone 3 is similar to the schools in Zones 1 and 2, with classrooms distributed throughout two floors. As can be seen from Figure 3.10, the school is located downwind south of the Panamerican Highway (E35), one of the main avenues that cross Quito. Figure 3.11 shows the school's basketball court that serves as the play area and physical education area for the children. Figure 3.12 shows a classroom.

Residences- A total of 41 homes were monitored in Zone 3. The homes were distributed throughout the zone all around the central monitor and the school.

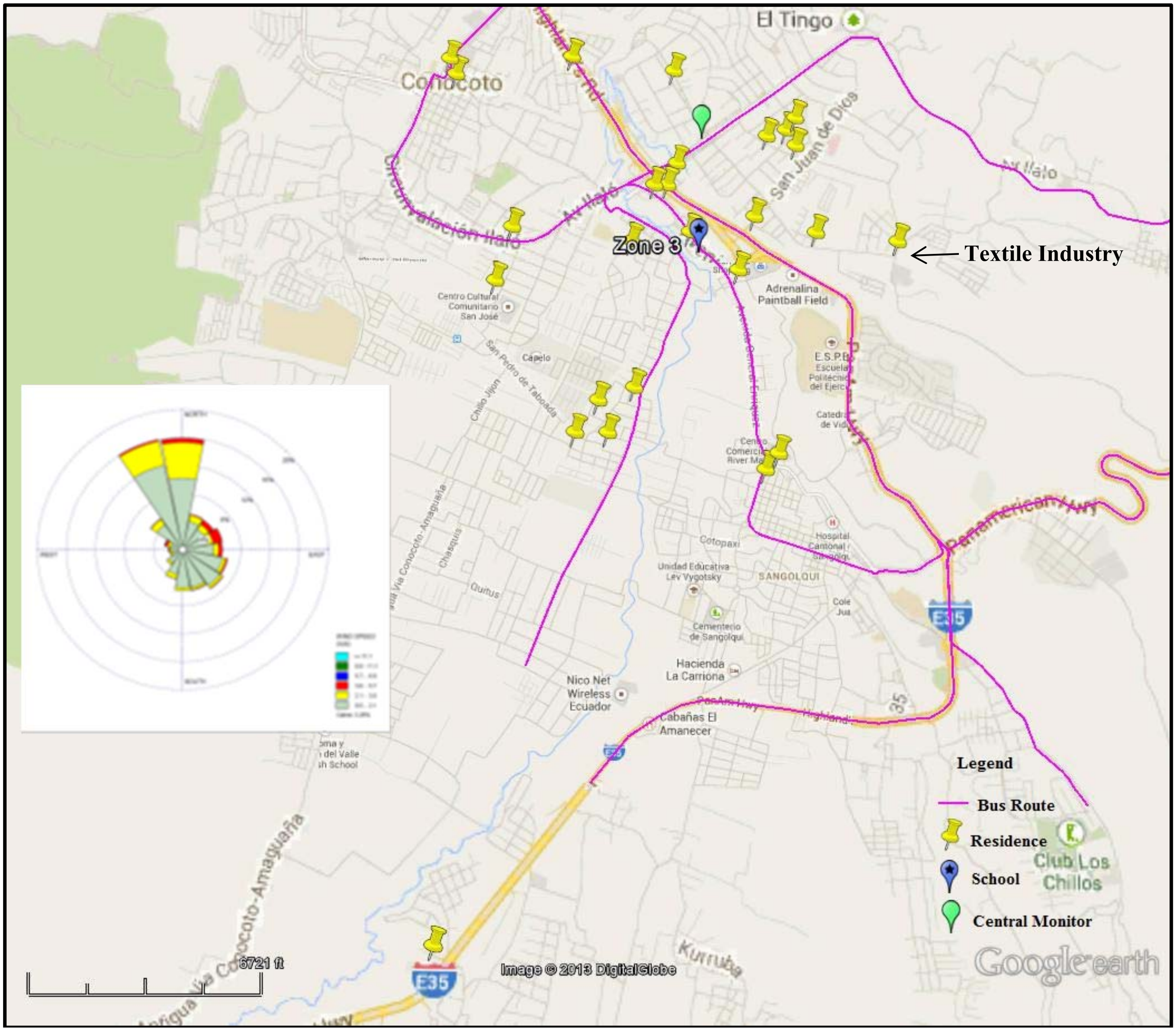


Figure 3.10: Location of school and residences sampled for Zone 3 *(Image from Google Earth)*

Figure 3.11: Outdoor play area for the school in Zone 3

Figure 3.12: Classroom area for school in Zone 3

3.3 Sampling Plan

Sampling locations that were selected in each of the three exposure zones included: one school site, kept constant throughout the monitoring period, four indoor residential sites, and four outdoor residential sites. Residential sites varied every month, although monitoring in some homes was repeated once or twice during the study period. Table 3.1 presents the sampling scheme at each exposure zone. School indoor microenvironments were monitored with two samplers and one duplicate. School outdoor microenvironments were monitored with one sampler and one duplicate. One blank was included for QA/QC at each school every month. Residential sites were monitored with four samplers at each indoor microenvironment and four samplers at each outdoor microenvironment. Residential indoor and outdoor samplers were not always paired. At each exposure zone, a total of 14 samples (including duplicates and blank) for both $PM_{10-2.5}$ and $PM_{2.5}$ per location were collected once a month for a seven-day period. Sampling was not done concurrently at all three exposure zones, it was done at only one zone per week. Table 3.2 shows the sampling schedule for each zone by showing the first and last day of the sampling during a particular month. Dates in bold denote school holidays.

At the school indoor microenvironments, samplers were placed inside classrooms while outdoor samplers were placed near the children's play area. Table 3.3 shows the specific sampling locations for the schools. At the residential sites, indoor samplers were usually placed in a common area, such as the living room, while outdoor samplers were placed within 500-ft from a subject's home. Outdoor samplers were installed in protected locations to reduce the possibility of tampering or wind and rain damage (Figure 3.13). Outdoor samplers were placed at a 10-ft height while indoor samplers were placed at a 6-ft height.

Table 3.1: Monthly sampling scheme per exposure zone*

No.	Site	Microenvironment	Sample Description
1	School	Indoor	Sample
2	School	Indoor	Sample
3	School	Indoor	Duplicate
4	School	Outdoor	Sample
5	School	Outdoor	Duplicate
6	School	Indoor/Outdoor	Blank
7	Residence 1	Indoor	Sample
8	Residence 2	Indoor	Sample
9	Residence 3	Indoor	Sample
10	Residence 4	Indoor	Sample
11	Residence 1	Outdoor	Sample
12	Residence 2	Outdoor	Sample
13	Residence 3	Outdoor	Sample
14	Residence 4	Outdoor	Sample

**For residential sampling, outdoor samples may not be located immediately adjacent to the indoor samples*

Table 3.2: Sampling schedule per exposure zone (Month/Day)

Month	Zone 1		Zone 2		Zone 3	
	Start	Stop	Start	Stop	Start	Stop
January	1/14	1/21	1/22	1/29	2/1	2/8
February	**2/10**	**2/17**	2/18	2/25	-	-
March	2/16	2/23	3/24	3/31	4/5	4/12
April	4/13	4/20	4/21	4/28	4/29	5/6
May	5/7	5/14	5/18	5/25	5/26	6/2
June	6/7	6/14	6/15	**6/22**	**6/23**	**6/30**
July	**7/2**	**7/9**	**7/12**	**7/19**	**7/20**	**7/27**
August	**8/2**	**8/9**	**8/16**	**8/23**	**8/24**	**8/31**
September	**9/1**	9/8	9/9	9/16	9/17	9/24
October	10/13	10/20	10/21	10/28	10/29	11/5
November	11/8	11/15	11/16	11/23	11/24	12/1
December	12/2	12/9	12/13	12/20	12/21	12/28

Table 3.3: School sampling locations

Area	Indoor Sampling Site 1	Indoor Sampling Site 2	Outdoor Sampling Site
Zone 1 School	Classroom 1st floor	Classroom 3rd floor	School terrace 2nd floor
Zone 2 School	Classroom 1st floor	Students conference room 1st floor	School terrace 1st floor
Zone 3 School	Computer room 2nd floor (Jan-Jun) Classroom 1st floor (Jul-Dec)	Director's office 2nd floor	Outside classroom 2nd floor (Jan-Jun) Outside classroom 1st floor (Jul-Dec)

Figure 3.13: Monitor set-up at a residence (outdoor)

3.4 Instrumentation

Portable Harvard cascade impactors were used to collect PM data at a volume of 5 L/min. Fine particulate matter ($PM_{2.5}$) was collected on a 37 mm Teflon filter and coarse particulate matter ($PM_{10-2.5}$) on a polyurethane foam (PUF) plug, approximately 0.5" high and ¼" in diameter. MEDCO pumps were

used to generate a constant air stream of 5 L/min into the cascade samplers. Sampler flow rates were measured at the start and at the end of the sampling period, in duplicate, using a BIOSTM flowmeter (USA). Figures 3.14 and 3.15 show the different components and the complete assembly of an impactor.

Figure 3.14: Components of a Harvard Cascade Impactor

Figure 3.15: Assembled impactor

The principle of impaction consists of an aerosol passing through a nozzle and the output stream directed against a flat plate (impaction plate) that deflects the flow to form an abrupt 90-degree bend in the streamlines. Particles whose inertia exceeds a certain value are unable to follow the streamlines and collide on the impaction plate. Smaller particles can follow the streamlines and avoid hitting the impaction plate. The impactor separates the particles larger than a certain aerodynamic size by removing them from the airstream and those smaller than that size remain airborne and pass through the impactor. The Stokes number, that defines collection efficiency for an impactor is defined as:

$$Stk = \frac{\tau U}{D_j/2} = \frac{\rho_p d_p^2 U C_c}{9\eta D_j} \quad \text{(Equation 3.1)}$$

where $D_j/2$ is defined as the nozzle radius, U is defined as the average nozzle exit velocity, τ is particle relaxation time, ρ_p is the particle density, d_p is the particle diameter, C_c is the Cunningham slip correction factor, and η is the viscosity of the air. Cascade impactors, such as the ones used in this study, operate several impactors in series, arranged in order of decreasing cutoff size with the largest cutoff

size first. The cutoff size is reduced at each stage by decreasing the nozzle size. Each stage is fitted with a removable impaction plate for gravimetric determination of the collected particles (Hinds, 1999).

3.5 PM Gravimetric Analysis

Filters were conditioned, pre-weighed, and stored in petri dishes for a period no longer than 30-days, prior to being placed into the PM samplers. The used filters from each week's sampling period were collected, identified, and stored in Ziploc plastic bags and transported to the Quito office of the Study Director for storage, until being sent to El Paso for gravimetric analysis at the UTEP Air Quality Laboratory. Prior to the gravimetric analysis, all samples were pre-conditioned to room temperature (20 ± 5ºC) and relative humidity (20 ± 5%) for at least 24-hours in a custom-made storage cabinet located in the Air Quality Laboratory.

Mass concentrations for $PM_{2.5}$ were determined by using a 6-digit CAHN model C-33 microbalance with an accuracy of 2 µg and ultimate precision of 1 µg (Orion Research, 1997). Mass concentrations for $PM_{10-2.5}$ PUFS were determined with a Mettler MX5 microbalance having a precision of 1 µg (Mettler-Toledo). The accuracy of the microbalance was checked with a certified mass prior to each weighing session. The effects of static were eliminated by using a static neutralizing bar (MEB Shockless Static Neutralizing Bar, SIMCO, Hartfield, PA, USA).

For each weighing session, laboratory blank filters were weighed. The average of three consecutive weight measurements was used as the final weight of each sampling media; if the consecutive measurements were not within 10 µg, then the media was re-weighed. The difference in mass was recorded for each sample utilizing the net weights of the filters (before-and-after). Mass concentrations were reported in micrograms of particulate matter per cubic meter of air ($\mu g/m^3$). Detailed laboratory procedures are provided elsewhere by Li et al, (2001).

3.6 Central Monitoring Network

Data obtained from the Quito Metropolitan Network of Air Monitoring for the 2005-2010 time period was utilized to construct a conceptual model of the different PM trends and concentration levels throughout the three exposure zones in Quito. Figure 3.16 shows the location of the monitoring stations and Table 3.4 shows data available for this study from each station. It is important to note that meteorological parameters are collected at all central monitors, however, for the present study, we only requested meteorological parameters from the three exposure zones chosen. Each of the parameters shown in Table 3.4 was collected hourly from the Automatic Network of Air Quality (RAUDO) system as described previously, except for PM_{10}, which was collected from the Active Network of Particulate Matter (RAPAR) by utilizing high volume samplers with 24-hr averages taken every six days.

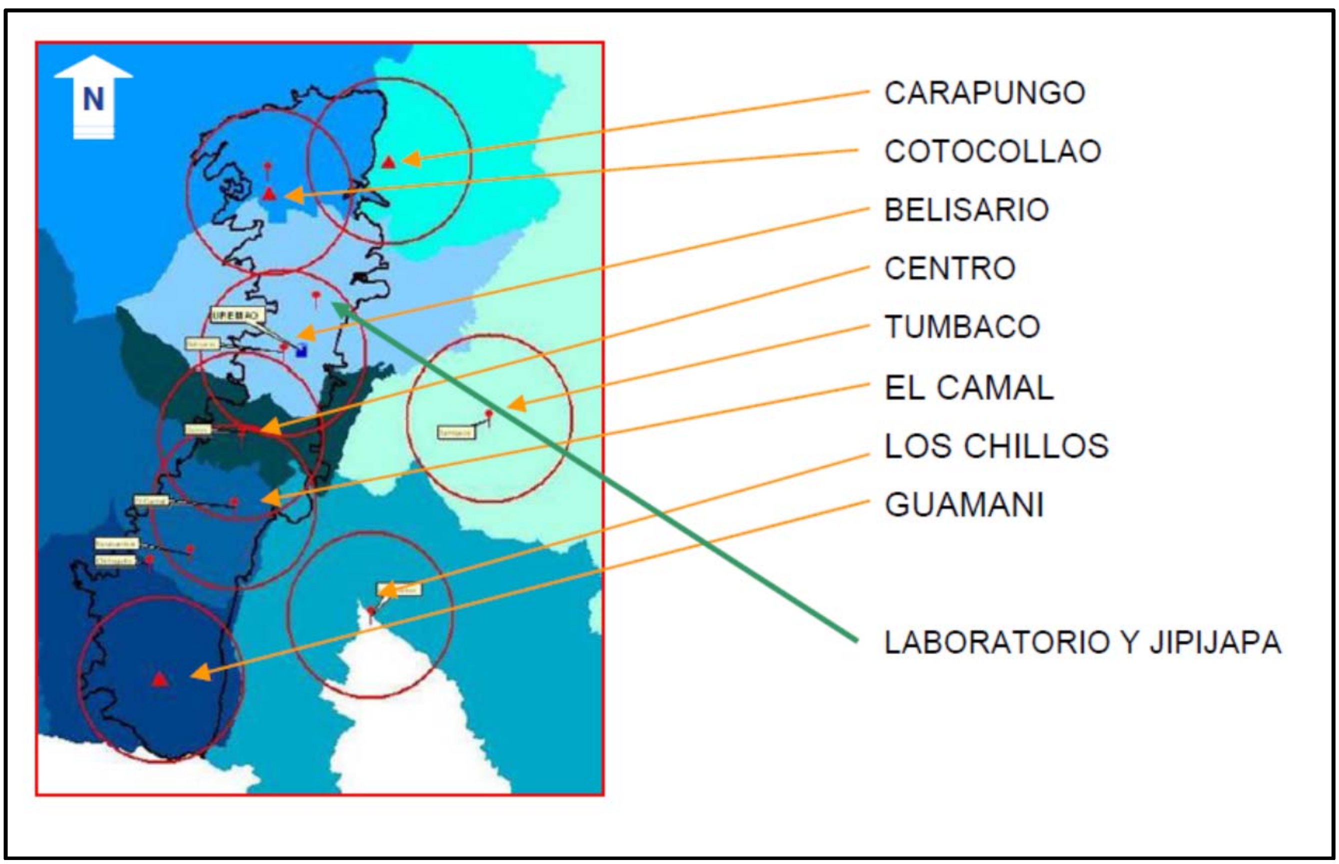


Figure 3.16: Location of Quito central monitoring stations and area of influence *(Source: CORPAIRE)*

Table 3.4: Available data at central monitors

Year	Station Name	Ambient Air Quality Data						Meteorological Data						
		CO	NO_2	O_3	$PM_{2.5}$	SO_2	PM_{10}	T	WS	WD	AP	RH	SR	P
	Cotocollao (Z1)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Carapungo	✓			✓	✓								
	Belisario	✓	✓	✓	✓	✓	✓							
	Jipijapa		✓				✓							
2005	El Camal (Z2)	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓
	Centro	✓	✓	✓	✓	✓								
	Guamaní	✓		✓			✓							
	Tumbaco			✓										
	Los Chillos (Z3)			✓			✓	✓	✓	✓	✓	✓	✓	✓
	Cotocollao (Z1)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Carapungo	✓	✓		✓	✓								
	Belisario	✓	✓	✓	✓	✓	✓							
	Jipijapa		✓				✓							
2006	El Camal (Z2)	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓
	Centro	✓	✓	✓	✓	✓								
	Guamaní	✓	✓	✓										
	Tumbaco			✓										
	Los Chillos			✓			✓	✓	✓	✓	✓	✓	✓	✓
	Cotocollao (Z1)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Carapungo	✓	✓		✓	✓								
	Belisario	✓	✓	✓	✓	✓	✓							
	Jipijapa		✓				✓							
2007	El Camal (Z2)	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓
	Centro	✓	✓	✓	✓	✓								
	Guamaní	✓	✓	✓			✓							
	Tumbaco			✓										
	Los Chillos			✓			✓	✓	✓	✓	✓	✓	✓	✓
	Cotocollao (Z1)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Carapungo	✓	✓		✓	✓								
	Belisario	✓	✓	✓	✓	✓	✓							
	Jipijapa		✓				✓							
2008	El Camal (Z2)	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓
	Centro	✓	✓	✓	✓	✓								
	Guamaní	✓	✓	✓			✓							
	Tumbaco			✓										
	Los Chillos			✓			✓	✓	✓	✓	✓	✓	✓	✓

Table 3.4 (cont'd): Available data at central monitors

Year	Station Name	Ambient Air Quality Data						Meteorological Data						
		CO	NO_2	O_3	$PM_{2.5}$	SO_2	PM_{10}	T	WS	WD	AP	RH	SR	P
2009	Cotocollao (Z1)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Carapungo	✓	✓		✓	✓								
	Belisario	✓	✓	✓	✓	✓	✓							
	Jipijapa		✓				✓							
	El Camal (Z2)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Centro	✓	✓	✓	✓	✓								
	Guamaní	✓	✓	✓			✓							
	Tumbaco			✓										
	Los Chillos (Z3)			✓			✓	✓	✓	✓	✓	✓	✓	✓
2010	Cotocollao (Z1)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Carapungo	✓	✓		✓	✓								
	Belisario	✓	✓	✓	✓	✓	✓							
	Jipijapa		✓				✓							
	El Camal (Z2)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Centro	✓	✓	✓	✓	✓								
	Guamaní	✓	✓	✓			✓							
	Tumbaco			✓										
	Los Chillos (Z3)			✓			✓	✓	✓	✓	✓	✓	✓	✓

3.7 Health Effects Study

Health data was collected in two sessions, 6-month apart, for the purpose of studying the association of transient $PM_{2.5}$ and PM_{10} exposure in 300 children from three neighborhood zones in Quito (low, medium, and high exposure zones). Health data collected included hpCRP, IL-6, and other inflammatory blood markers to understand the impact of PM exposure on systemic inflammation, oxidative stress, and atherogenesis in children. The following two sections describe the process of selecting the subjects for the study and the protocol that was followed to collect health information.

3.7.1 Subject Recruitment

Once the schools in each zone were selected, staff from the research project (Dr. Armijos, Dr. Eschanique, and Dr. Weigel) held meetings with children (grades K-6) and parents at the selected

schools to discuss the purpose of the study, its requirements, potential risks and benefits, and address any questions. Parents who expressed an interest in having their child participate were administered a screening questionnaire to evaluate whether they met the study selection criteria that included the following guidelines:

- Current enrollment in any of the three target elementary schools.
- Age 7-12 years.
- Lifelong residency in one of the three target neighborhood zones.
- Residency within 5 miles of the central monitoring station in the zone.
- Negative history of frequent travel outside the QMD.
- Unremarkable clinical histories for major chronic (e.g. diabetes) or infectious diseases (e.g. rheumatic fever).
- Children residing in a household with non-smokers.
- One child per household eligible for study participation in order to minimize household over-sampling.

Children who met eligibility criteria were assigned an identification number. Identification numbers were used in a computerized random numbers program to make the final selection. Selected subjects and their parents who agreed for participation in the study went through and signed an informed consent.

3.7.2 Health Data Collection

The first part of the health data collection for this study consisted of a visit to a health clinic. On the first visit, conducted at the beginning of the study (January 2010), clinical and laboratory data, such as questionnaire, food and physical activity histories, medical history, physical exam, anthropometry, blood pressure, cIMT, aIMT, and blood tests, were collected. The first task during this visit was for the child to provide a fasting blood sample from a finger prick; next child and parent were provided with breakfast in the cafeteria. Afterwards, the ultrasound specialist performed the arterial thickness studies (cIMT aIMT), followed by the pediatric cardiologist collecting the subject's medical history from the

parent. Next, the interviewer conducted a face-to-face diet and physical activity histories with the parents. Prior to leaving the clinic, the study team members informed the parents about the results and answered any questions. A second visit (May-June 2010), with activities and data collection similar to the one described above with the exception of the ultrasound, was conducted six months later. Subjects that completed both visits received an honorarium and bus money to help compensate for their time and travel costs. A questionnaire was also administered to the parents at the time of the first interview to collect data on children's sociodemographic and household characteristics, including: physical address of the home, school, and playgrounds, source and location of any recreatinonal/hobby pollutant sources inside the home and neighborhood, fuel source used for cooking, lighting, heating, opening of windows and other ventilation practices.

This dissertation will summarize selected data included in the health questionnaire regarding the subject's medical history and sociodemographic characteristics (age, grade, and ethnicity) and is presented in Appendix C. Analysis of the associations between the health data and indoor/outdoor PM exposure is discussed elsewhere.

Chapter 4: Central Monitoring Results

Hourly data for air pollutants (CO, NO_2, $PM_{2.5}$, O_3 and SO_2) were collected from the Automatic Network of Air Quality (RAUDO for its initials in Spanish) in Quito from 2005 to 2010. Data for PM_{10} was collected from the Active Network of Particulate Matter (RAPAR), which provided 24-hr levels every six days. Meteorological data (wind speed and direction, temperature, relative humidity, precipitation, atmospheric pressure, and solar radiation) were acquired from the Meteorological Network (REMET) in Quito from 2005 to 2010 period for the three exposure zones (Cotocollao, El Camal, and Los Chillos). Table 3.4 shows the pollutant and meteorology data available at the different stations whereas, Figure 3.16 shows the location of the stations. In section 4.1, this chapter presents the QA/QC that was followed for the analysis of the data. Section 4.2 presents historical trends (2005-2010) for the meteorology and air pollutant data (except PM) to understand Quito's weather patterns and air quality problems from the last few years. Section 4.3 presents meteorology and air pollutant data for the time-frame of the study, with data averaged for the seven-day periods when sampling took place in each zone. Section 4.4 presents historical (2005-2010) and study-period (2010) PM data in a conceptual model that analyses PM trends, seasonal, daily, and hourly variations, exceedances to Ecuador's NCAA standards (Table 1.1) as well as correlations with meteorological and co-pollutant factors. Knowledge of the meteorology in the Quito region will help in understanding air pollutant trends. The PM conceptual model at the end of the chapter presents the level of PM exposure in the region according to the central monitoring network and will serve as a basis of comparison (presented in Chapter 6) with the school and residential site monitoring conducted in this dissertation.

4.1 Quality Assurance/Quality Control

A data set comprising the 2005-2010 time-frame was analyzed. For the purpose of this dissertation, data was deemed invalid if less than 75% of the data was not available for the time frame considered. The Municipal Environmental Department of the Quito Metropolitan District also uses the 75% criteria to validate their data and estimate averages as required by the Quito standards. From 2006-2011, more than 95% of the data collected was considered valid data for most pollutants. A review of

the monitoring network was conducted by the USEPA in 2008. The report submitted by the EPA states that, “the monitoring system is accurate and well-implemented” (USEPA 2008).

4.2 Historical Data (2005-2010)

4.2.1 Meteorology (2005-2010)

Figures 4.1-4.8 show historical data (2005-2010), in terms of monthly averages, for the meteorology collected at the stations from the selected zones in Quito. Quito experienced low north-easterly winds with speeds ranging from 1 to 2.5 m/s (Figures 4.1 and 4.2). The majority of the winds at the Cotocollao (Zone 1) station came from the northeast while El Camal (Zone 2) experienced winds coming from the northeast and southwest. Los Chillos (Zone 3) experienced winds from all directions, with a few strong breezes (5.7-8.8 m/s) coming from the southeast. Wind speed and direction are important factors for air quality as they inhibit or promote pollutant transportation, mixing, and resuspension.

Temperature (Figure 4.3) in Quito varies only a few degrees throughout the year due to its geographical location and proximity to the Equator. It only has two seasons defined by its precipitation patterns Summer (dry season) from June to September and Winter (wet season) from October to May. The coolest months from October through December have average temperatures at 12-13ºC (53.6-55.4ºF) while the warmest months (July-September) show average temperatures of 14-15ºC (57.2-59ºF). Humidity levels stay above 50 percent (according to Figure 4.4), while precipitation levels vary from an average of 15 (in August) to 170 mm (in April) according to Figure 4.5. Figure 4.6 shows annual total precipitation levels at each station.

As expected, levels of atmospheric pressure stay relatively constant throughout the year at each station (Figure 4.7) with values between 725 mb (at El Camal) to 760 mb (at Los Chillos). It is also an indication of their respective elevations. The stations of Cotocollao (Zone 1, elevation of 2800 m) and El Camal (Zone 2, elevation of 2840 m) are located at higher elevations than the station of Los Chillos (Zone 3, elevation of 2453 m), as shown in the 3-dimensional figure of the Quito region (Figure 4.9).

Solar radiation has been observed to be a significant predictor of visibility in an urban region, with visibility defined as the public perception of healthy or unhealthy air quality (Raina et al, 2005). It also promotes the formation of secondary pollutants, such as ozone (O_3). At Quito (Figure 4.8), solar radiation stays relatively constant with values varying between 140 W/m^2 (at El Camal) to 210 W/m^2 (at Cotocollao).

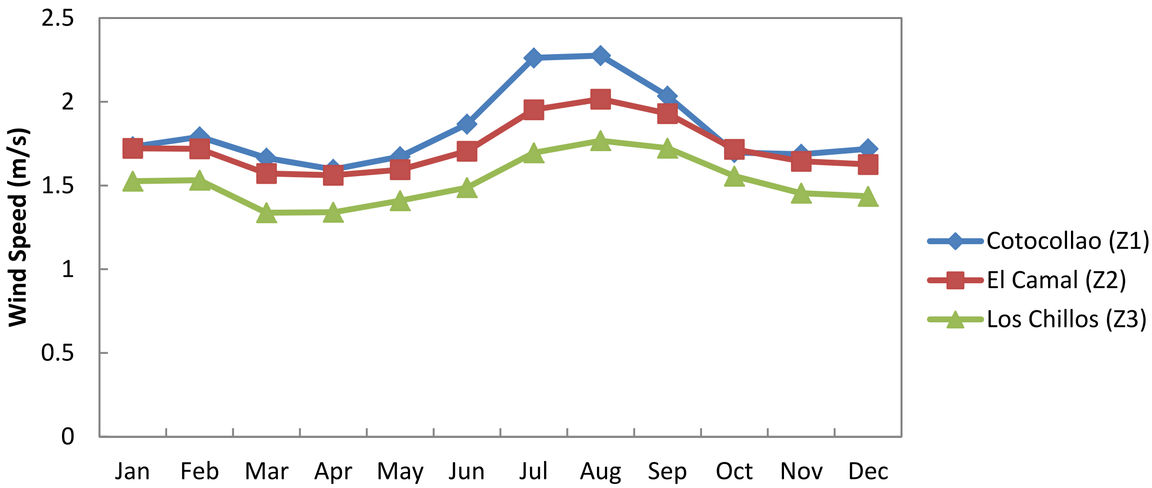


Figure 4.1: Monthly wind speed averages (2005-2010)

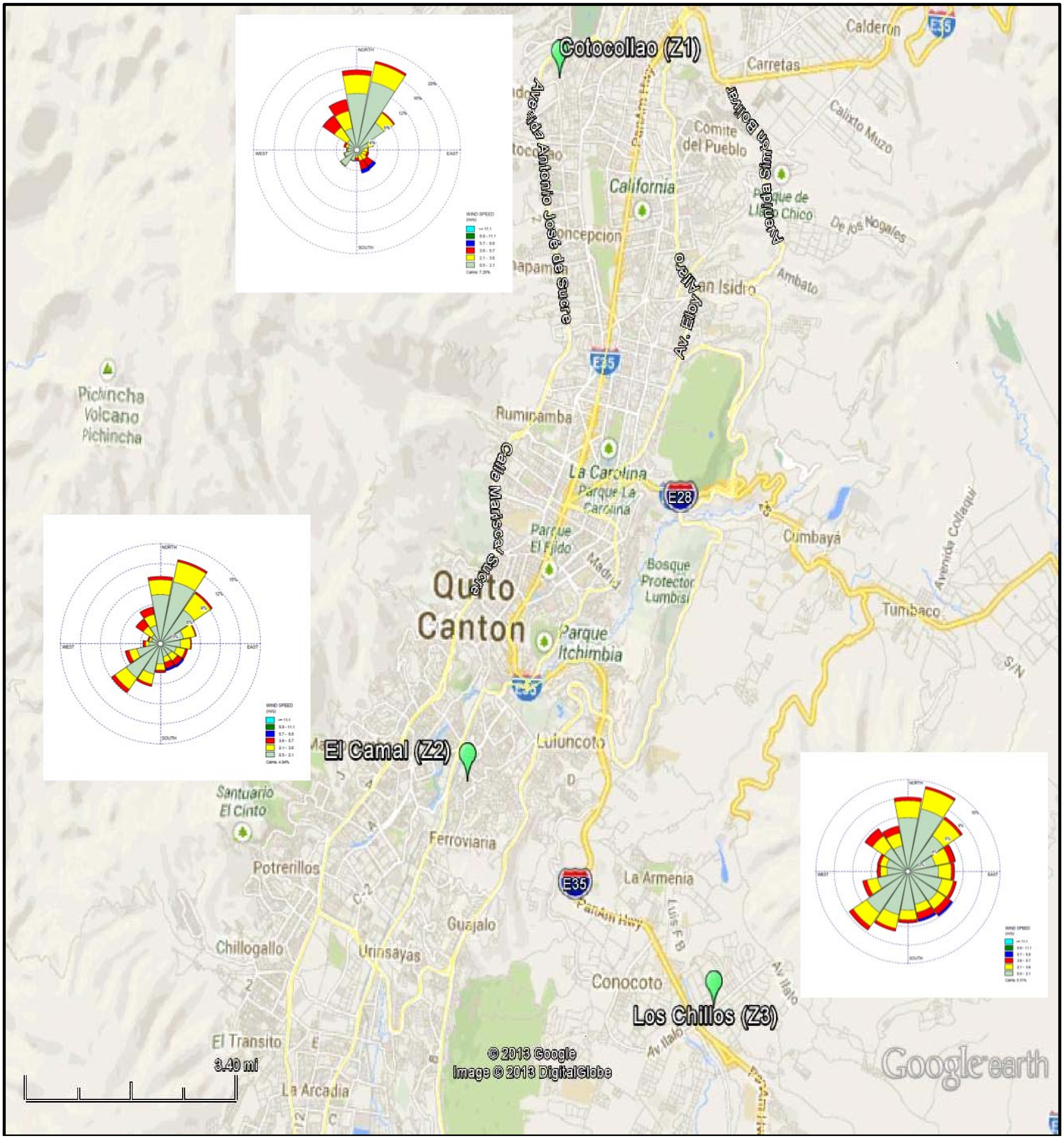


Figure 4.2: Wind roses from 2005-2010

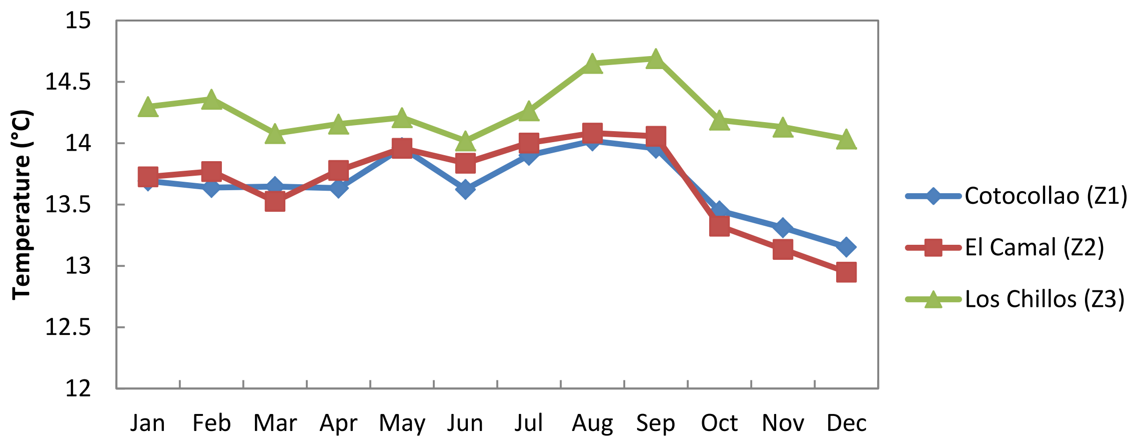


Figure 4.3: Monthly temperature averages (2005-2010)

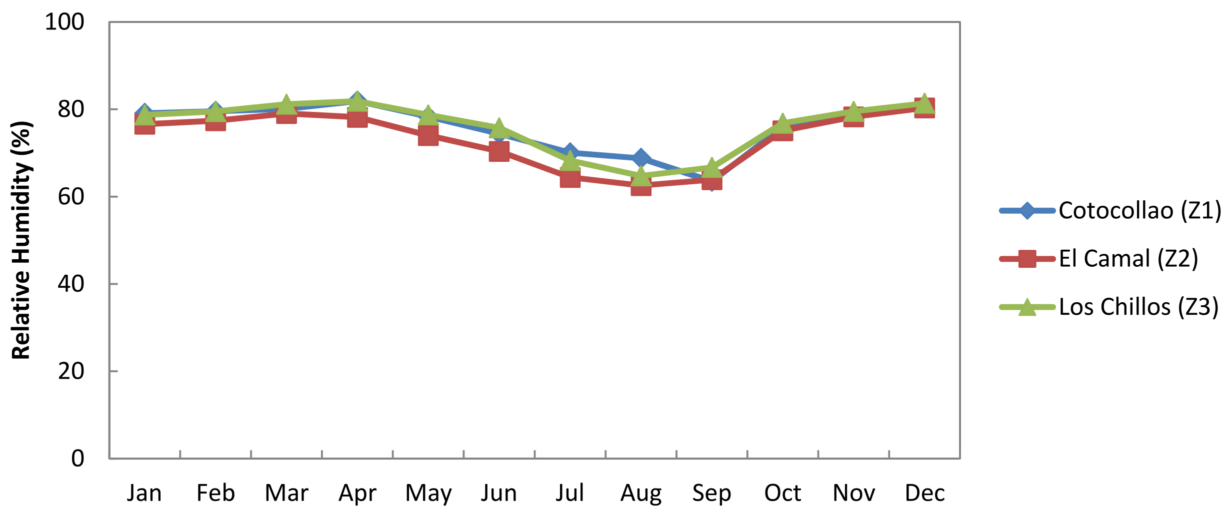


Figure 4.4: Monthly relative humidity averages (2005-2010)

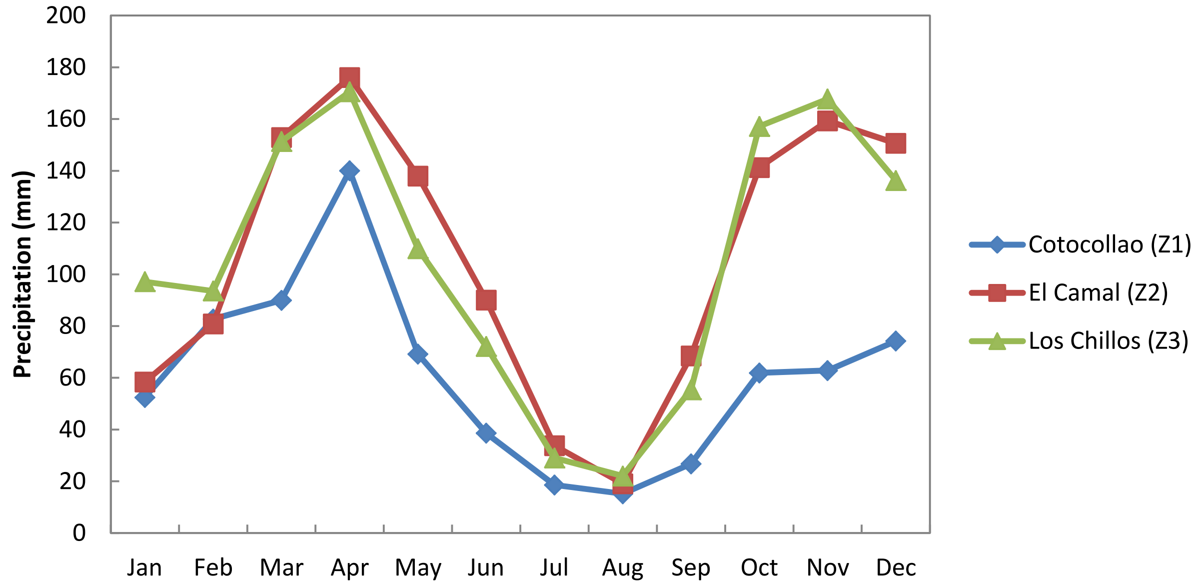


Figure 4.5: Monthly precipitation averages (2005-2010)

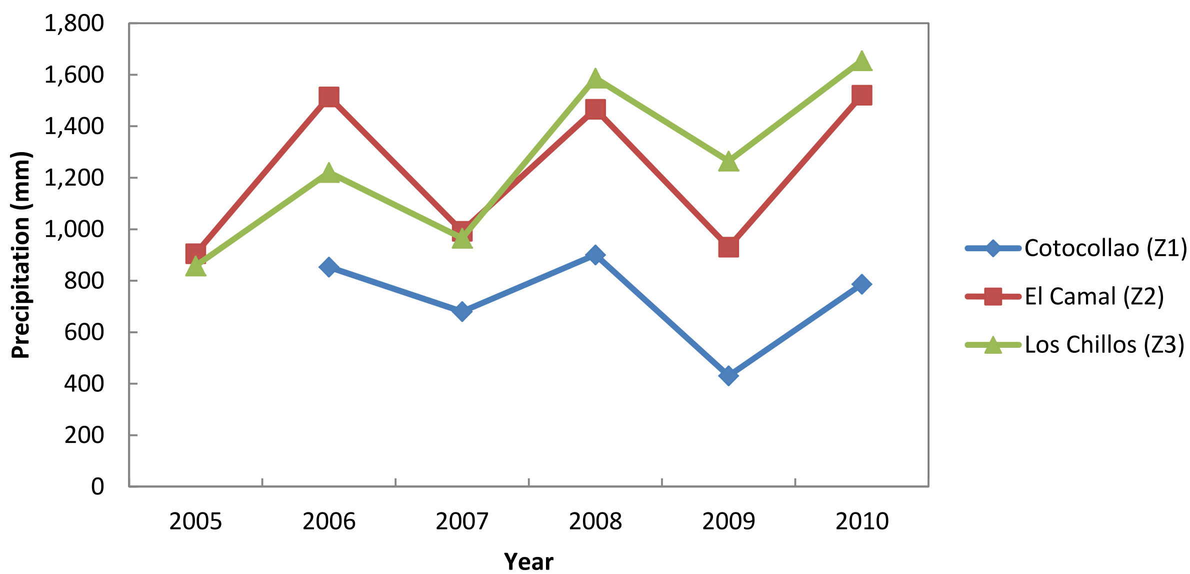


Figure 4.6: Annual precipitation totals

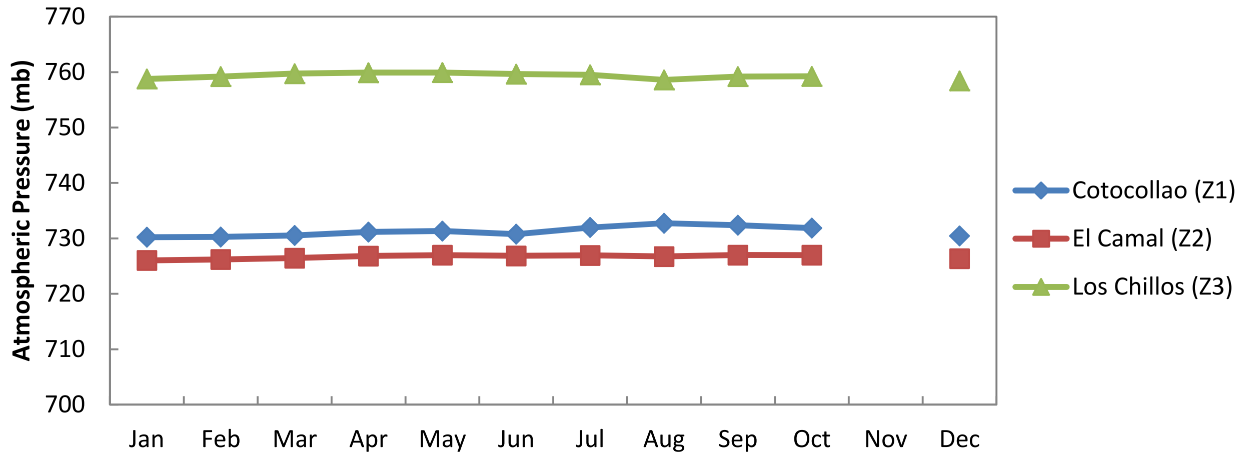


Figure 4.7: Monthly atmospheric pressure averages (2005-2010)

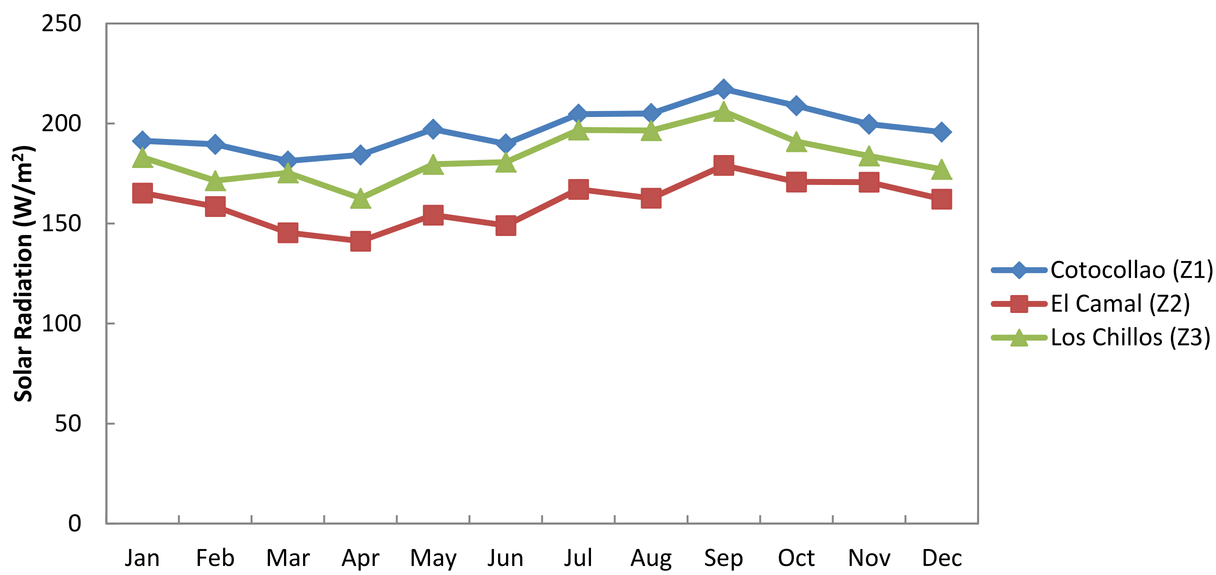


Figure 4.8: Monthly solar radiation averages (2005-2010)

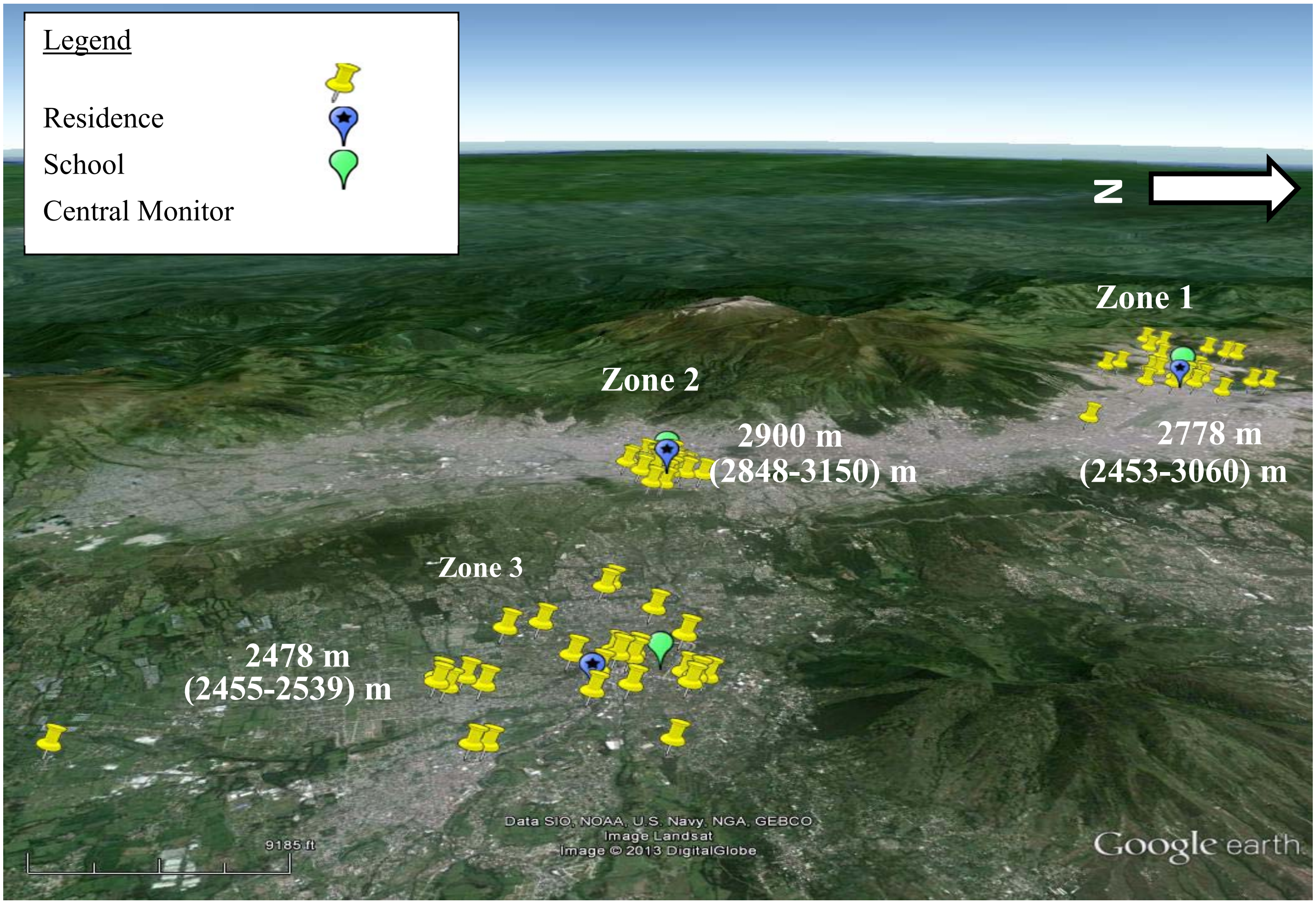


Figure 4.9: 3-D model of the Quito region with average (min, max) elevations.

4.2.2 Air Pollutants (2005-2010)

Terrain elevation will have an effect on local temperature and pressure conditions of the region. Higher elevations will result in lower temperatures and lower pressure levels. Air pollutant concentrations, expressed in terms of mass per unit volume (e.g. $\mu g/m^3$) at sea level will decrease with increasing altitude. Concentration decrease will be directly proportional to the pressure decrease. Since Quito is located significantly above sea level (average of 2800 m), the environmental ministry requires air pollutant data collected from the central monitoring network to be adjusted to standard temperature (25ºC) and pressure (760 mmHg) conditions. Collected levels are adjusted according to local temperature and pressure conditions using the following equation:

$$C_c = C_o * \frac{760\ mmHg}{P_l\ mmHg} * \frac{T_l K}{298\ K} \qquad \text{(Equation 4.1)}$$

C_c = concentration adjusted to standard conditions (T=25ºC and P=760mmHg)

C_o= original concentration according to local conditions

P_l= local atmospheric pressure (mmHg)

T_l = local temperature (K)

(Source: Norma Ecuatoriana de Calidad del Aire)

Based on average temperature and pressure values collected for 2010 and applied to equation 4.1, concentrations collected to local conditions (C_o) would be raised approximately by 30 percent according to the following factors,

$$Cotocollao\ (Zone\ 1) = \frac{760\ mmHg}{(730\ mb * 0.75)mmHg} * \frac{(14 + 273)K}{298\ K} = 1.34$$

$$El\ Camal\ (Zone\ 2) = \frac{760\ mmHg}{(725\ mb * 0.75)mmHg} * \frac{(14 + 273)K}{298\ K} = 1.35$$

$$Los\ Chillos\ (Zone\ 3) = \frac{760\ mmHg}{(757\ mb * 0.75)mmHg} * \frac{(16 + 273)K}{298\ K} = 1.30$$

Particulate matter concentration levels collected from ambient monitors and presented in this chapter (Chapter 4) are adjusted to standard conditions. However, particulate matter concentration levels collected for the school and residential sites and presented in Chapters 5 and 6 are reported to local conditions. Central monitoring data presented in Chapters 5 and 6 were also adjusted to local conditions in order to match the site data.

Carbon Monoxide (CO)

Carbon monoxide monthly averages for the 2005-2010 period are shown in Figure 4.10 and yearly averages are shown in Figure 4.11. Both figures show the station at Belisario registering the highest CO concentrations followed by El Camal (Zone 2) and Centro, the stations located in the center

of the city and receiving the most exposure to traffic emissions that greatly contribute to CO concentrations. In a study by Estrella et al. (2005) children attending schools near high traffic areas had higher levels of carboxyhemoglobin (COHb) as a result of being exposed to high levels of CO than their peers attending schools near low traffic areas. Lowest concentrations fluctuate between the stations at Cotocollao (Zone 1) and Carapungo located in the northern region of the city, and Guamani located south of the city. March seems to be the month registering the highest concentrations, at least among the stations with the highest concentrations. July and August seem to be the months with the lowest concentrations at the stations with the highest concentrations. The stations with the lowest concentrations have slightly different trends, with their monthly averages remaining fairly constant throughout the year. Figure 4.11 shows that CO concentrations decreased from 2005-2010 in the three stations with the highest readings (Belisario, Centro, and El Camal, Zone 2). The bottom three stations (Cotocollao, Zone 1, Carapungo, and Guamani) remain constants. Main sources for CO include traffic emissions, therefore, reasons for the decline in CO concentrations include the implementation of the inspection and maintenance program for vehicles (*Revisión Técnica Vehicular)* and the establishment of the *Pico y Placa* program explained in full detail in Chapter 1 and aimed at reducing traffic emissions (Secretaría de Ambiente, 2011).

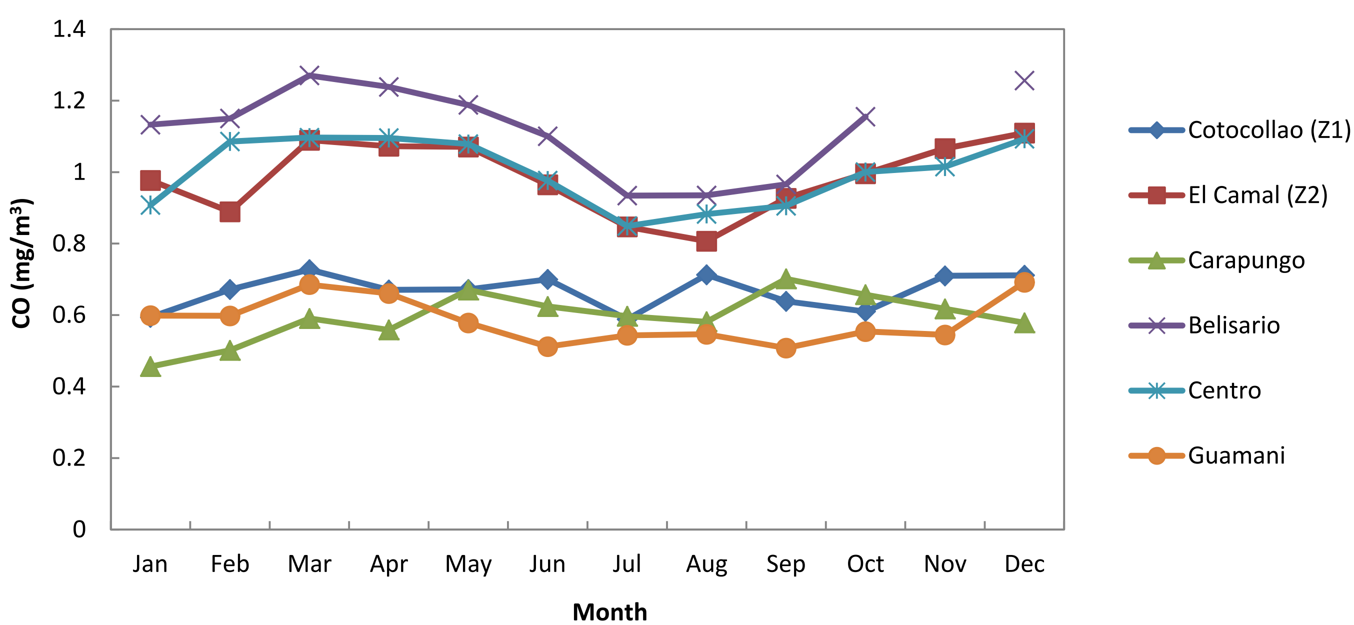


Figure 4.10: CO monthly averages from central monitors for 2005-2010

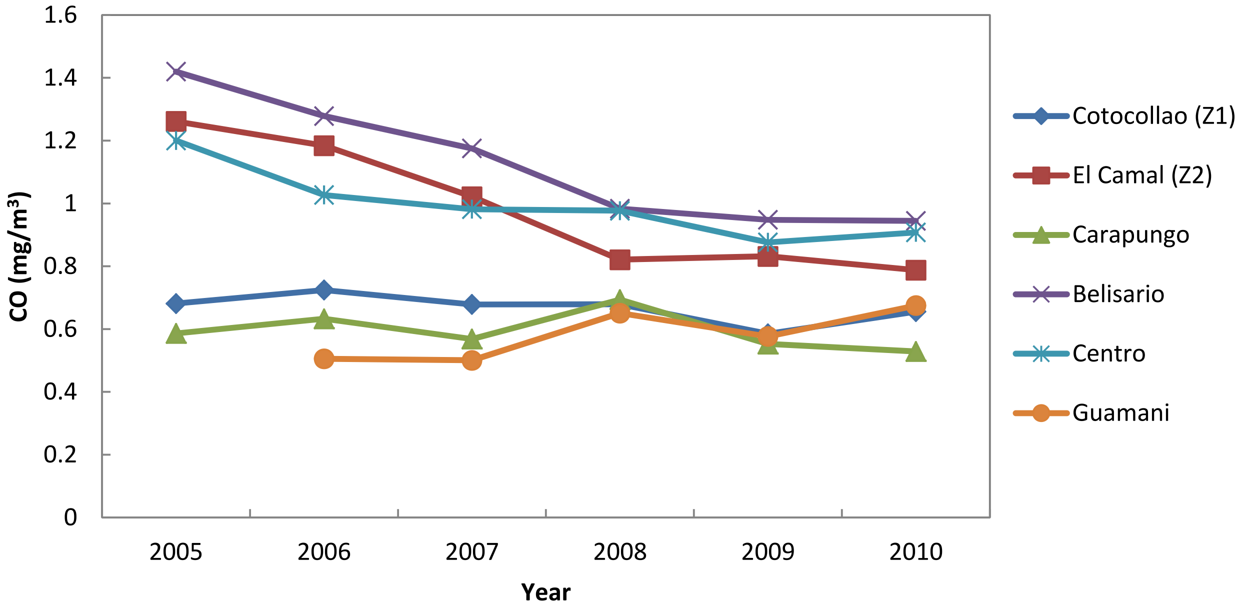


Figure 4.11: CO yearly averages from central monitors for 2005-2010

Ozone (O_3)

Figures 4.12 and 4.13 show the monthly and annual averages for O_3. Guamani station had the highest levels of O_3 in both figures due in part to the amount of sunlight it receives (Secretaría de Ambiente, 2011). The rest of the stations registered similar levels, with Belisario having the lowest levels. The month of September is clearly the month with the highest concentrations at all stations, while May is the month with the lowest concentrations. Solar radiation is highest during the month of September as seen in Figure 4.8. Figure 4.13 shows that annual averages have remained relatively constant, which is consistent with NO_2 levels that have also remained constant and NO_2 plays an important role in O_3 formation. Reports from the Environmental Department of Quito report no exceedances to the WHO or Quito guidelines.

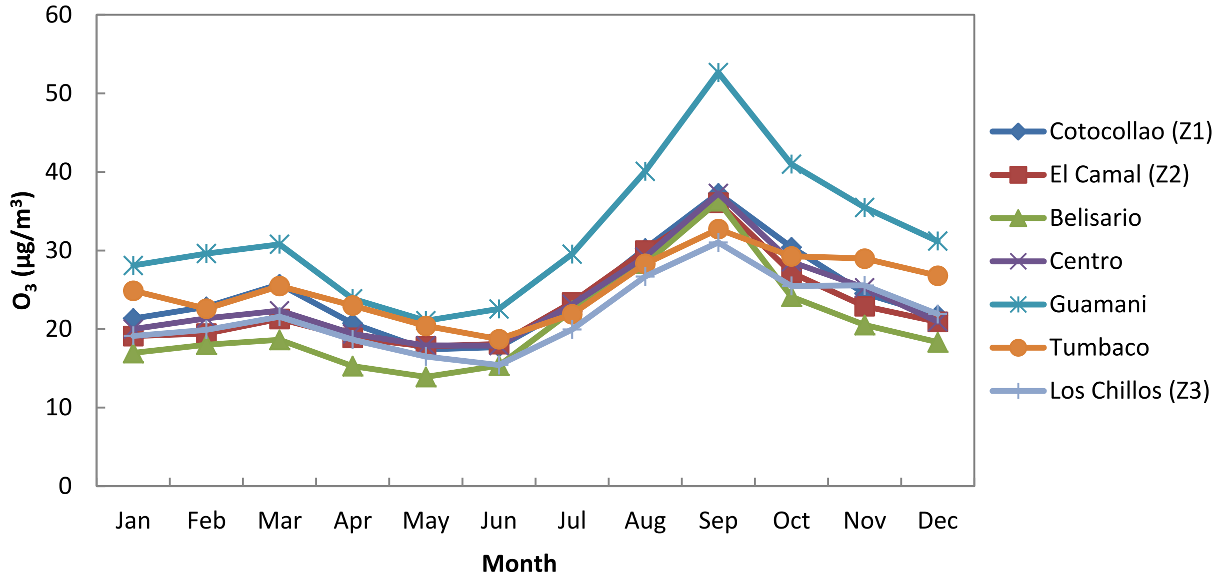


Figure 4.12: O_3 monthy averages from central monitors for 2005-2010

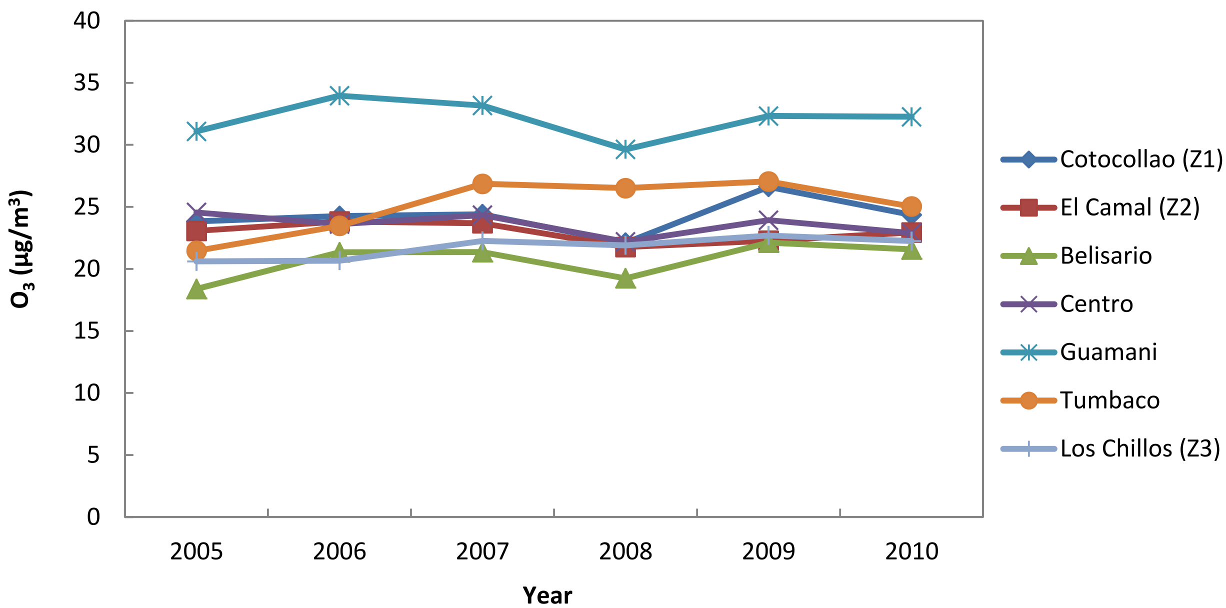


Figure 4.13: O_3 yearly averages from central monitors for 2005-2010

Nitrogen Dioxide (NO_2)

Figures 4.14 and 4.15 capture the monthly and annual averages for NO_2. The stations at El Camal (Zone 2) and Belisario registered the highest averages for both figures, as they are located in the

center of downtown Quito and right where traffic flows are high while the stations to the south (Guamani) and north (Carapungo) register the lowest averages (less traffic). The months of September and October registered the highest averages of the year in part because of higher vehicle traffic due to the beginning of classes (Secretaría de Ambiente, 2010). Figure 4.15 does not show a marked trend of concentrations going up or down, rather they remain constants, similar to the O_3 concentrations. Although it is not indicated in this study, exceedances to the NO_2 WHO annual guideline were reported for *La Marín* and *Necochea* (passive monitoring stations) due in part to high traffic density (Secretaría de Ambiente, 2010).

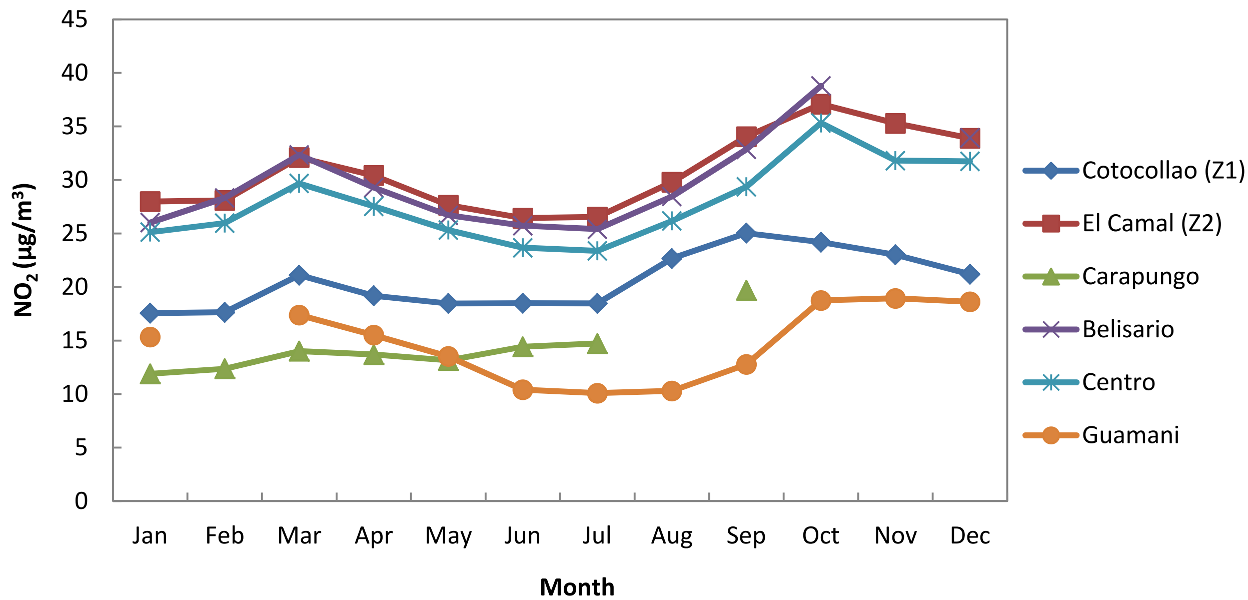


Figure 4.14: NO_2 monthly averages from central monitors for 2005-2010

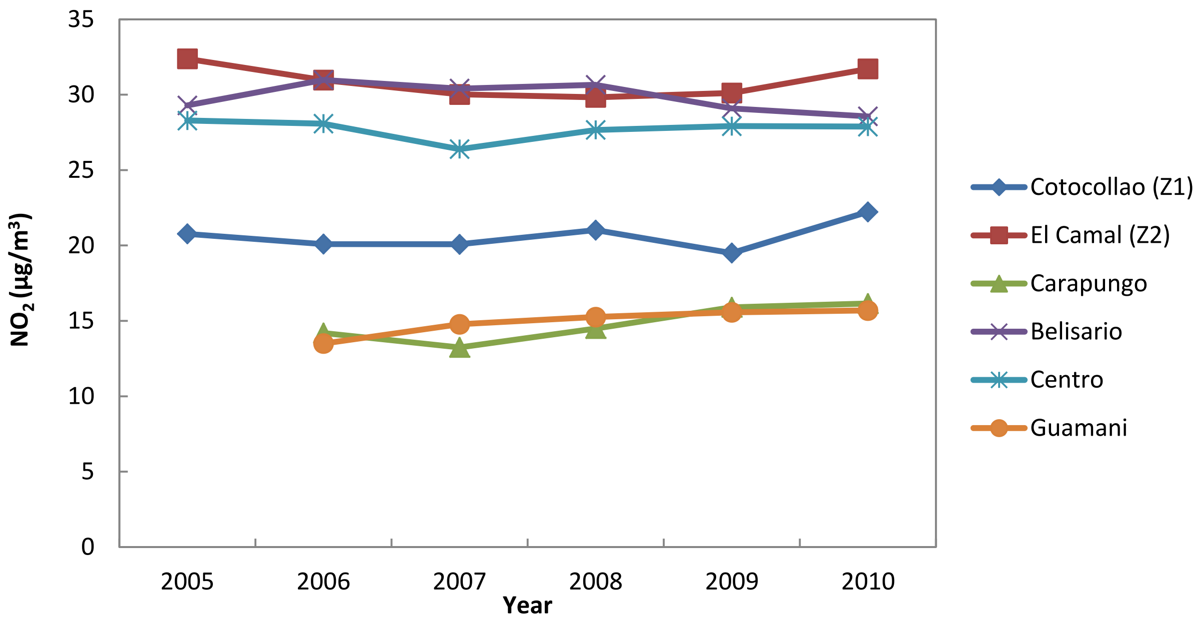


Figure 4.15: NO_2 yearly averages from central monitors for 2005-2010

Sulfur Dioxide (SO_2)

Monthly and annual averages for SO_2 are shown in Figures 4.16 and 4.17 respectively for the 2005-2010 period. El Camal (Zone 2) is clearly the station with the highest average concentrations in both figures, while Carapungo and in a few instances Cotocollao (Zone 1) registered the lowest average concentrations. Concentration patterns for SO_2 mirror traffic patterns in Quito: El Camal, Belisario, and Centro are located in the center portion of the city, subjected to traffic congestion from both private and public transportation, while Cotocollao and Carapungo are located in the northern portion of the city. Although not shown here, El Camal also exceeded the WHO 24-hour guidelines on several occasions in 2010 (Secretaría de Ambiente, 2010). Figure 4.16 shows that the months with the highest averages were March and November at all the stations while August seems to be the month with the lowest average concentrations. Figure 4.17 clearly shows a downward trend in the concentrations at all stations from 2005-2010. This trend is the result of Quito's efforts to reduce traffic congestion and emissions, including, as mentioned before the inspection and maintenance program, the *Pico y Placa* program, and Quito's switch to low sulfur level gasoline in 2010 (*Extra* went from having 2,000 ppm to 750 ppm and *Super* went from having 2,000 ppm to 1,000 ppm).

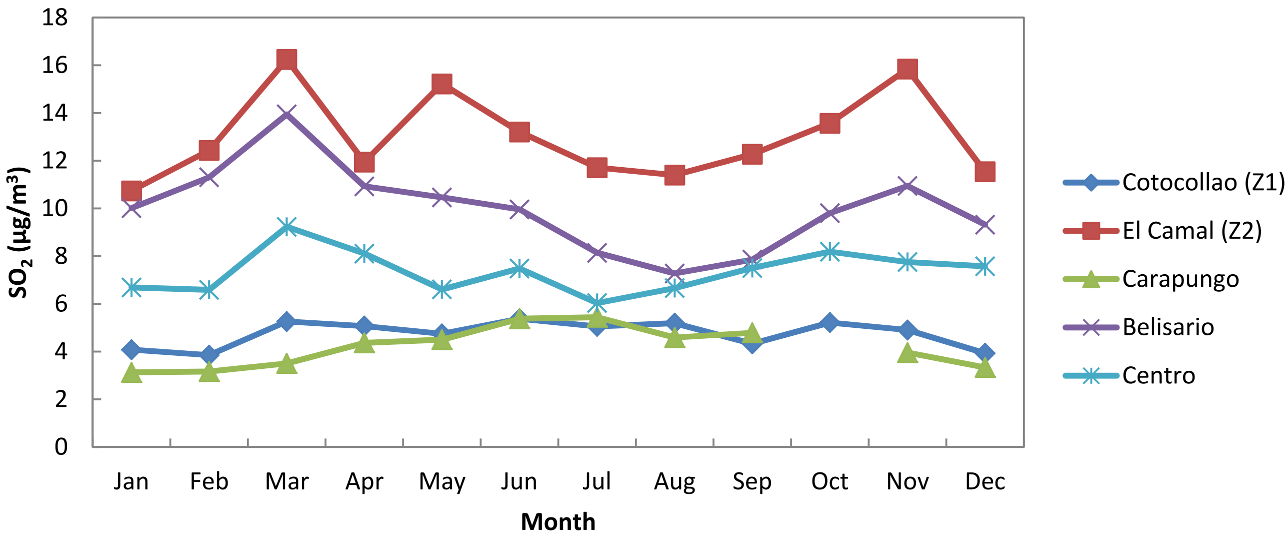


Figure 4.16: SO_2 monthly averages from central monitors for 2005-2010

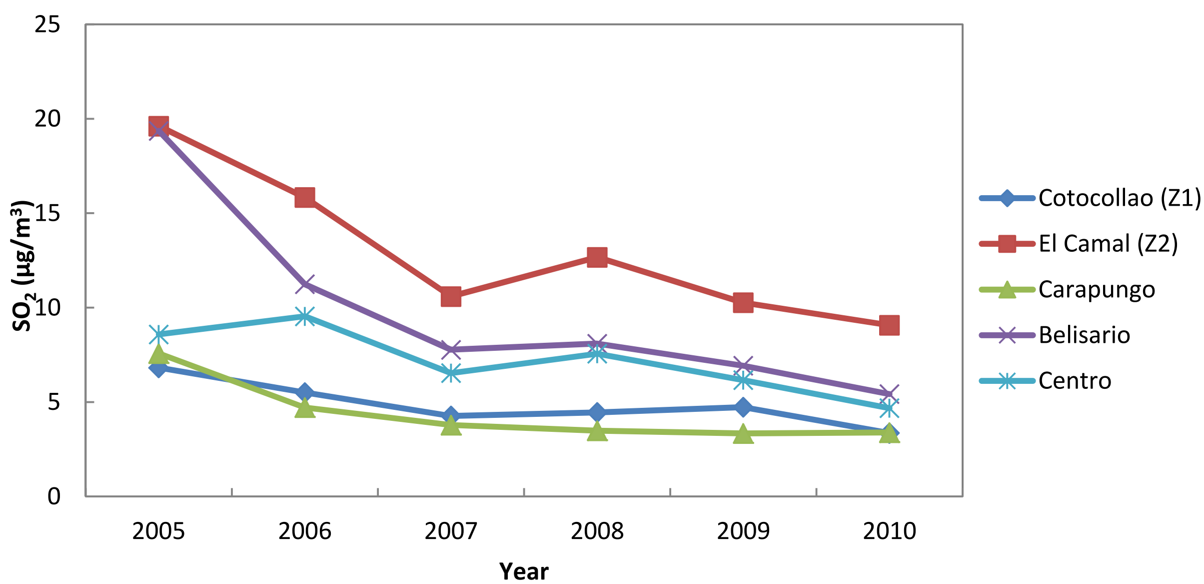


Figure 4.17: SO_2 yearly averages from central monitors for 2005-2010

4.3 Study Period (2010 Data)

4.3.1 Meteorological Parameters (2010)

Meteorological data for the weeks when the study took place is presented in Figures 4.18 to 4.24. Monthly averages for each of the factors (except wind roses) were estimated for the 7-day period when the monitoring for a particular zone took place. Monthly wind roses are presented in Appendix A. The zones were monitored in different weeks each month, so data trends may differ across the three zones. Wind data is shown in Figures 4.18 and 4.19, with the mostly low wind speeds. At Cotocollao (Zone 1) the majority of the winds came from the north and north east with speeds below 2.1 m/s. At El Camal (Zone 2) most of the winds came from the south west and north east below 3.6 m/s. At Los Chillos (Zone 3) most of the winds came from the north and north west also with relatively low speeds below 2.1 m/s. El Camal was the zone that experienced higher wind speeds during the study period.

The weather in Quito can be described as cool and spring-like all year long, with average 7-day temperatures (for the three zones) varying between 12 and 18ºC (54-64ºF) throughout the study (Figure 4.20). Los Chillos (Zone 3) showed slightly higher temperatures, coinciding with its lowest elevation and higher atmospheric pressure. November and December were the months with the lowest temperatures. Relative humidity (Figure 4.21) stayed above 50 percent and below 85 percent. Precipitation totals (Figure 4.22) for the 7-day period each month show a high of 140 mm in the month of February at Los Chillos (Zone 3) to a no rain for the month of May at Cotocollao (Zone 1).

Atmospheric pressure (Figure 4.23) stays relatively constant at each zone throughout the study period at 730 mb at Cotocollao (Zone 1), 725 mb at El Camal (Zone 2), and 760 mb at Los Chillos (Zone 3). Solar radiation (Figure 4.24) varies throughout the study period, with Cotocollao (Zone 1) receiving the least amount. Cotocollao received the most solar radiation in February, El Camal in September, and Los Chillos in June.

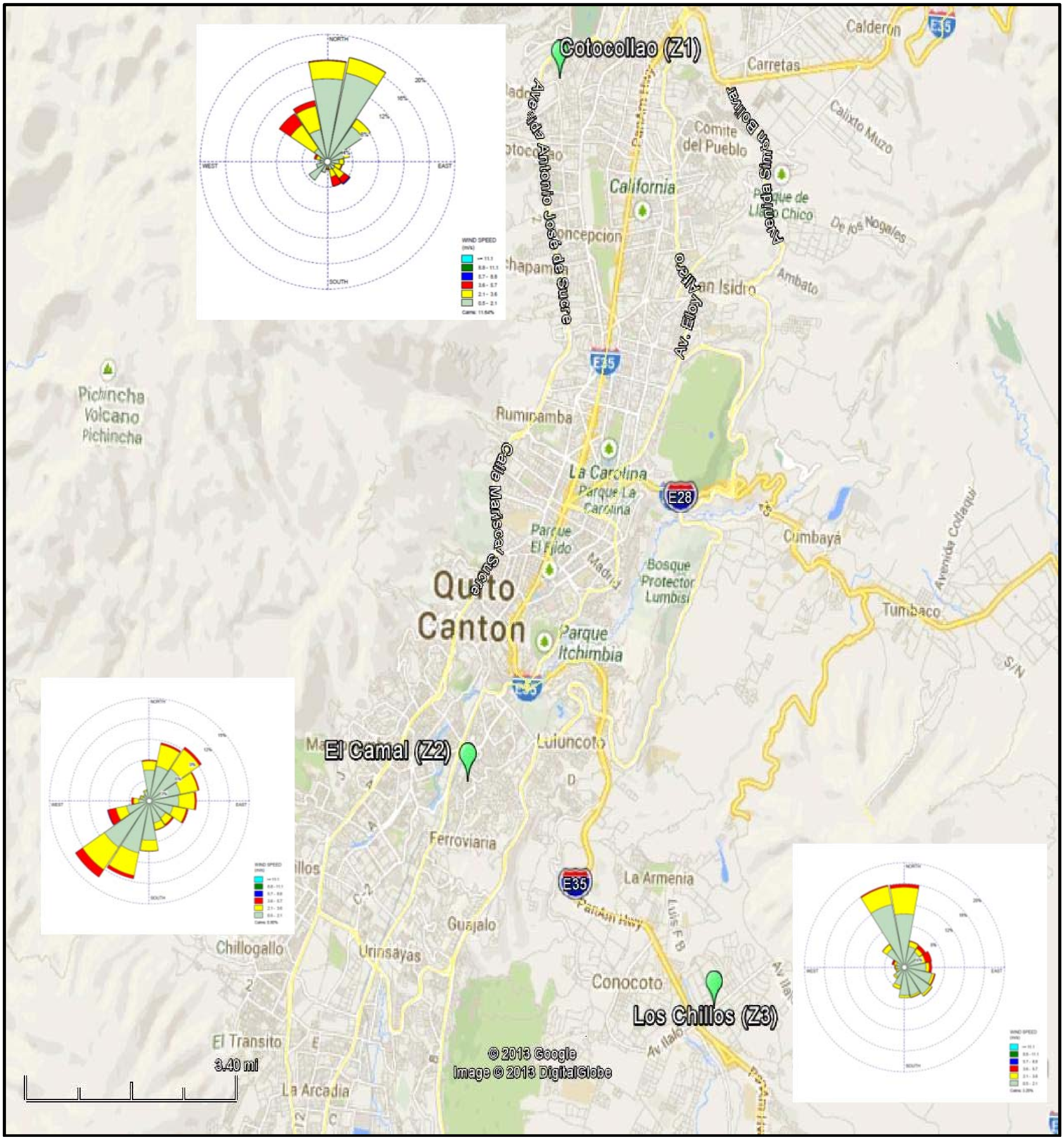


Figure 4.18: Wind roses for 2010 at the three selected zones for this study

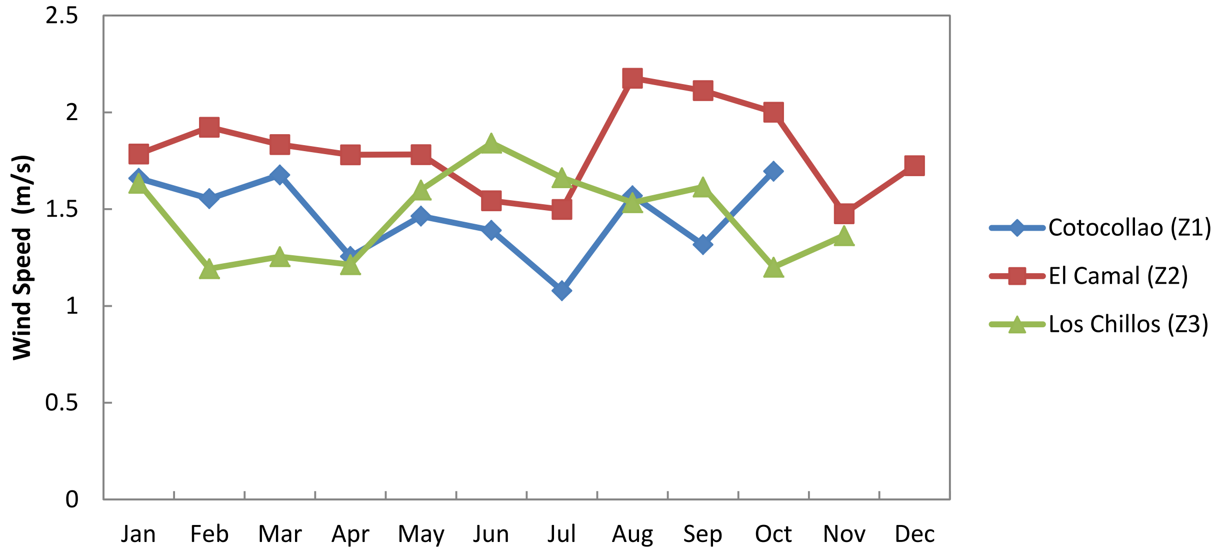


Figure 4.19: Seven-day average wind speed for 2010

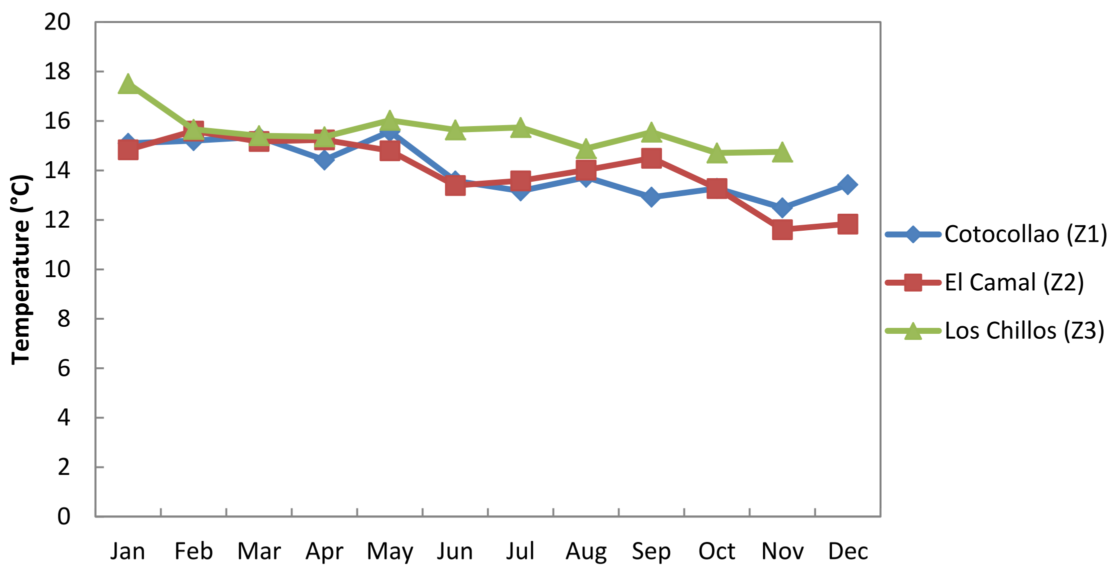


Figure 4.20: Seven-day average temperatures for 2010

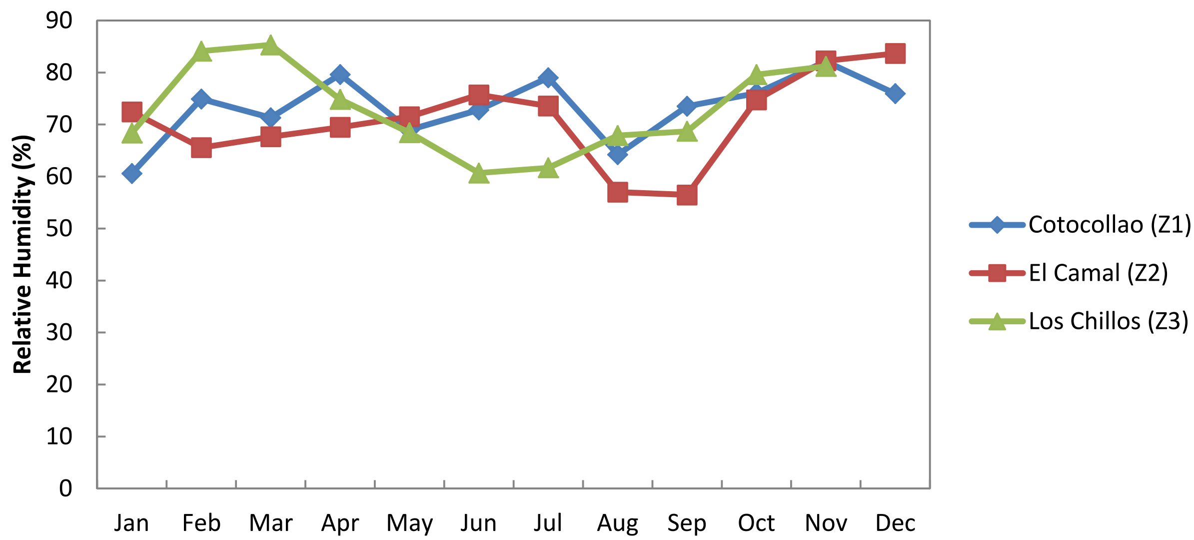


Figure 4.21: Seven-day average relative humidity for 2010

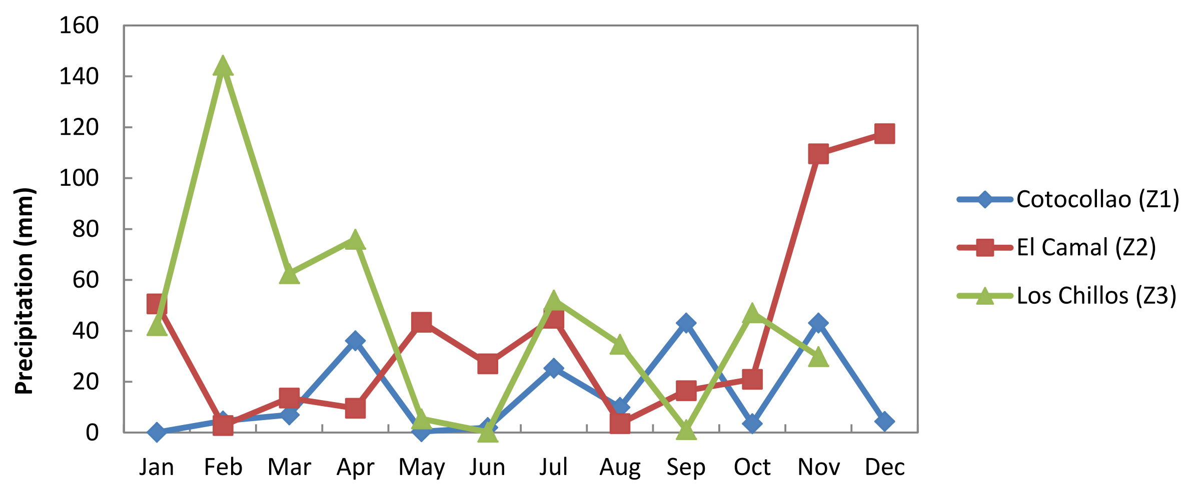


Figure 4.22: Seven-day precipitation totals for 2010

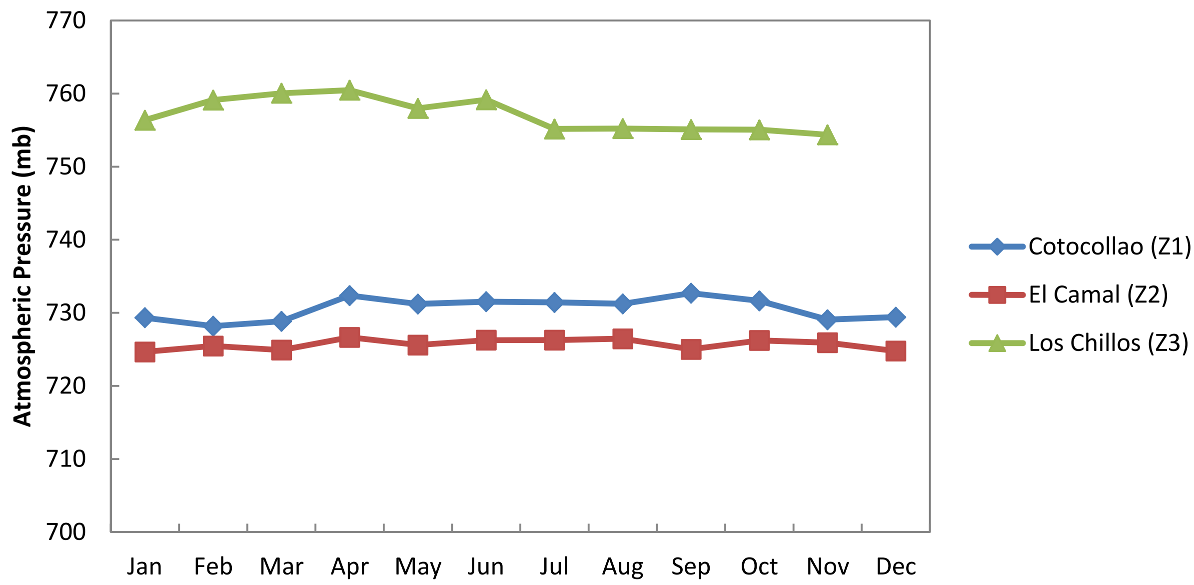


Figure 4.23: Seven-day average atmospheric pressure for 2010

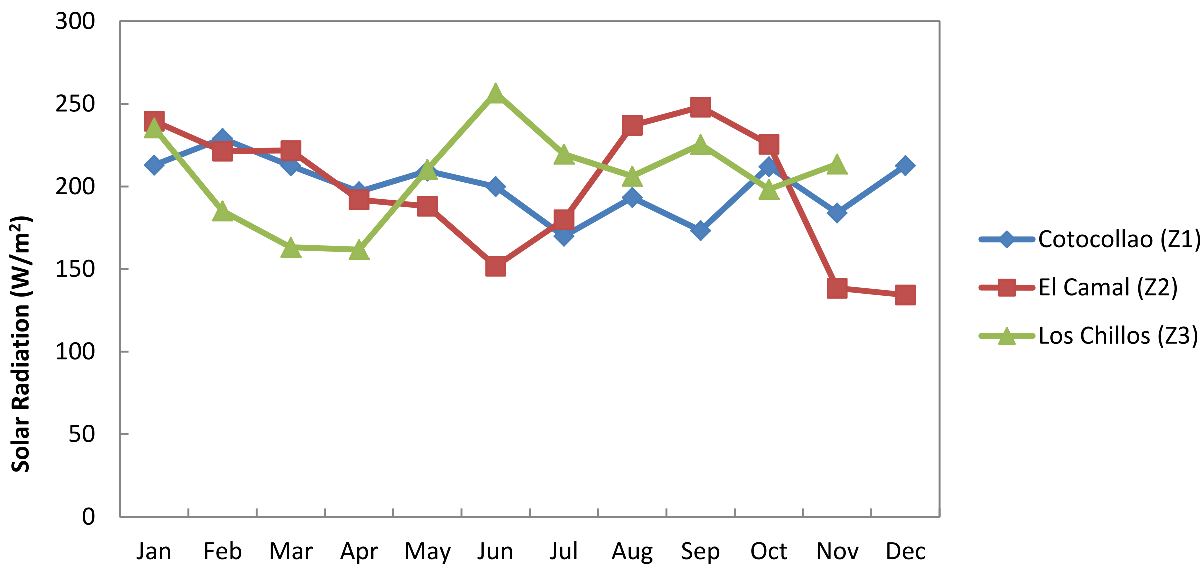


Figure 4.24: Seven-day average solar radiation for 2010

4.3.2 Air Pollutants (2010)

Air pollutant data was collected from ambient monitors in the selected exposure zones. The hourly data was averaged over 7-day periods each month following the sampling schedule in each zone (Figures 4.25-4.28). In the low exposure zone, (Los Chillos, Zone 3) O_3 was the only pollutant available.

It is evident that for NO_2 and SO_2 (Figure 4.27 and 4.28) concentration levels are the highest in the high exposure zone, El Camal (Zone 2), coinciding with the high traffic zone, while O_3 (Figure 4.26) concentration levels are similar across the zones. For CO (Figure 4.25), concentrations are higher at El Camal most of the months in 2010 and were the highest in November, again a reflection of the high traffic exposures. For O_3, concentrations were the highest in September at Cotocollao (Zone 1) and El Camal (Zone 2). Although there was no data for that particular month at Los Chillos (Zone 3), the trend indicates that the highest concentration would have been in that month also. Figure 4.24 indicates that at El Camal, the highest amount of solar radiation happened in September also, even though that was not the case at Cotocollao and Los Chillos. However, Figure 4.8 showing monthly averages with data from 2005-2010 does show September as the month with the greatest amount of solar radiation at all three stations, while Figure 4.24 only shows data for the particular week when sampling for this study took place. Concentration levels of NO_2 and SO_2 were the highest at El Camal, particularly in the weeks of November and December. Both contaminants are attributable to emissions from vehicles, especially diesel vehicles and higher traffic is present at El Camal due to its location in the center of Quito.

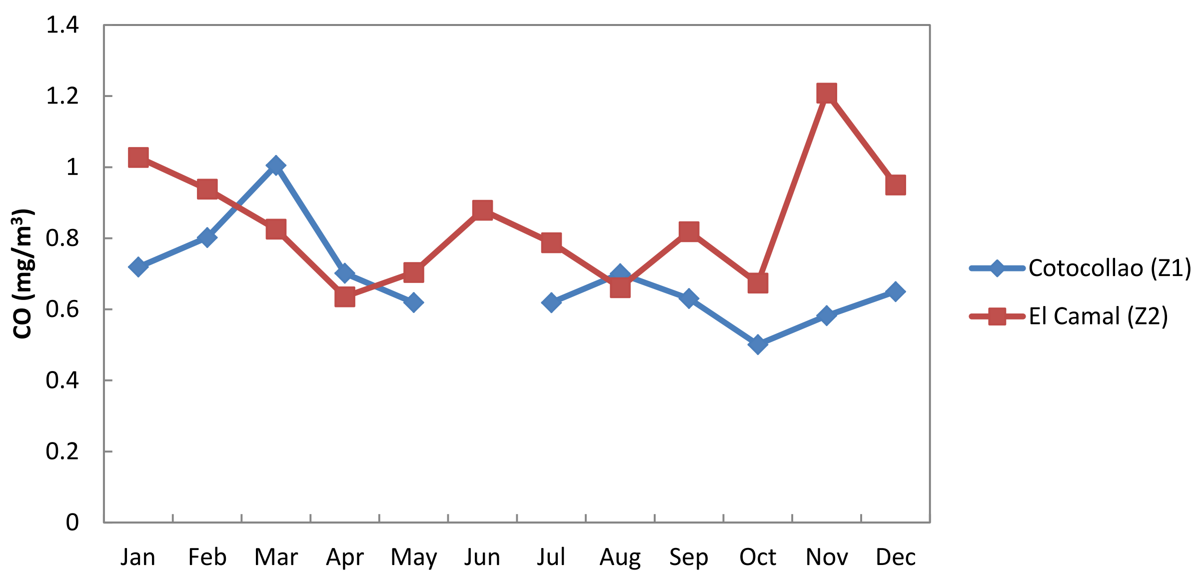


Figure 4.25: Seven-day average CO for 2010

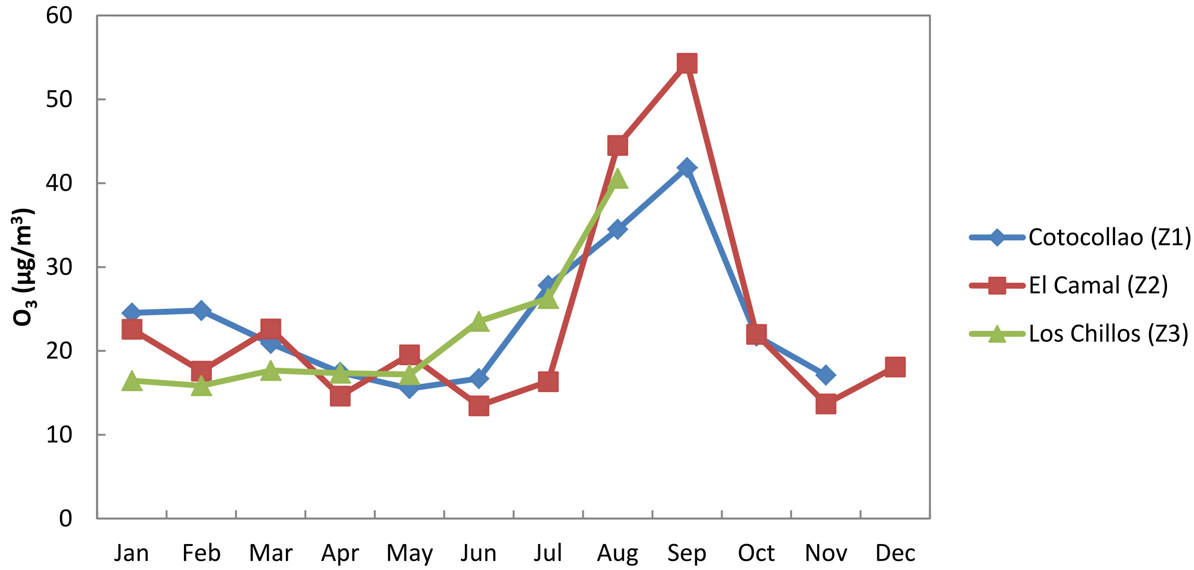


Figure 4.26: Seven-day average O_3 for 2010

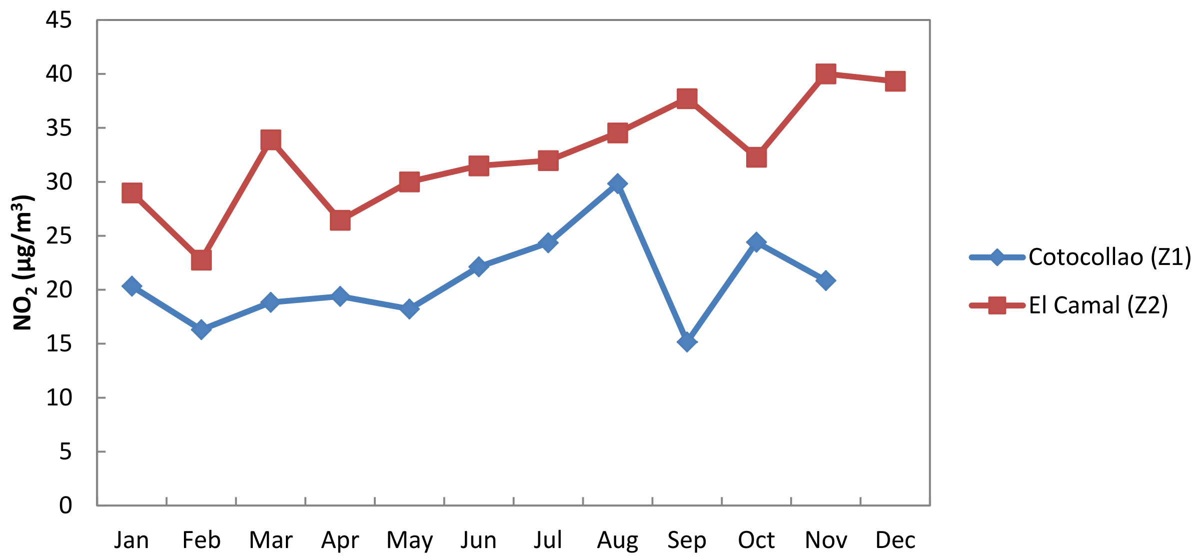


Figure 4.27: Seven-day average NO_2 for 2010

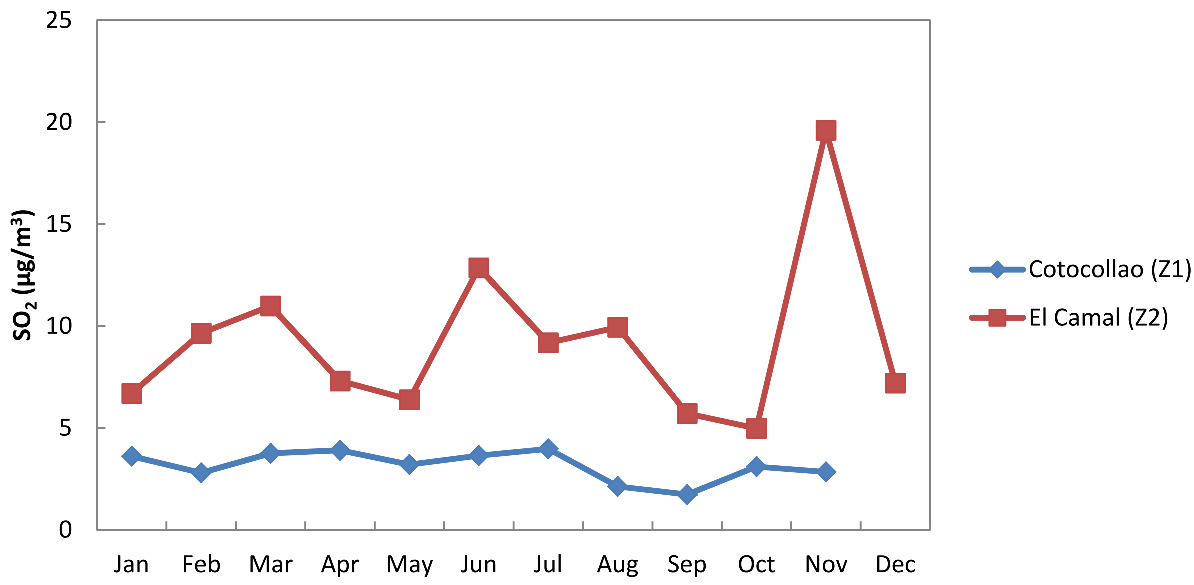


Figure 4.28: Seven-day average SO_2 for 2010

4.4 PM Conceptual Model

Particulate matter levels in Quito, Ecuador are collected as $PM_{2.5}$, PM_{10}, and total suspended particles (TSP). Fine particulate matter ($PM_{2.5}$) is collected hourly as part of the Automatic Network of Air Quality (RAUDO) and thoracic particulate matter (PM_{10}) is collected with 24-hr measurements every six days as part of the RAPAR system. The PM values reported are adjusted for standard conditions (T=25°C and P=760mmHg) and presented as such in Chapter 4. For subsequent chapters (5 & 6), PM values will be adjusted to local conditions to match the school and residential site data collected at local conditions. Particulate matter data (PM_{10} and $PM_{2.5}$) was analyzed from 2005-2010; $PM_{10\text{-}2.5}$ was estimated by subtracting monthly averages of $PM_{2.5}$ from PM_{10}. According to the Quito Air Quality Report (Secretaría de Ambiente, 2011), one of the main problems in air quality for Quito is particulate matter. Annual concentrations exceeded Ecuador Standards (NCAA) at ambient monitors located in El Camal, Centro, Carapungo, and Belisario (See Figure 3.16). According to the 2007 emission inventory, more than 50% of PM_{10} can be attributed to quarries, unpaved roads, and soil erosion coming especially from the north of Quito (San Antonio, Guayllabamba, Pomasqui, and Calderon) while 25% is attributed to traffic emissions and 25% to stationary sources (CORPAIRE,

2007). For $PM_{2.5}$, according also to the 2007 emission inventory, 46% is attributed to traffic emissions, mostly coming from diesel vehicles, 31% is attributed to quarries, and resuspension from unpaved roads, and 23% to combustion processes originated at point sources (CORPAIRE, 2007).

4.4.1 PM Time Series

$PM_{2.5}$

Figures 4.29 and 4.30 show $PM_{2.5}$ monthly and annual averages from 2005-2010. In both figures, El Camal (Zone 2) shows the highest averages while the stations at Cotocollao (Zone 1) and Carapungo show the lowest averages. This coincides again with the central, high traffic zone (El Camal) showing higher averages, while the northern zones (Carapungo and Cotocollao) exposed to lower traffic flows registered the lowest averages. In Figure 4.29, the month of July registered the lowest averages while the months of October and November seem to register the highest concentrations. Annual averages remain relatively constant between 2005-2010 (Figure 4.30). Figure 4.31 shows $PM_{2.5}$ monthly averages for 2010, the year of the study. El Camal (Zone 2) was the station with the highest concentrations and Cotocollao (Zone 1) was the stations with the lowest concentrations. An increase in $PM_{2.5}$ levels is registered in the month of September, coinciding with the beginning of the school year and reflecting an increase in vehicle traffic.

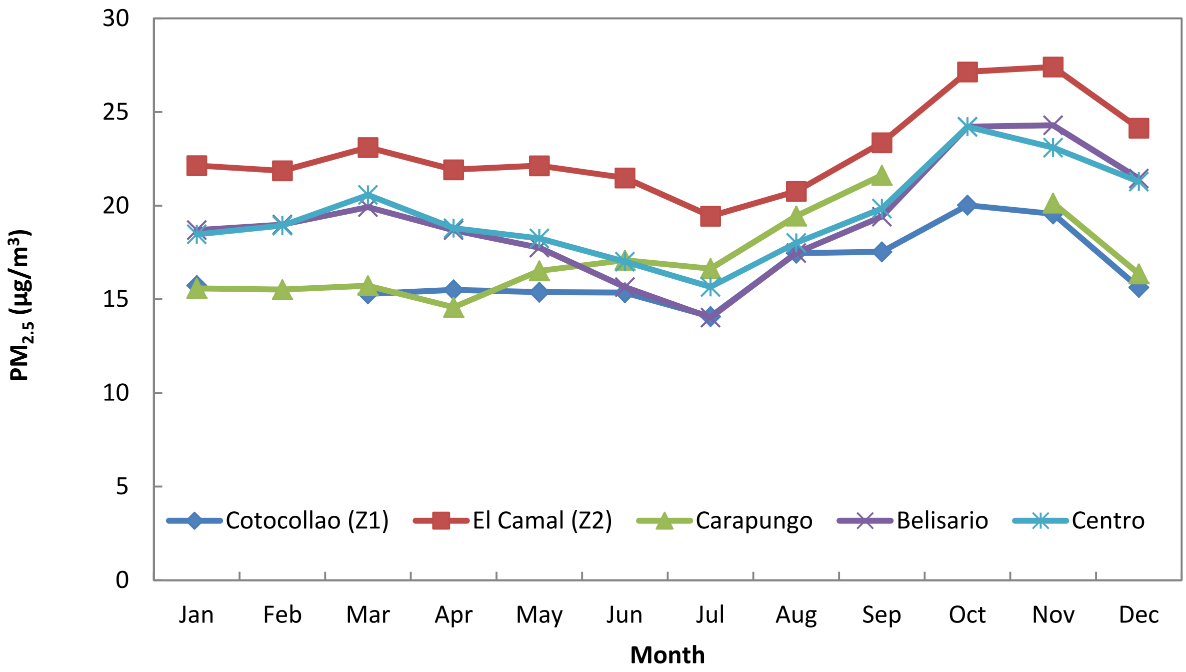


Figure 4.29: $PM_{2.5}$ monthly averages from central monitors for 2005-2010

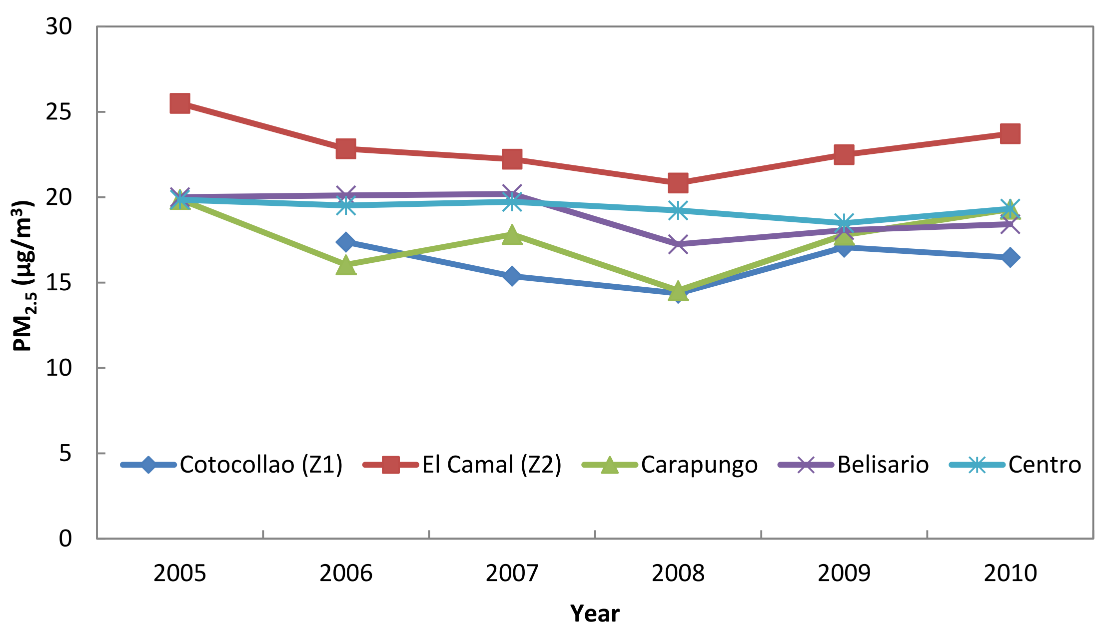


Figure 4.30: $PM_{2.5}$ yearly averages from central monitors for 2005-2010

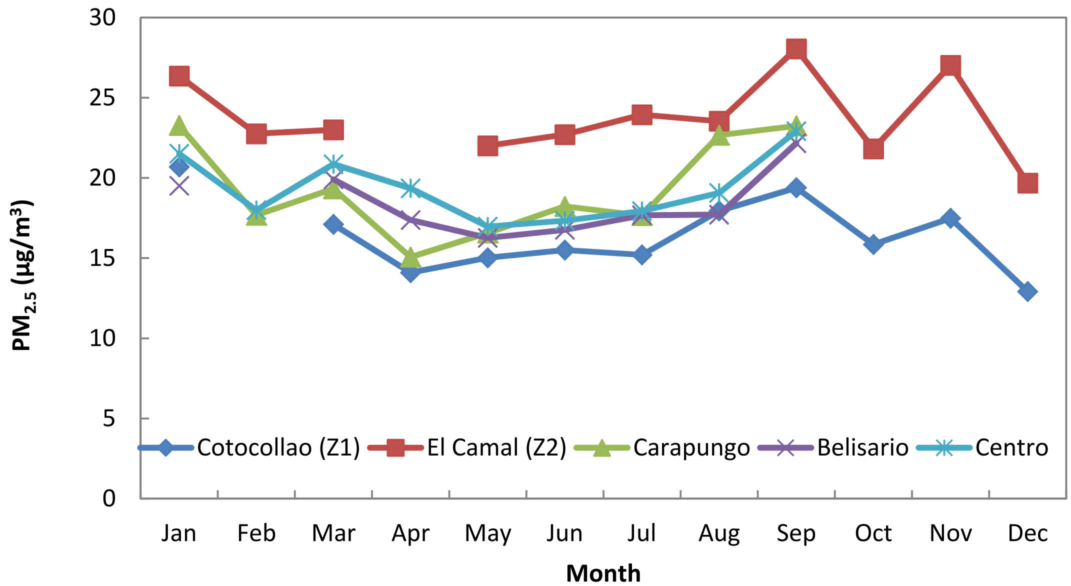


Figure 4.31: $PM_{2.5}$ monthly averages from central monitors for 2010

Figures 4.32 and 4.33 show the daily and hourly variations respectively for $PM_{2.5}$ estimated with data from all the stations presented in Figures 4.29 and 4.30. The $PM_{2.5}$ levels slightly drop on Sunday (Figure 4.32), an effect of lower traffic counts because less people are working. Hourly variations show a pronounced peak at 7:00 AM (traffic morning rush-hour), high traffic due to getting children to school and people commuting to work, while lower concentration levels are registered during the early hours of the morning (3-4:00 AM) and early hours in the afternoon (1-2:00 PM). A second, slightly smaller than the morning peak, is observed in the afternoon, early evening, between 7-8:00 PM, due to people commuting back home from work or running errands.

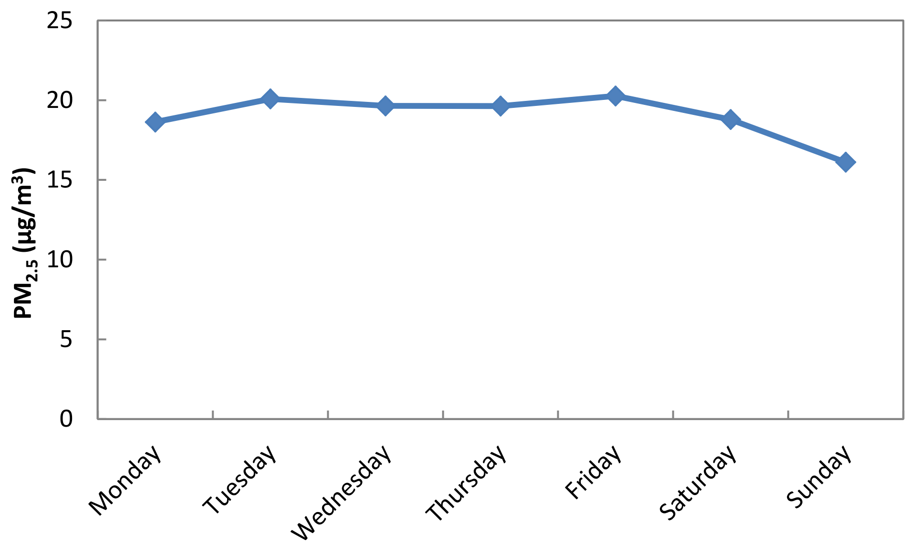


Figure 4.32: $PM_{2.5}$ daily variations (2005-2010)

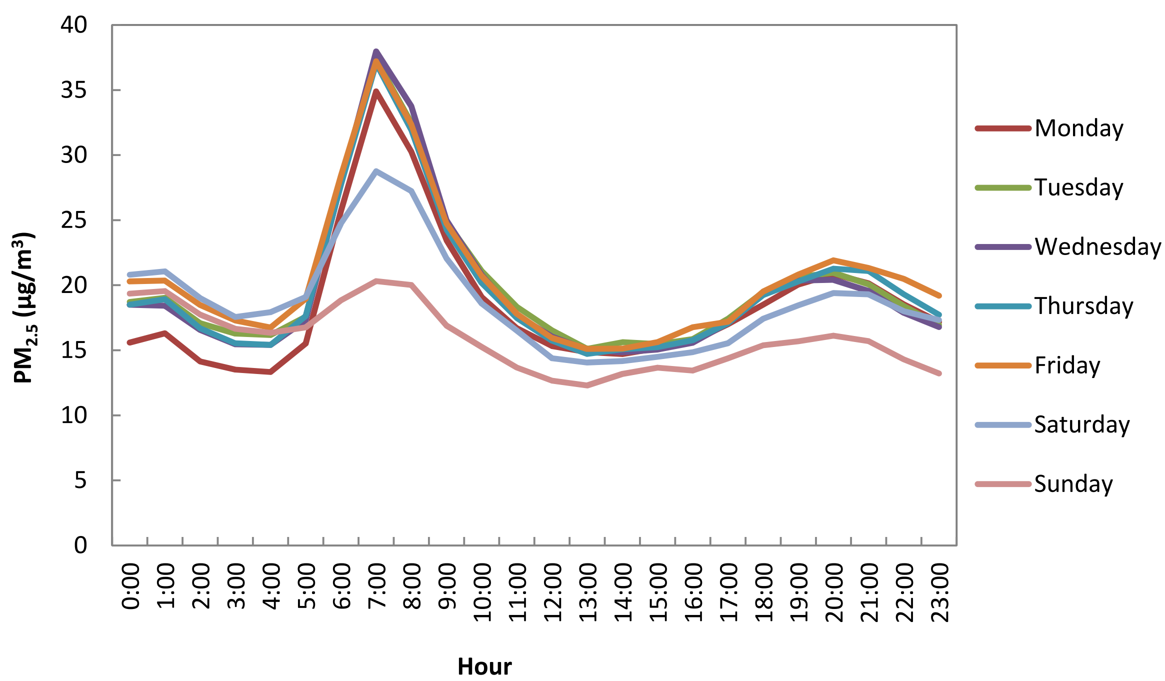


Figure 4.33: $PM_{2.5}$ hourly variations (2005-2010)

PM_{10}

Figures 4.34 and 4.35 show the monthly and annual averages estimated for PM_{10} (2005-2010). Highest concentrations, at most stations, are seen during the months of August and September coinciding with the dry period of the year (see Figure 4.5). El Camal (Zone 2) shows the highest concentrations during the month of January, noting that for El Camal, the only available data was for years 2009-2010. Guamani, located south of Quito registers the highest concentrations throughout most of the year according to Figure 4.34 probably due to resuspension from soil erosion. Figure 4.35 shows concentrations greatly decreasing from 2005-2006 for all stations coinciding with an increase in precipitation from 2005 to 2006 (Figure 4.6). Similar to what was found at Santiago, Chile, were PM_{10} was above normal during phases of below-normal rain and below normal during phases of above normal rainfall in Santiago Chile (Ragsdale et al. 2013). Afterwards 2006, PM_{10} levels remain nearly unchanged. Figure 4.36 shows monthly averages for the year of the study, 2010.

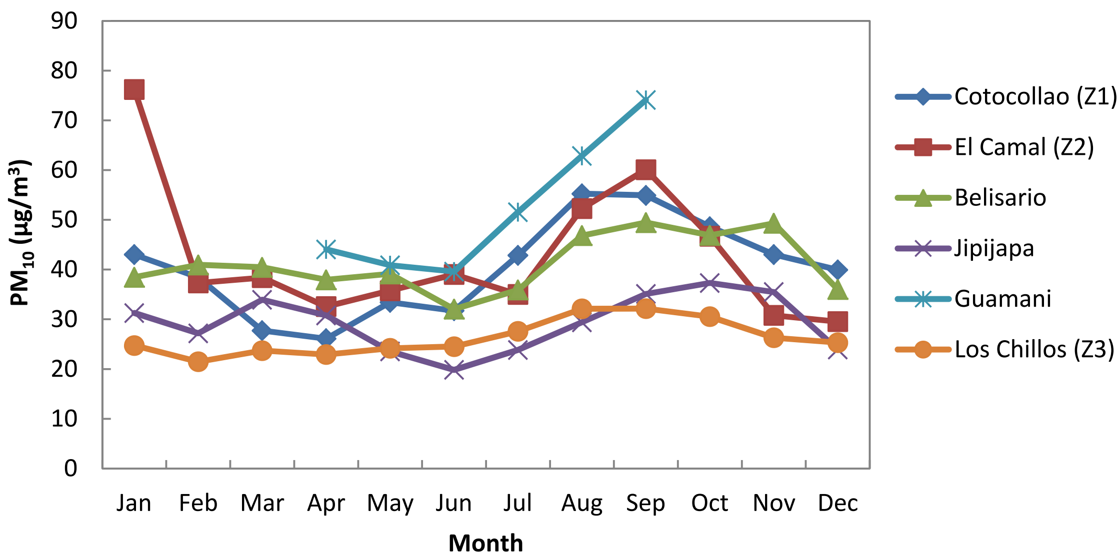


Figure 4.34: PM_{10} monthly averages from central monitors for 2005-2010

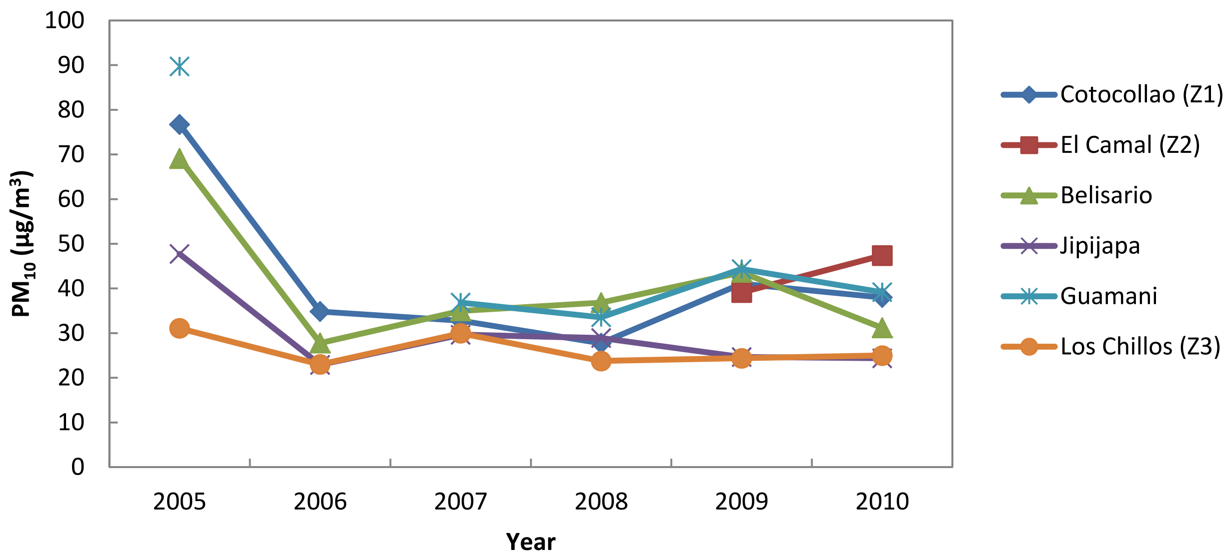


Figure 4.35: PM_{10} yearly averages from central monitors for 2005-2010

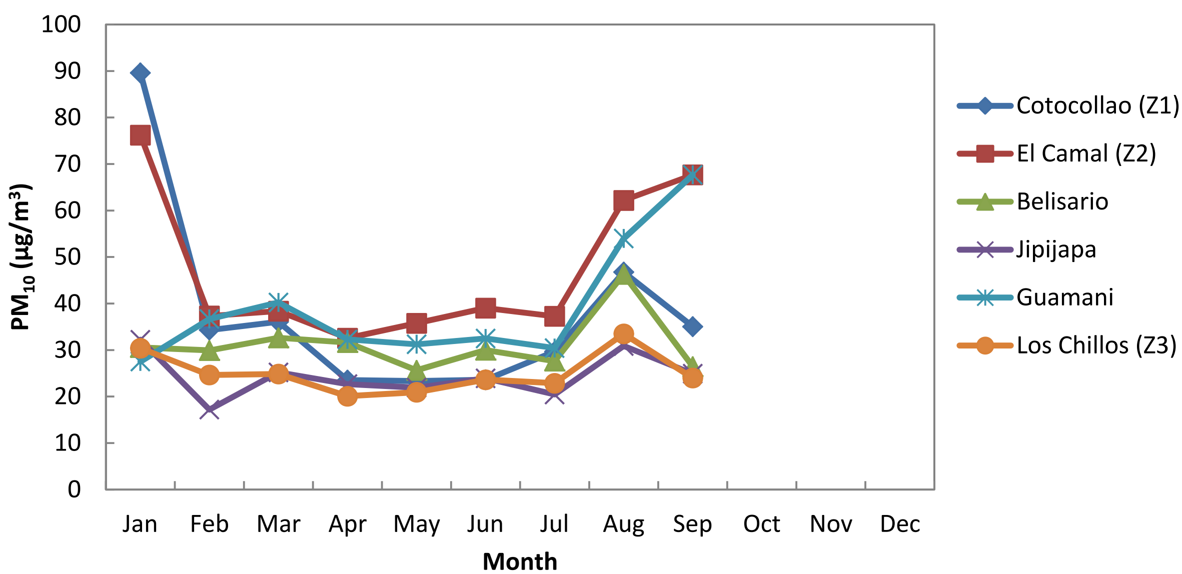


Figure 4.36: PM_{10} monthly averages from central monitors for 2010

Figure 4.37 shows the daily variations of PM_{10} averages estimated with data from 2005-2010 period. The PM_{10}, concentration levels seem relatively unchanged throughout the week because most of its sources come from soil erosion, resuspension from unpaved roads and quarry activity. Slight decrease during the weekend, similarly to $PM_{2.5}$, that can be attributed to no work performed at the quarry and

probably less traffic, especially on Sunday, causing resuspension on unpaved roads. It was not possible to display hourly variations for PM_{10} because concentration levels are collected as 24-hour averages every six days.

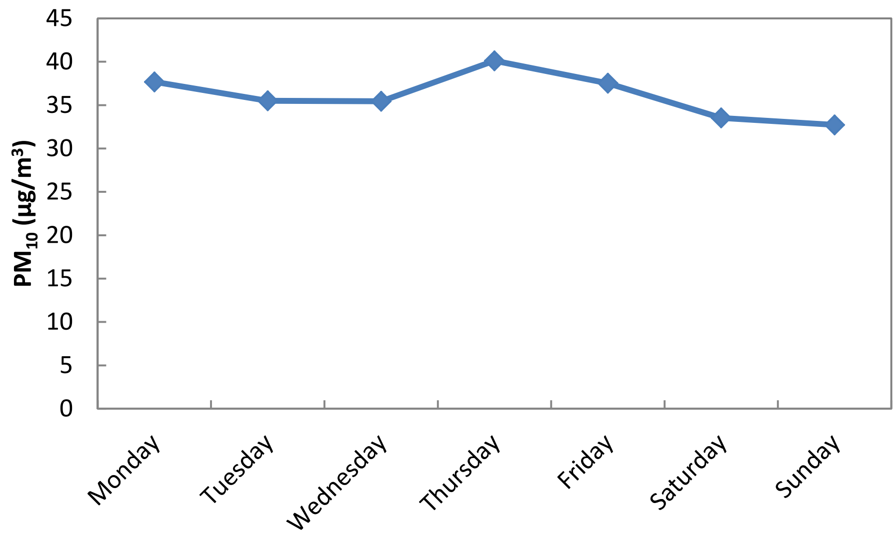


Figure 4.37: PM_{10} daily variations (2005-2010)

$PM_{10-2.5}$

$PM_{10-2.5}$ was not directly measured by ambient monitors, but estimated by subtracting monthly $PM_{2.5}$ averages from monthly PM_{10} averages. Only three central monitors had data for both PM_{10} and $PM_{2.5}$, and the monitor at El Camal only had data from July 2009 to September 2010. Monthly and annual averages are shown in Figures 4.38 and 4.39. Whereas it was very distinct that $PM_{2.5}$ concentrations were the highest at El Camal, for $PM_{10-2.5}$, concentrations among the three stations are very similar throughout the year, with slightly higher concentrations most months at Cotocollao and a few peaks at El Camal during the month of January and December. Unlike the other stations, El Camal only had PM_{10} data available for 1 year, so $PM_{10-2.5}$ concentrations reflect that 1 year only. Similarity in the coarse PM ($PM_{10-2.5}$) levels is expected because main sources include geological factors, such as

resuspension of dust in the area, and traffic emissions do not contribute significantly. To the north of Quito (where Cotocollao is located), the presence of quarries and unpaved roads can contribute to the slight increase in the levels observed in Figure 4.38. Figure 4.40 shows monthly averages for 2010 only, slightly lower than the monthly averages for the 2005-2010 period, with the dry season (month August) showing a peak at all stations. Hourly and daily factors were not estimated for $PM_{10-2.5}$ because $PM_{2.5}$ and PM_{10} data was not measured for the same time frame.

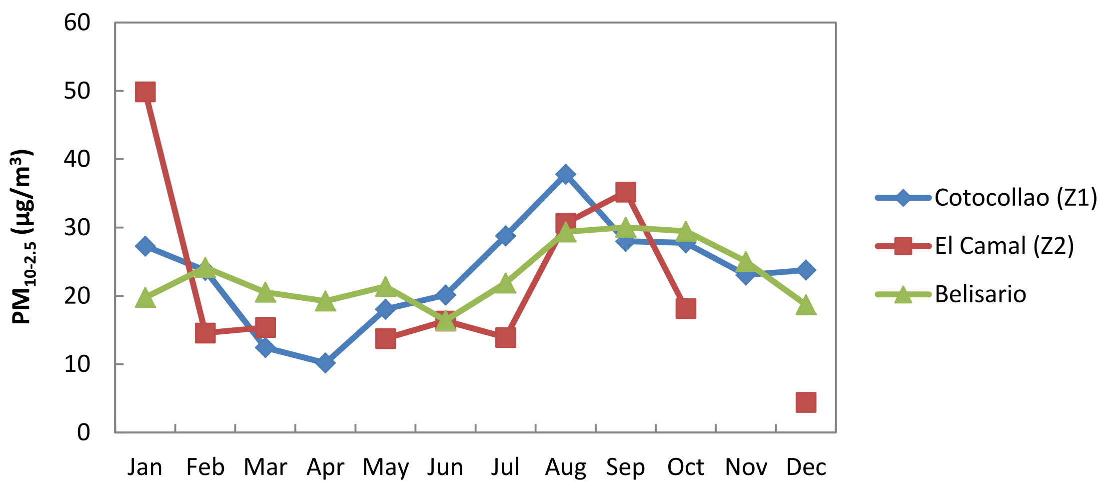


Figure 4.38: $PM_{10-2.5}$ monthly averages from central monitors for 2005-2010

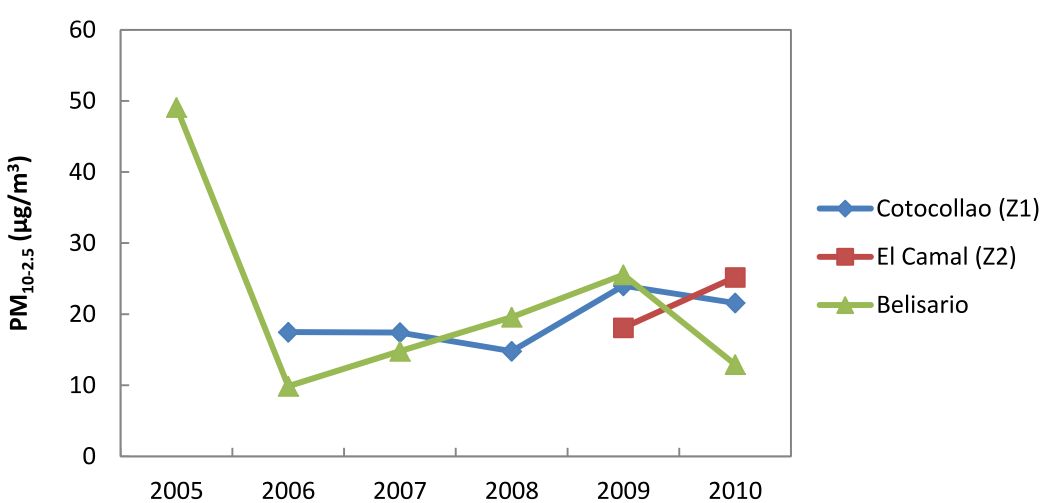


Figure 4.39: $PM_{10-2.5}$ yearly averages from central monitors for 2005-2010

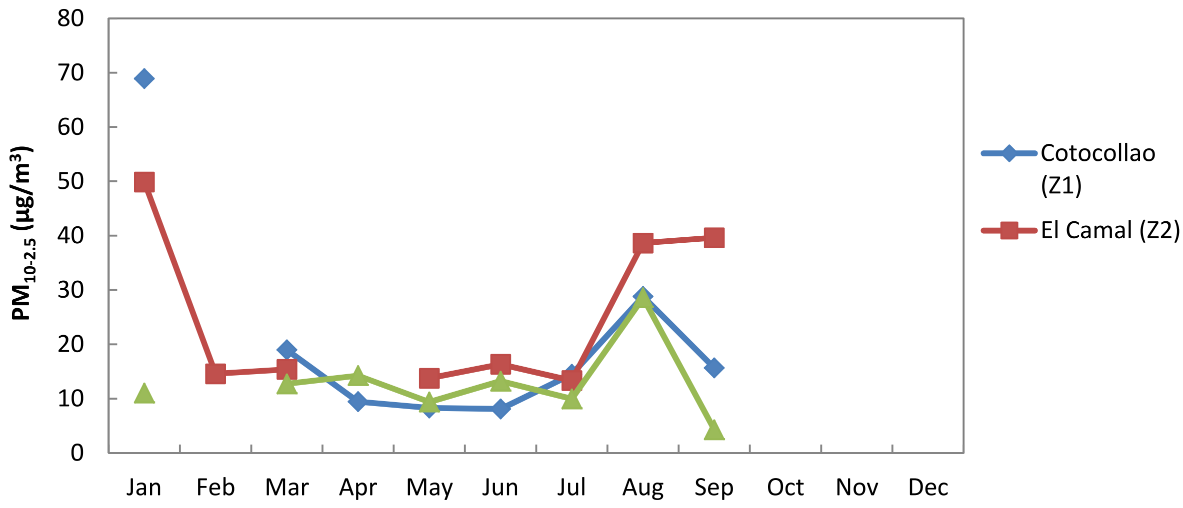


Figure 4.40: $PM_{10\text{-}2.5}$ monthly averages from central monitors for 2010

4.4.2 PM Exceedances

$PM_{2.5}$

Figures 4.41 and 4.42 show the $PM_{2.5}$ annual averages and 98th percentile 24-hr averages at all the stations from 2005-2010 along with the $PM_{2.5}$ Quito standards (NCAA) represented by a black line. All stations were above the annual standard of 15 µg/m^3 for all years, except Cotocollao (Zone 1) and Carapungo in 2008 when they were just below the standard (Figure 4.41). For the 24-hr standard (50 µg/m^3), most stations were below the standard except El Camal (Zone 2) in 2005. We can see that the $PM_{2.5}$ problem in the city of Quito is of special concern, especially when it cannot meet its annual standard.

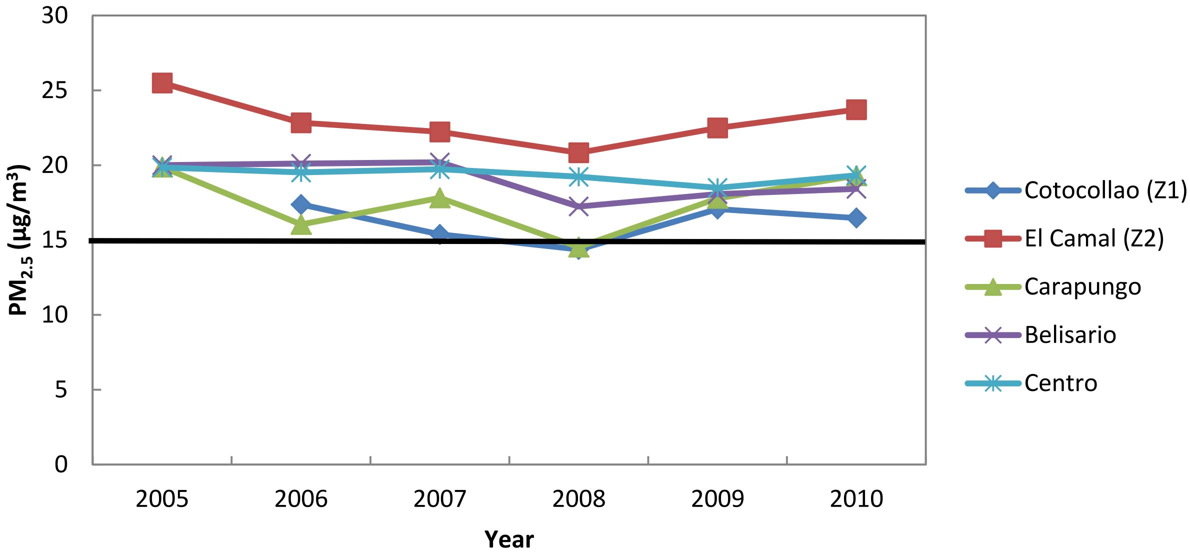


Figure 4.41: $PM_{2.5}$ exceedances to annual averages (2005-2010)

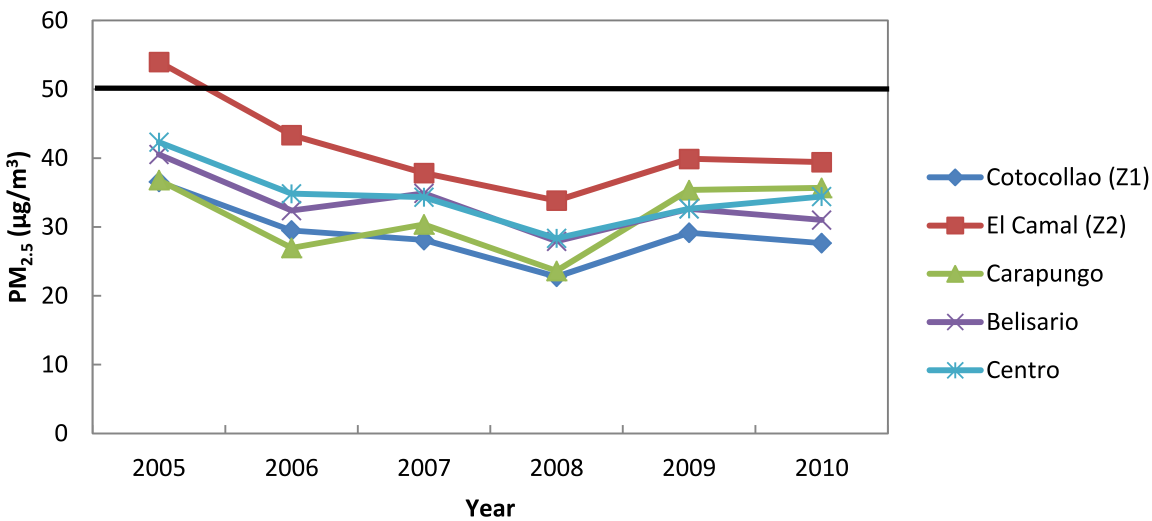


Figure 4.42: 98^{th} percentile of 24-hr averages for $PM_{2.5}$ (2005-2010)

PM_{10}

Figures 4.43 and 4.44 show annual average and the 98^{th} percentile 24-hr averages for PM_{10} at all stations from 2005-2010. Three out of the five stations were above the annual standard (50 µg/m^3) in

2005 (Figure 4.43). The rest of the years (2006-2010) the annual average at every station were below the standard, although in 2010 the average at El Camal came close to the standard at 47 μg/m^3. Overall, there was a marked decrease in the annual averages from 2005 to 2006 that, as mentioned before, corresponds to an increase in annual precipitation. The 24-hour average standard (100 μg/m^3) was exceeded in 2005 by the stations at Guamani, Cotocollao (Zone 1), Jipijapa, and Belisario and in 2010 by Cotocollao (Zone 1) and El Camal (Zone 2). The problem with PM_{10} in Quito seems to be not as pronounced as the $PM_{2.5}$ problem, however, it is still of concern because it is at the borderline of meeting the 24-hour standard, and some stations, such as El Camal surpass it. However, if efforts are made to reduce $PM_{2.5}$ emissions, they would too have an impact on reducing PM_{10} levels, since $PM_{2.5}$ is included in PM_{10}.

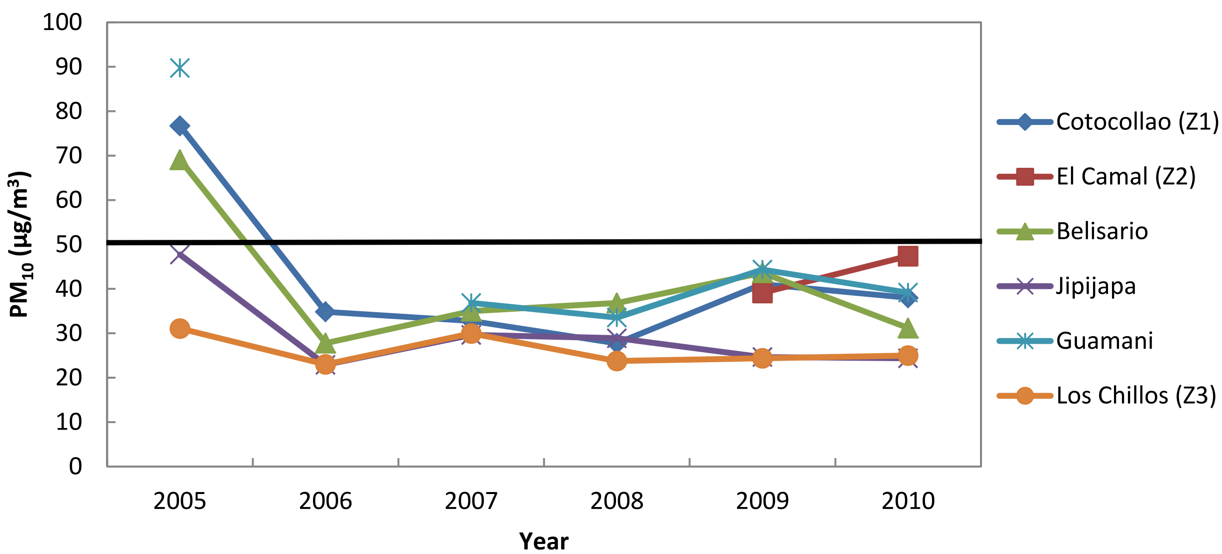


Figure 4.43: PM_{10} exceedances to annual averages (2005-2010)

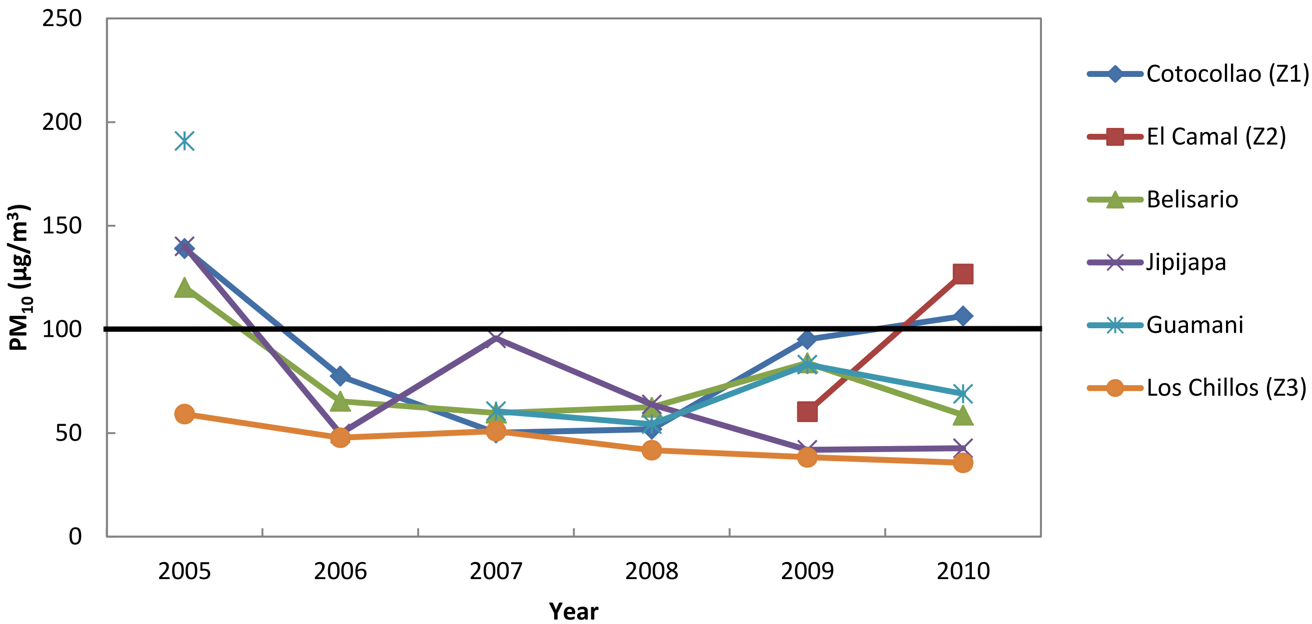


Figure 4.44: 98th percentile of 24-hr averages for PM_{10} (2005-2010)

4.4.3 $PM_{2.5}/PM_{10}$

For the ambient stations with data available for both $PM_{2.5}$ and PM_{10}, ratios were computed to verify the dominant size fraction for particulate matter in Quito. Ratios were estimated utilizing monthly averages because data for $PM_{2.5}$ was taken on an hourly basis, while data for PM_{10} was taken as 24-hr averages every six days. Figures 4.45 and 4.46 show annual and monthly $PM_{2.5}/PM_{10}$ ratios. In 2005 (Figure 4.45) the dominant fraction at the Belisario station was PM_{10} (due to the lack of precipitation) and in 2006, the dominant fraction was $PM_{2.5}$. The following years $PM_{2.5}/PM_{10}$ ratios stay slightly above 0.5 indicating higher concentrations of the fine particulate matter fraction ($PM_{2.5}$). Figure 4.46 shows ratios below 0.5 from July through September, coinciding with the dry period of the year and higher concentrations of PM_{10}. The rest of the year, concentrations stay around 0.5 and 0.6, again indicating higher dominance from the $PM_{2.5}$ size fraction. Figure 4.47 shows the $PM_{2.5}/PM_{10}$ monthly ratios for 2010. Overall, fine PM ($PM_{2.5}$) composition dominates most of the year, except for the dry period (June-September), when PM_{10} levels dominate particulate matter composition.

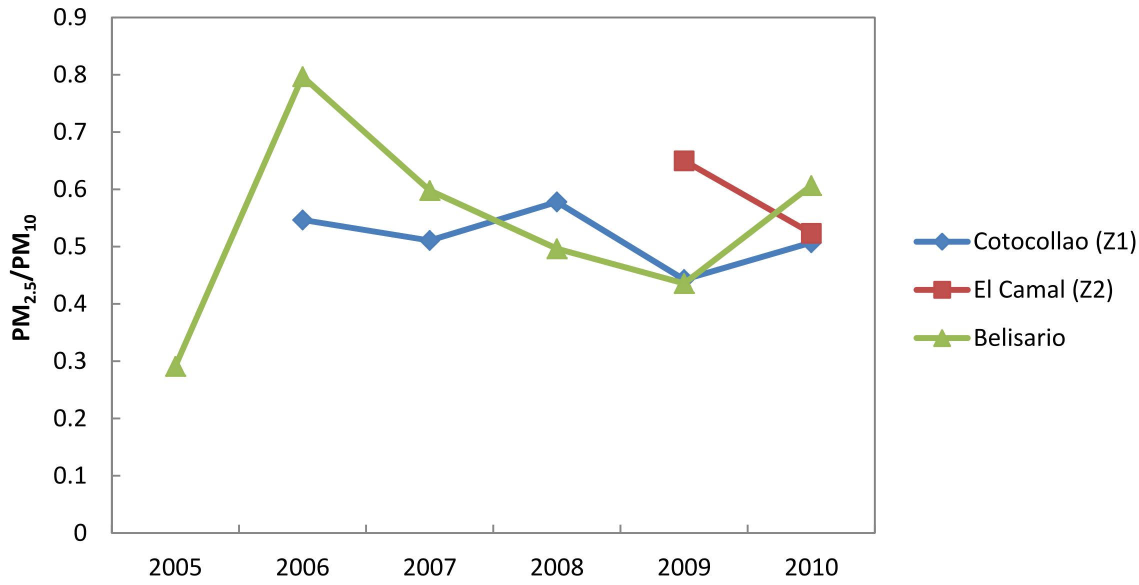


Figure 4.45: $PM_{2.5}/PM_{10}$ annual ratios (2005-2010)

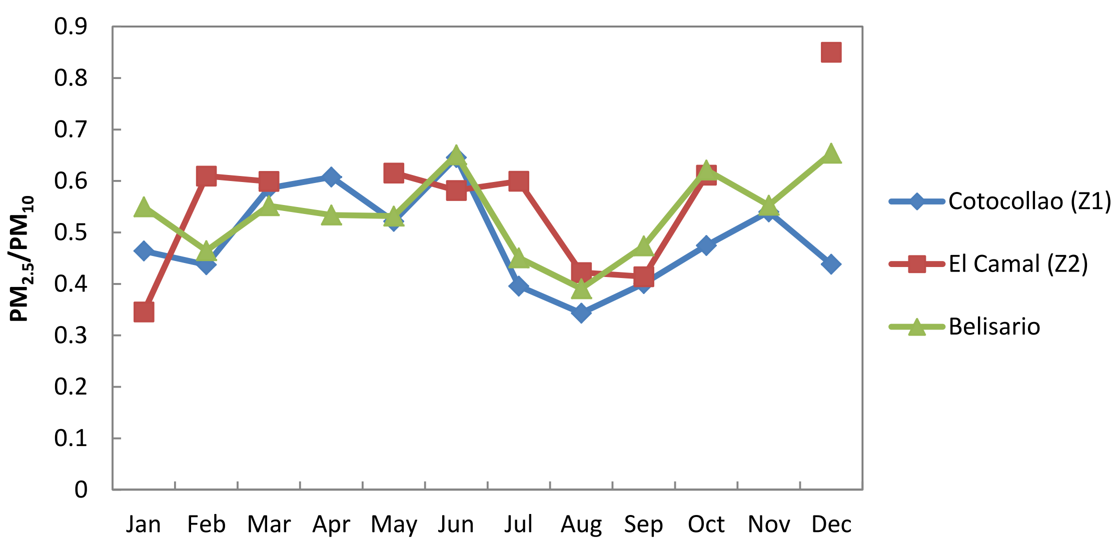


Figure 4.46: $PM_{2.5}/PM_{10}$ monthly ratios (2005-2010)

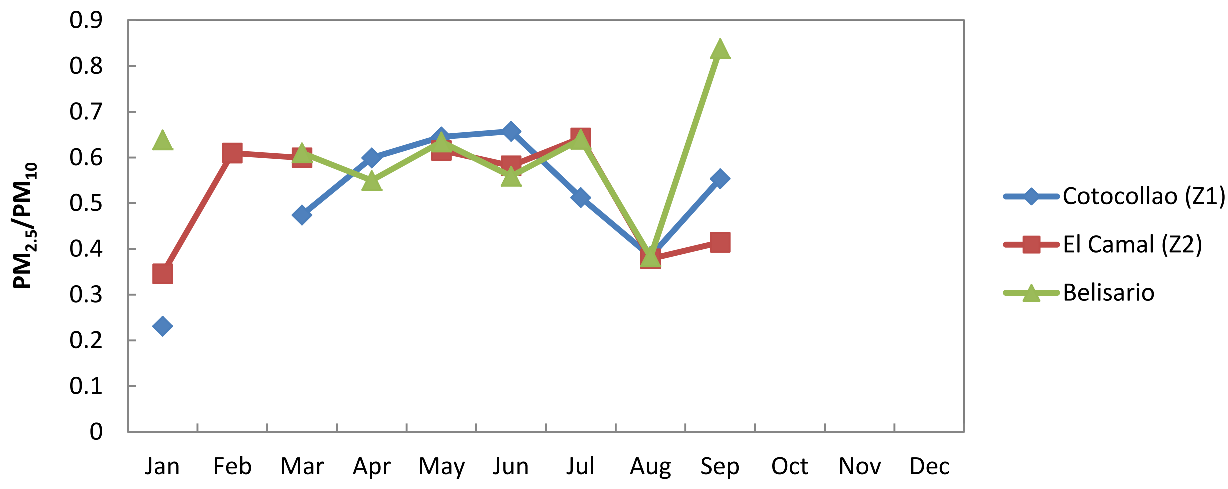


Figure 4.47: $PM_{2.5}/PM_{10}$ monthly ratios (2010)

4.4.4 PM and Meteorology

$PM_{2.5}$

Scatter plots were used to analyze correlations between $PM_{2.5}$ concentrations and meteorological data from ambient monitors. Hourly data was analyzed for 2010 and results are shown in Figures 4.48-4.52. Most of the correlations found between $PM_{2.5}$ and meteorology were weak and significant ($p < 0.01$), with the exception of the correlation between $PM_{2.5}$ and solar radiation at the Cotocollao station that was not significant ($p > 0.05$). However, some patterns can be observed between meteorological data and $PM_{2.5}$. Slightly higher correlations (R^2=0.04 and 0.09) in Figure 4.48 were seen between wind speed and $PM_{2.5}$ levels, showing that lower wind speeds tended to see increase levels of $PM_{2.5}$ due to lack of mixing and stagnation. Changes in temperature did not seem to affect $PM_{2.5}$ concentration levels (Figure 4.49), while an increase in relative humidity showed a tendency to increased $PM_{2.5}$ concentrations at both stations (Figure 4.50). Some particles have affinity to moisture and levels can be overestimated in the presence of high humidity. Low precipitation levels (Figure 4.51) show higher $PM_{2.5}$ concentrations, while higher precipitation levels would "wash-out" $PM_{2.5}$ and decrease concentration levels. Finally, solar radiation levels (Figure 4.52) did not seem to affect in any way $PM_{2.5}$ concentration levels, unlike O_3 levels that depend on sunlight for their formation.

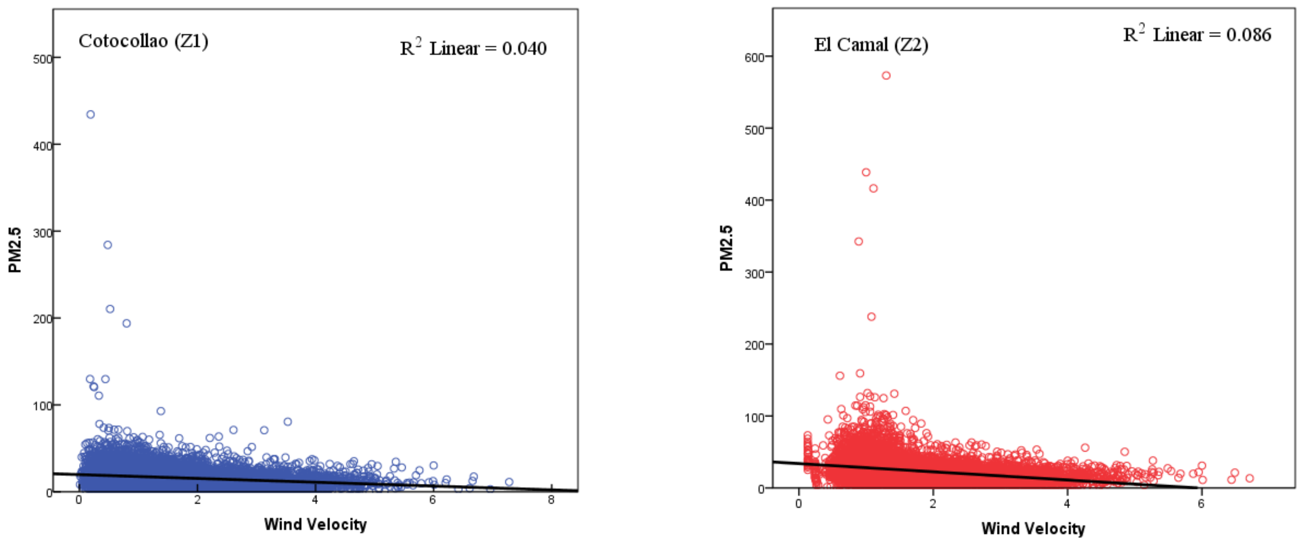


Figure 4.48: Hourly $PM_{2.5}$ and wind velocity correlations (2010)

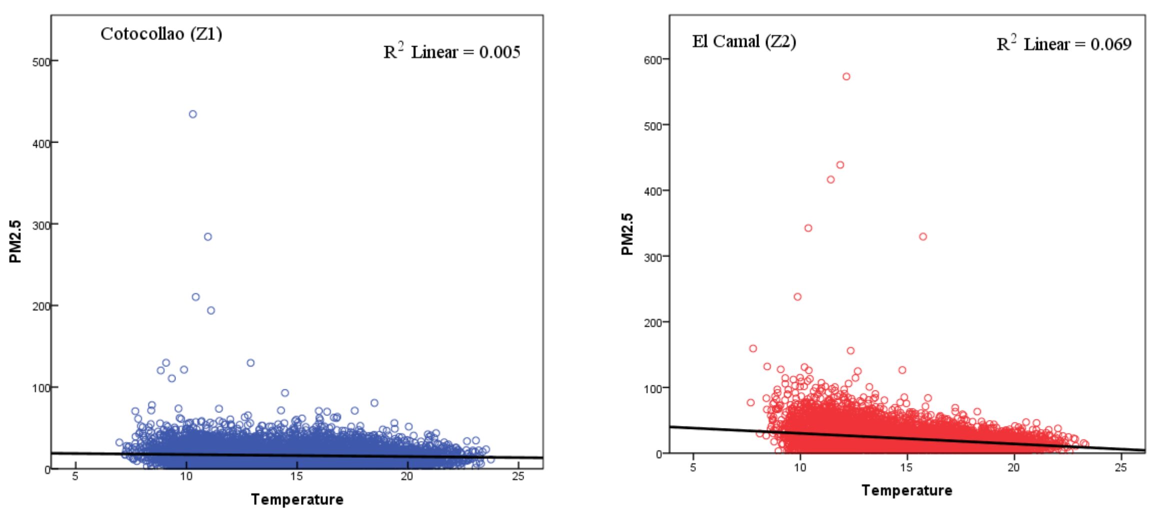


Figure 4.49: Hourly $PM_{2.5}$ and temperature correlations (2010)

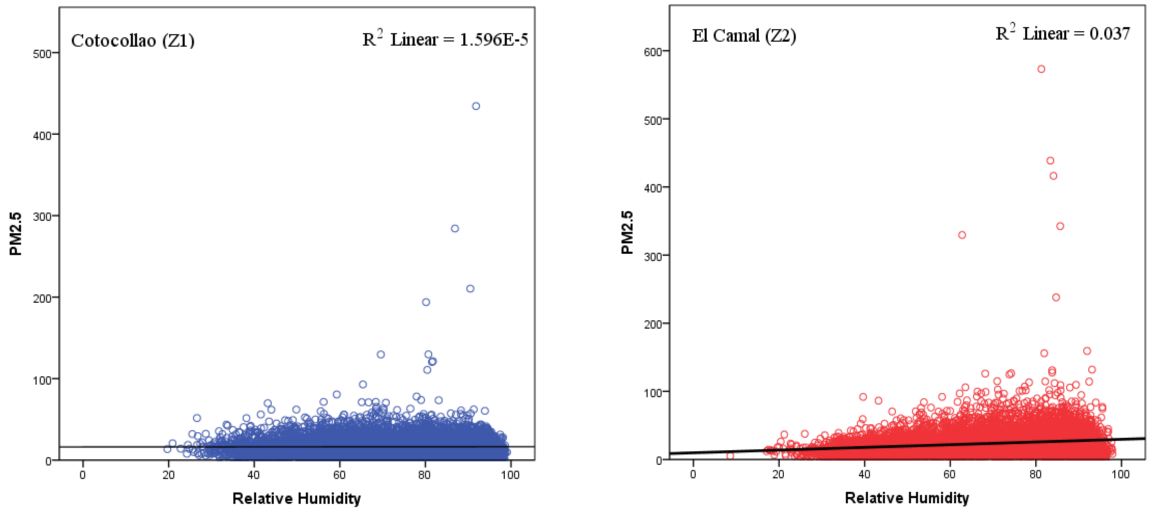


Figure 4.50: Hourly $PM_{2.5}$ and relative humidity correlations (2010)

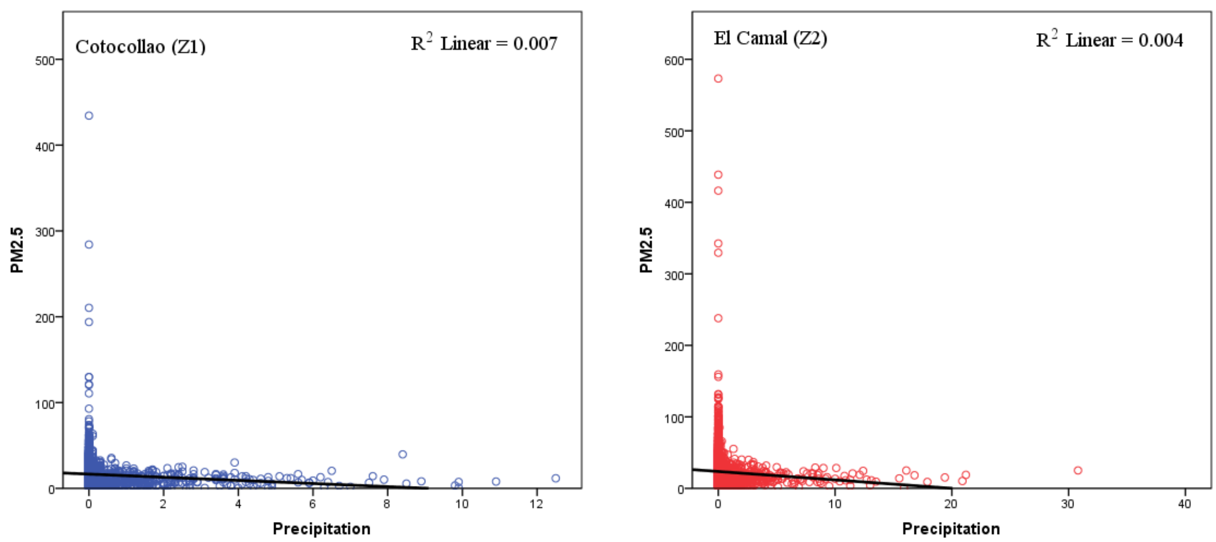


Figure 4.51: Hourly $PM_{2.5}$ and precipitation correlations (2010)

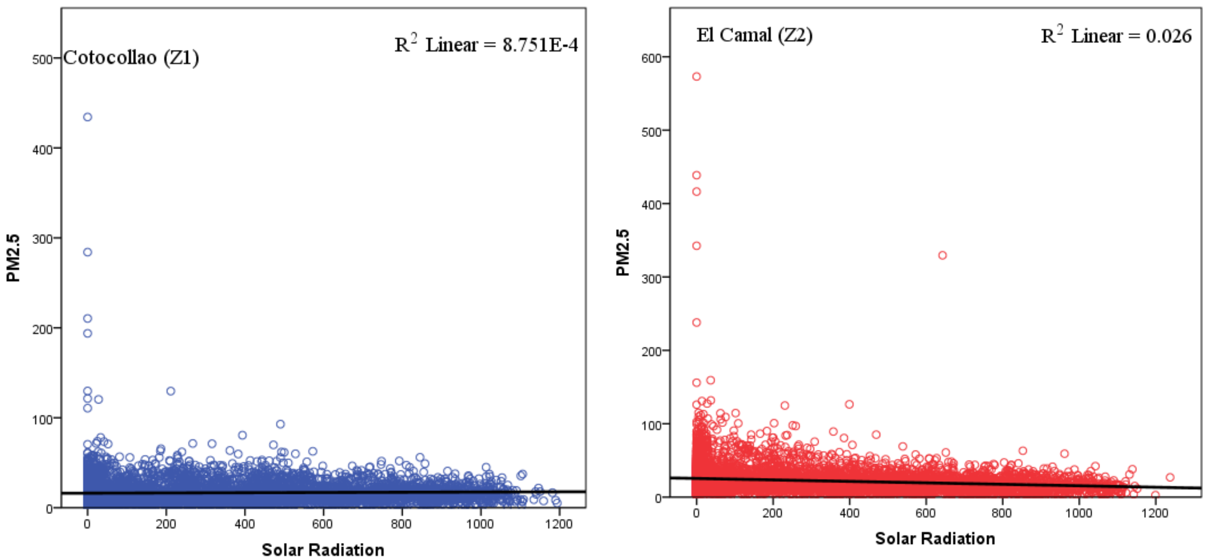


Figure 4.52: Hourly $PM_{2.5}$ and solar radiation correlations (2010)

PM_{10}

Scatter plots were also used to analyze correlations between PM_{10} and meteorological factors. Data for PM_{10} was collected as 24-hour averages every 6-days, so monthly averages were computed to compare them with monthly meteorological values. In order to have more points, monthly averages were estimated from 2005-2010 for the stations at Cotocollao (Zone 1) and Los Chillos (Zone 3). El Camal (Zone 2) station only had PM_{10} data for 2010 and it was not included in this part of the analysis. Robust positive correlations were found between PM_{10} and wind velocity (R^2=0.190, $p < 0.01$ and 0.073, $p < 0.05$) with higher wind speeds promoting resuspension and the collision of smaller particles into larger ones, yielding higher PM_{10} concentrations (Figure 4.53). No distinct pattern was observed between PM_{10} and temperature (Figure 4.54, $p < 0.05$ at Cotocollao and $p > 0.05$ at Los Chillos) or relative humidity (Figures 4.55, $p > 0.05$ at Cotocollao and $p < 0.01$ at Los Chillos). Robust negative correlations (Figure 4.56) were found between PM_{10} and precipitation (R^2=0.179, $p < 0.01$ and 0.219, $p < 0.01$) at Cotocollao and Los Chillos respectively, with low precipitation levels coinciding with higher PM_{10} concentrations. High precipitation levels will settle larger particles. The effect of precipitation was also observed on

PM_{10} monthly and annual averages (Figures 4.34 and 4.35). Finally solar radiation (Figure 4.57) did not have an effect on PM_{10} levels ($p < 0.05$ at Cotocollao and $p > 0.05$ at Los Chillos).

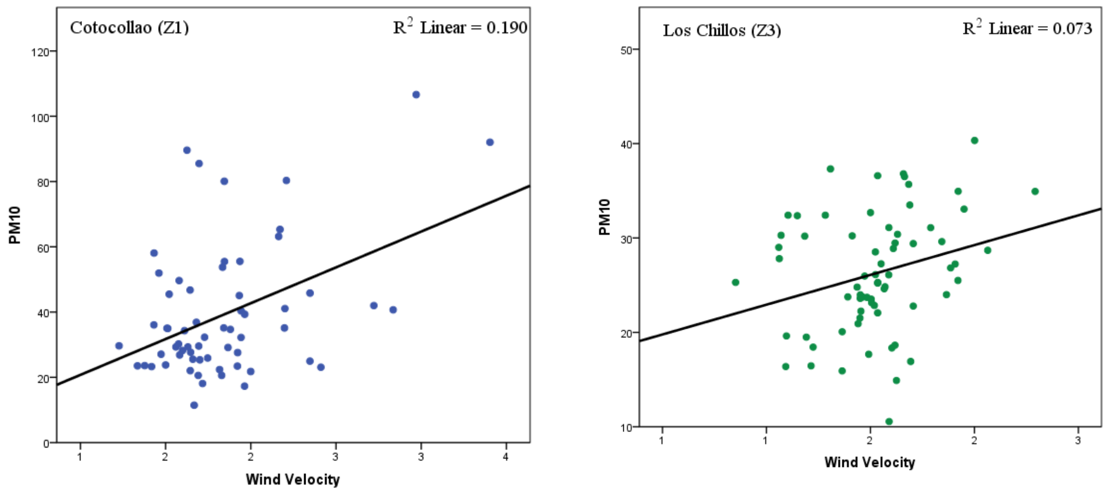


Figure 4.53: Monthly PM_{10} and wind velocity correlations (2005-2010)

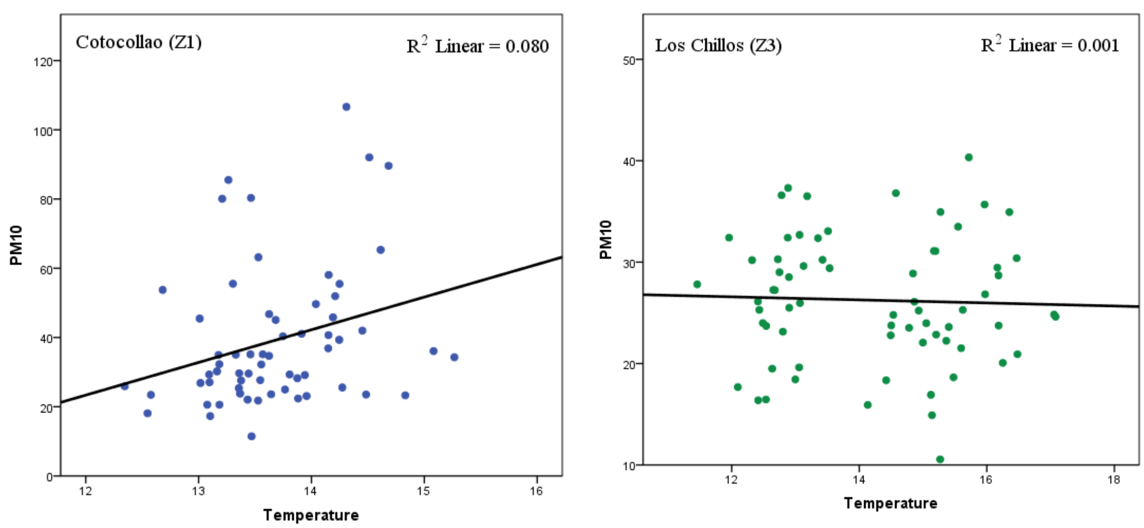


Figure 4.54: Monthly PM_{10} and temperature correlations (2005-2010)

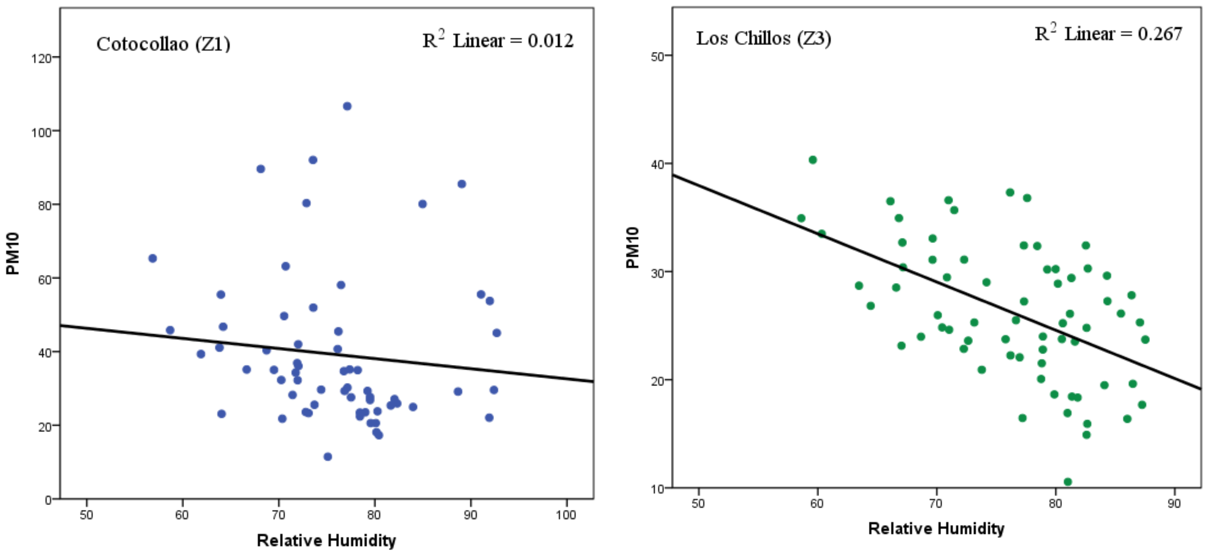


Figure 4.55: Monthly PM_{10} and relative humidity correlations (2005-2010)

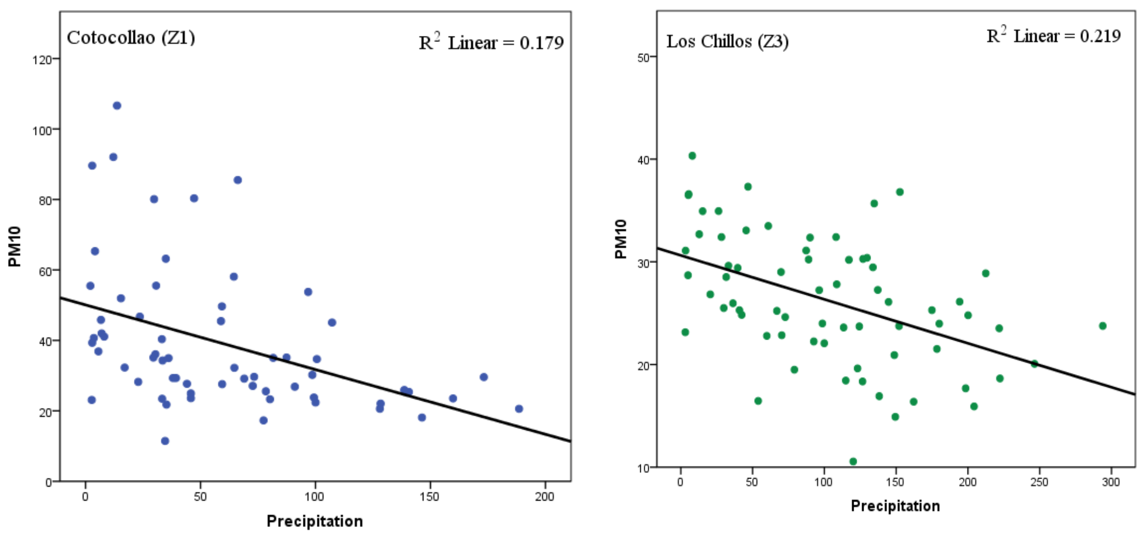


Figure 4.56: Monthly PM_{10} and precipitation correlations (2005-2010)

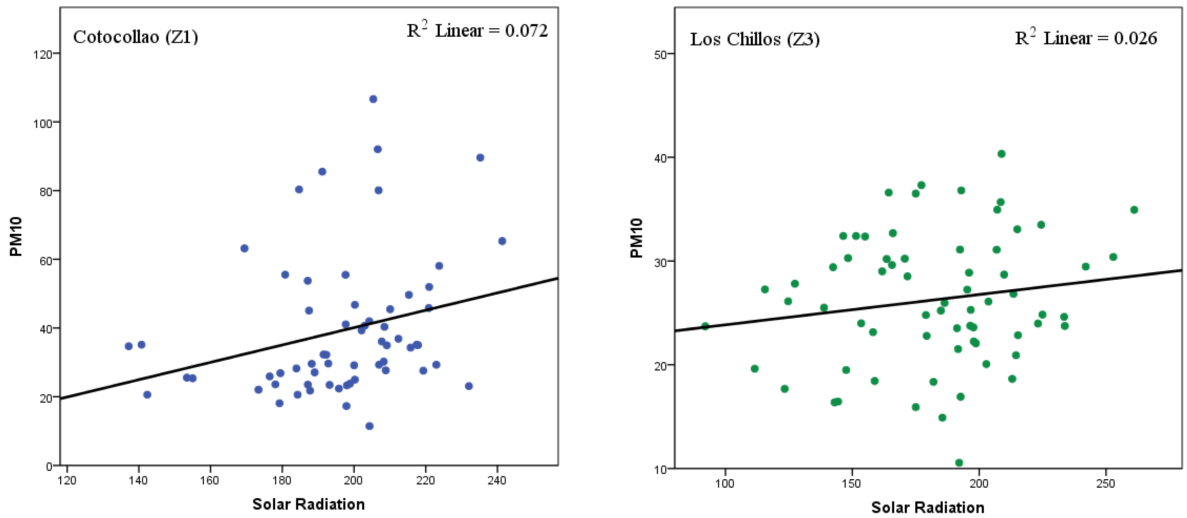


Figure 4.57: Monthly PM_{10} and solar radiation correlations (2005-2010)

4.4.5 PM and Co-pollutants

$PM_{2.5}$

Scatter plots (Figure 4.58-4.61) were used to investigate the correlations between $PM_{2.5}$ levels collected at ambient monitors and several co-pollutants (CO, NO_2, SO_2, and O_3). Positive robust correlations were observed between $PM_{2.5}$ and CO (R^2=0.215 and 0.352), $PM_{2.5}$ and NO_2 (R^2=0.206 and 0.259), and $PM_{2.5}$ and SO_2 (R^2=0.258 and 0.194) at Cotocollao and El Camal respectively indicating the commonality of sources between both sets of contaminants, such as vehicle emissions and combustion processes from industrial sources, such as the thermoelectric plants. On the other hand, weak correlations or trends were observed between $PM_{2.5}$ levels and O_3. All correlations had a $p < 0.01$.

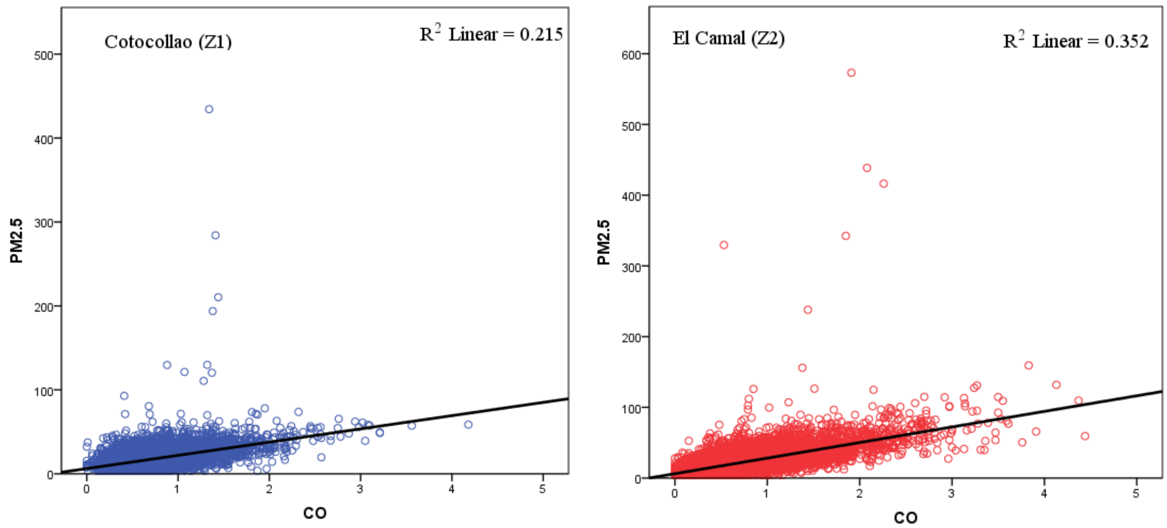


Figure 4.58: Hourly $PM_{2.5}$ and CO correlations (2010)

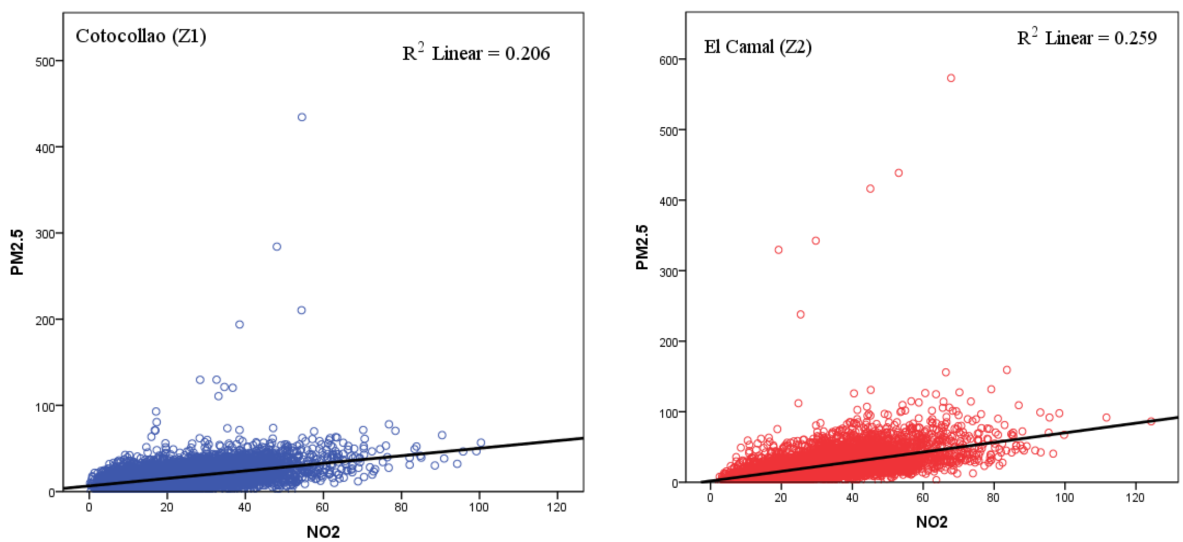


Figure 4.59: Hourly $PM_{2.5}$ and NO_2 correlations (2010)

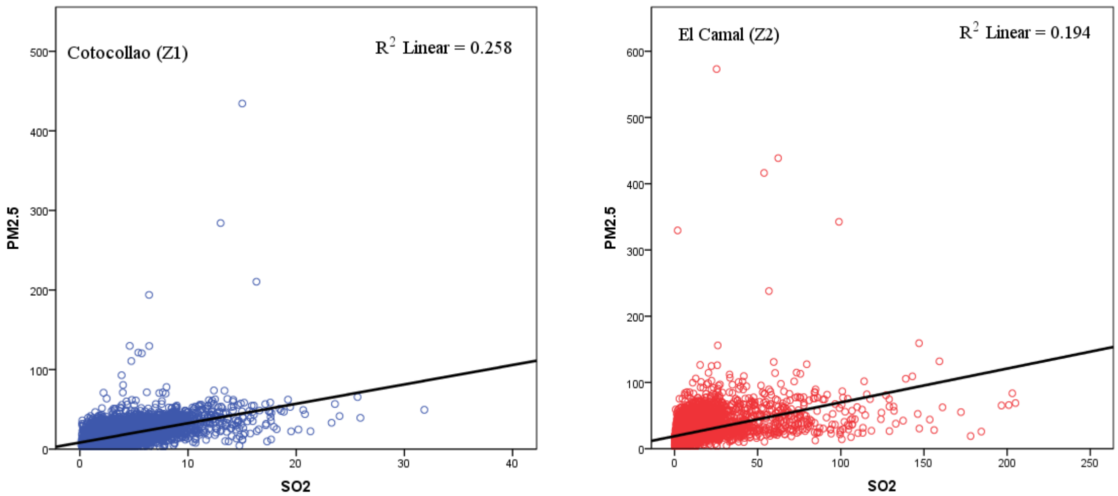


Figure 4.60: Hourly $PM_{2.5}$ and SO_2 correlations (2010)

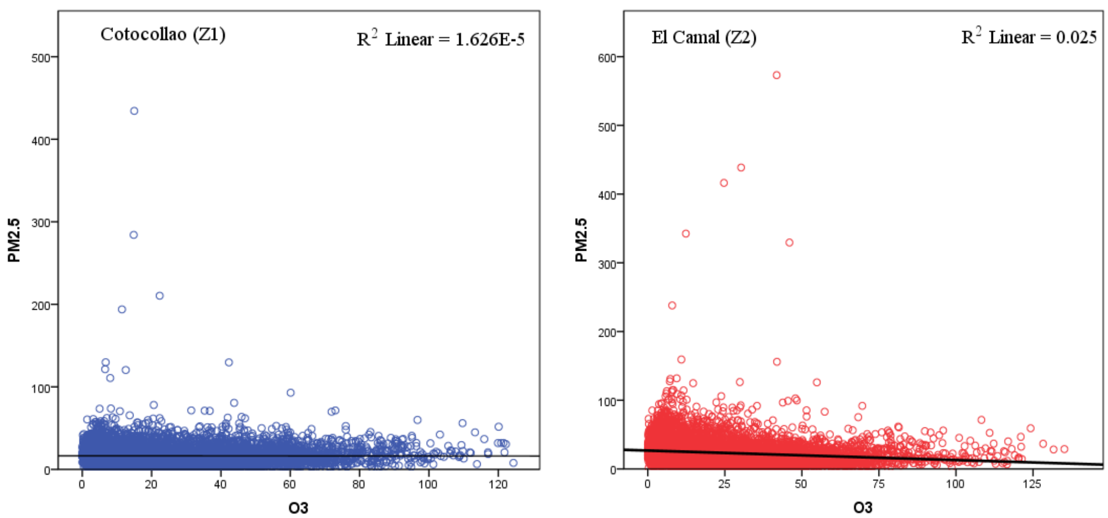


Figure 4.61: Hourly $PM_{2.5}$ and O_3 correlations (2010)

PM_{10}

Scatter plots between PM_{10} levels and other co-pollutants are shown in Figures 4.62 to 4.65. Cotocollao (Zone 1) was the only station with enough data (PM_{10} and co-pollutants) to estimate monthly averages from 2005-2010. The station at Los Chillos (Zone 3) only had data for O_3, and it was included as part of Figure 4.65. Weaker correlations were observed between PM_{10} and most co-pollutants as compared to $PM_{2.5}$ because the larger size fraction of particulate matter can be attributed more directly

to resuspension and erosion as opposed to combustion processes. Negative correlation was observed between CO levels and PM_{10}, while positive correlations were observed between PM_{10} and NO_2, PM_{10} and SO_2. Correlations were not significant between PM_{10} and CO, PM_{10} and NO_2 ($p > 0.05$), while correlations were significant between PM_{10} and SO_2, and PM_{10} and O_3 ($p < 0.01$).

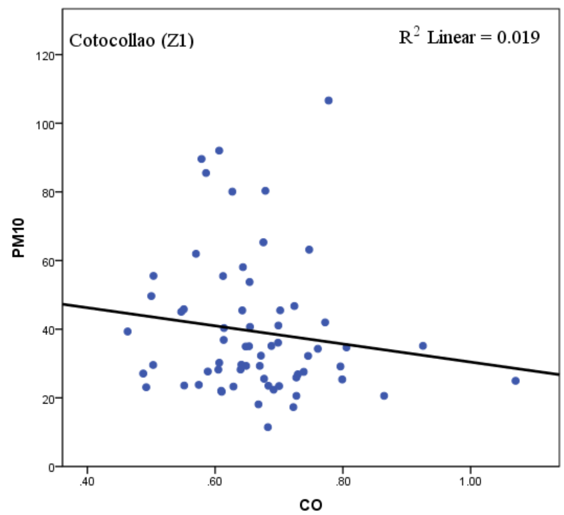


Figure 4.62: Monthly PM_{10} and CO correlations (2005-2010)

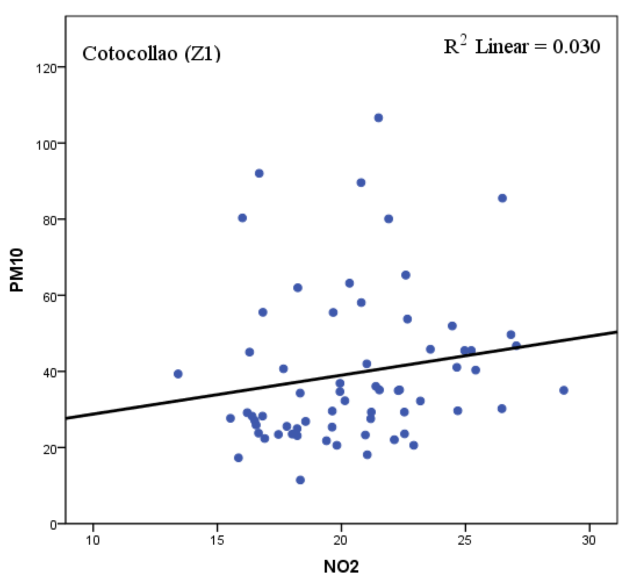


Figure 4.63: Monthly PM_{10} and NO_2 correlations (2005-2010)

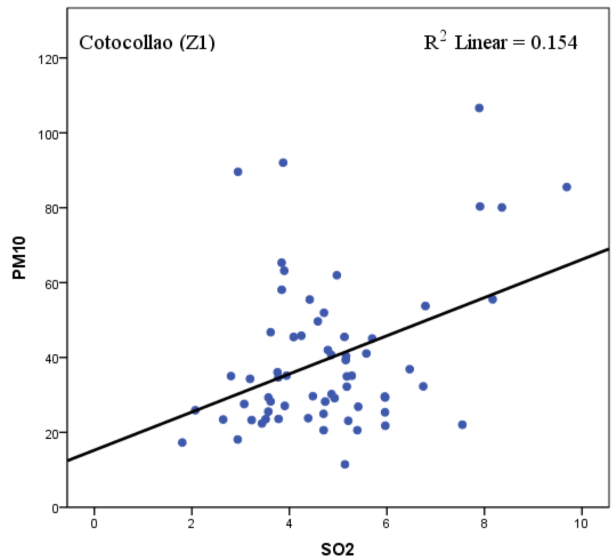


Figure 4.64: Monthly PM_{10} and SO_2 correlations (2005-2010)

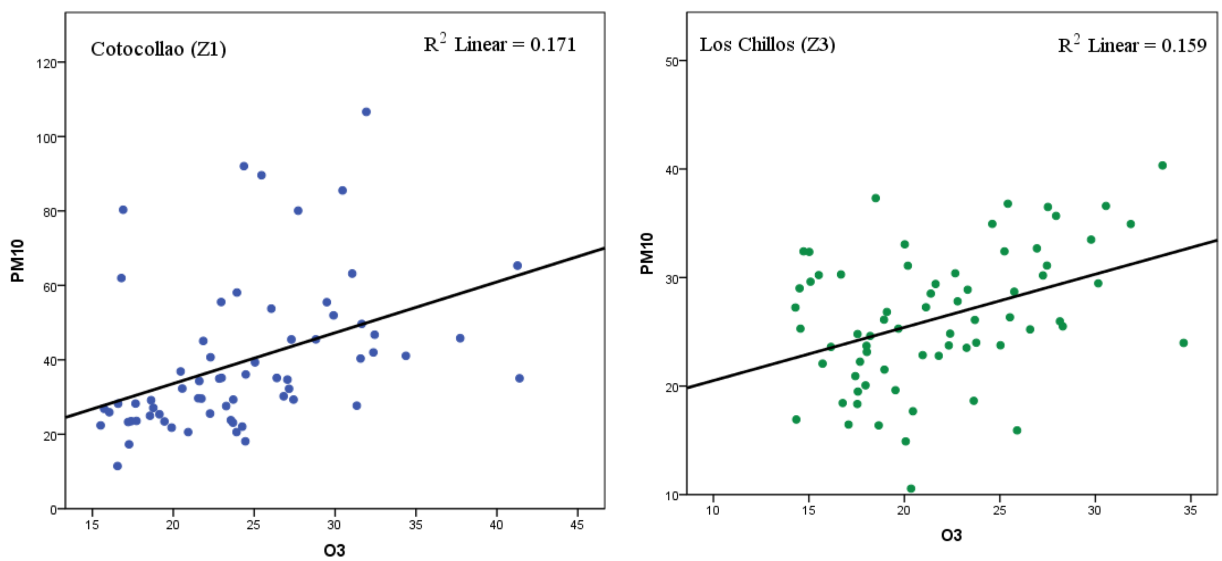


Figure 4.65: Monthly PM_{10} and O_3 correlations (2005-2010)

4.5 Conclusion

Results from the analysis presented in this chapter fulfills research task No. 1 of performing a conceptual model to understand the PM trends in Quito, Ecuador. The most important points are as follows,

- In terms of meteorological factors, Quito can be described as a cool, spring-like region with low variation in temperatures all year long, low wind velocities that can affect stagnation of air pollutants, and high levels of humidity. Rain patterns allow for the designation of summer during the dry season (June-September) and winter during the wet season (October-May). Because of its unique topography, Quito's atmospheric pressure can vary greatly from zone to zone.
- The trend of most gaseous air pollutants in Quito has been to decline since 2005 (CO and SO_2) or to remain stable (O_3 and NO_2). The decline in pollutant levels can be attributed to the implementation of programs such as *Revisión Técnica Vehicular, Pico y Placa,* and the lowering of sulfur levels in gasoline. Central monitoring stations located right in the center of Quito and subjected to higher traffic levels, such as El Camal, Belisario, and Centro were also subjected to higher concentrations of CO, NO_2, and SO_2, while stations further north (Cotocollao and Carapungo) or further south (Guamani) showed lower levels. Ozone levels were closer together amongst the different stations. Pollutant data for 2010 also has El Camal as the station with higher concentrations for most pollutants CO, NO_2, and SO_2, while lower concentrations were observed at Cotocollao.
- The trends for particulate matter are slightly different. In the case of $PM_{2.5}$, similar trends as with the gaseous pollutants were observed with higher traffic zones having higher $PM_{2.5}$ levels (e.g. El Camal, Belisario, and Centro), while lower traffic zones to the north (Cotocollao and Carapungo) showed lower $PM_{2.5}$ levels. Hourly variations coincide also with rush hour traffic. In terms of annual variations, levels have remained virtually unchanged, for the most part and at most stations. However, in the case of PM_{10}, levels significantly dropped since 2005, attributing this drop to higher precipitation levels. In subsequent years, it went up and down attributed to resuspension of dust from quarries and unpaved roads, soil erosion, and aggravated by lack of precipitation in some years. Although the high traffic zones (El Camal, Belisario, and Jipijapa) still collect higher levels of PM_{10} than the low traffic zones (Guamaní, Los Chillos, and Cotocollao), the differences between the levels is almost negligible. $PM_{10-2.5}$ data was also plotted and the differences between the stations was almost negligible, more so than with PM_{10}.

- Exceedances are especially a concern for annual $PM_{2.5}$ levels. For PM_{10}, less exceedances were registered between 2005-2010, but still levels are at the borderline. It is important for Quito to keep making efforts into reducing both $PM_{2.5}$ and PM_{10} concentrations.
- Fine particulate matter ($PM_{2.5}$) seems to dominate PM concentration levels (according to the $PM_{2.5}/PM_{10}$) data, especially during the months of the rainy season, while the months of the dry season, $PM_{2.5}/PM_{10}$ ratios were mostly below 0.5, showing the dominance of PM_{10} concentrations.
- As far as meteorological factors and co-pollutant data are concerned, their effects on PM levels varied depending on the PM size fraction. For fine particulate matter ($PM_{2.5}$) lower wind speeds and lower precipitation levels will result in higher concentrations. On the other hand, for PM_{10}, lower wind speeds resulted in lower concentrations because there is no resuspension and the larger particles have settled, while higher precipitation totals resulted in lower PM_{10} concentrations. Pollutant correlations were relatively strong and positive between $PM_{2.5}$ and CO, NO_2, and SO_2 pointing to common sources for that group of pollutants, mainly traffic emissions. On the other hand, co-pollutant correlations with PM_{10} did not have any significance pointing to the fact that slightly larger particles have different sources from gaseous particles, mainly consisting of resuspension of soil from unprotected surfaces, such as quarries, unpaved roads, among others.

Chapter 5: Field Sampling Results

Chapter 5 describes the analysis of the field samples and discusses the results. Section 5.1 covers the QA/QC analysis of the study. Section 5.2 presents the overall analysis of the samples collected at the schools and at the residences including basic descriptive statistics and exploratory data analysis, spatial analysis, indoor-outdoor concentration analysis, and correlations. Section 5.3 summarizes the main findings of the chapter.

5.1 Quality Assurance/Quality Control

Standard quality assurance/quality control procedures in the field and laboratory were followed for this study (U.S. EPA, 2001). Duplicate samples were collocated indoor and outdoor at the schools every monitoring period at every zone. Field blanks were transported with the school samples and briefly exposed to the environment before being re-sealed. Sealed field blanks were then placed in proximity with the rest of the samples at the schools for the entire sampling period. A field blank at each school was used per sampling period, per zone. The following subsections describe statistical analysis and the results that evaluate the quality of the collected data.

5.1.1 Field Blanks

Field blank analysis helps in identifying contamination resulting from field sampling and transportation (Raysoni, 2011). One field blank was used for $PM_{2.5}$ and another one for $PM_{10-2.5}$ every month per school, per zone. A total of 36 field blanks for $PM_{2.5}$ and 36 for $PM_{10-2.5}$ were collected, but because of problems during field sampling, some blanks were invalidated reducing the total number to 31 for $PM_{2.5}$ and 35 for $PM_{10-2.5}$. For the $PM_{2.5}$ samples, several field blanks were eliminated because of equipment malfunction (to measure flow rate) or because of the filters getting wet due to strong rain and hail during that particular sampling week. One field blank was eliminated from the $PM_{10-2.5}$ samples because in the month of February, for Zone 3, the equipment to measure flow rate did not work and the samples for that month were eliminated including the field blank.

Field blank means, standard deviation, and limit of detection (LOD) are shown in Table 5.1 with outliers and without outliers. The limit of detection (LOD) is defined as the lowest concentration level that can be determined to be statistically different from a blank. In this case, the LOD is estimated as three times the standard deviation of the field blanks. Several outliers were excluded, these outliers were collected during weeks of extreme rain or rain with hail and there is a strong probability that the filters might have been tampered during the weather events, thus showing high masses. As can be seen from the value of the means, some field blanks resulted in negative values because the post-weight was greater than the pre-weight. Factors that can influence filter weighing in such a way as to make the pre-weight greater than the post-weight include electric charge, air buoyancy, conditions affecting balance stability, and water content due to relative humidity (Jantunen et al, 2002).

Table 5.1: Field blank analysis

Pollutant	Outliers					No Outliers				
	N	Mean (µg)	SD[a] (µg)	LOD[b] (µg)	LOD[b] ($\mu g/m^3$)	N	Mean (µg)	SD[a] (µg)	LOD[b] (µg)	LOD[b] ($\mu g/m^3$)
$PM_{2.5}$	31	-78.1	410.4	1231.1	24.4	27	-55.0	88.0	264.0	5.2
$PM_{10-2.5}$	35	8.9	114.9	344.6	6.8	33	-7.5	31.7	95.2	1.9

[a]Standard Deviation
[b]Limit of Detection obtained by using a flow rate of 5 LPM and 7 day period.

Field blank analysis from Table 5.1 did not suggest the need for adjustment due to filter contamination.

5.1.2 Samples and Data Precision

Duplicate samples of $PM_{2.5}$ and $PM_{10-2.5}$ were collected during each sampling round. Duplicate air monitors were deployed at schools only, one duplicate in each microenvironment, per zone, per month, for a total of 6 paired duplicates per month. The expected number of paired duplicates for the total study period was 72. However, because of rain (wet filters), prolonged blackouts, and school personnel interrupting the measurement procedure, four sets of paired duplicates were removed from the

$PM_{2.5}$ samples and three sets from the $PM_{10\text{-}2.5}$ samples. Paired duplicates were examined utilizing precision analysis, scatter plots, descriptive statistics, and t-tests.

Precision is defined as the ability of repeated measurements, under unchanged conditions to show the same results. Precision was assessed by utilizing collocated samples (duplicates). For a given pollutant, absolute precision was estimated as the root mean squared difference between the sample and the duplicate divided by the square root of two.

$$s = \sqrt{\frac{(\sum_{i=1}^{n} \Delta i^2)}{2n}} \quad \text{(Equation 5.1)}$$

Where Δi is the difference in concentrations between the collocated samples and n is the sample number. Relative precision is defined as the percentage of mean observations as indicated in equation (5.2):

$$p = \frac{s}{(\sum_{i=1}^{n} \frac{C_i}{n})} x100\% \quad \text{(Equation 5.2)}$$

Where C_i is the sample or duplicate's concentration value. Relative precision should be around a value of ±10% (Li et al, 2011; Raysoni et al, 2011; Raysoni et al, 2013). Extreme outliers among the pollutants were identified by plotting the differences between the sample and the duplicate in a box plot utilizing SPSS (Tabachnick and Fidell, 2007). One outlier was detected in the $PM_{2.5}$ data and six outliers in the $PM_{10\text{-}2.5.}$ Table 5.2 shows the results of the precision analysis with and without outliers.

Relative precision, excluding outliers, was above the target goal for both $PM_{2.5}$ (22.3%) and $PM_{10\text{-}2.5}$ (16.7%). Table 5.3 revisits $PM_{2.5}$ paired duplicates and excludes those that are below the limit of detection (< 5.2 μg/m^3), leaving a total of 55 paired duplicates with a relative precision of 15.1%.

Table 5.2: Paired duplicate precision statistics

Pollutant	With Outliers				Without Outliers			
	N	RMSD	Absolute Precision (µg/m^3)	Relative Precision (%)	N	RMSD	Absolute Precision (µg/m^3)	Relative Precision (%)
$PM_{2.5}$	68	11.6	8.2	70.5	67	3.3	2.4	22.3
$PM_{10-2.5}$	69	4.8	3.4	37.1	63	2.0	1.4	16.7

Table 5.3: Paired duplicate precision statistics excluding samples below $PM_{2.5}$ LOD (5.2 µg/m^3)

Pollutant	Above LOD (< 5.24 µg/m^3)			
	N	RMSD	Absolute Precision (µg/m^3)	Relative Precision (%)
$PM_{2.5}$	55	2.5	1.8	15.1

Figures 5.1, 5.2, and 5.3 show the scatter plots of the paired duplicates for the $PM_{2.5}$ and the $PM_{10-2.5}$ pollutants. The scatter plot for $PM_{2.5}$ (Figure 5.1) shows an R^2 = 0.50 and a slope of 0.70. Another scatter plot was generated (Figure 5.2) eliminating the paired duplicates below the LOD, improving the R^2 = 0.62 and the slope to 0.78. The scatter plot for $PM_{10-2.5}$ (Figure 5.3) shows an R^2 = 0.88 and a slope of 0.96 implying a good correlation between the collocated samples. In all plots, the data was refitted using a straight line (dashed line) with a zero intercept to eliminate the existence of a measurement drift showing no significant changes in the correlation values in both $PM_{2.5}$ (R^2= 0.42 for Figure 5.1, R^2= 0.58 for Figure 5.2) and $PM_{10-2.5}$ (R^2=0.88).

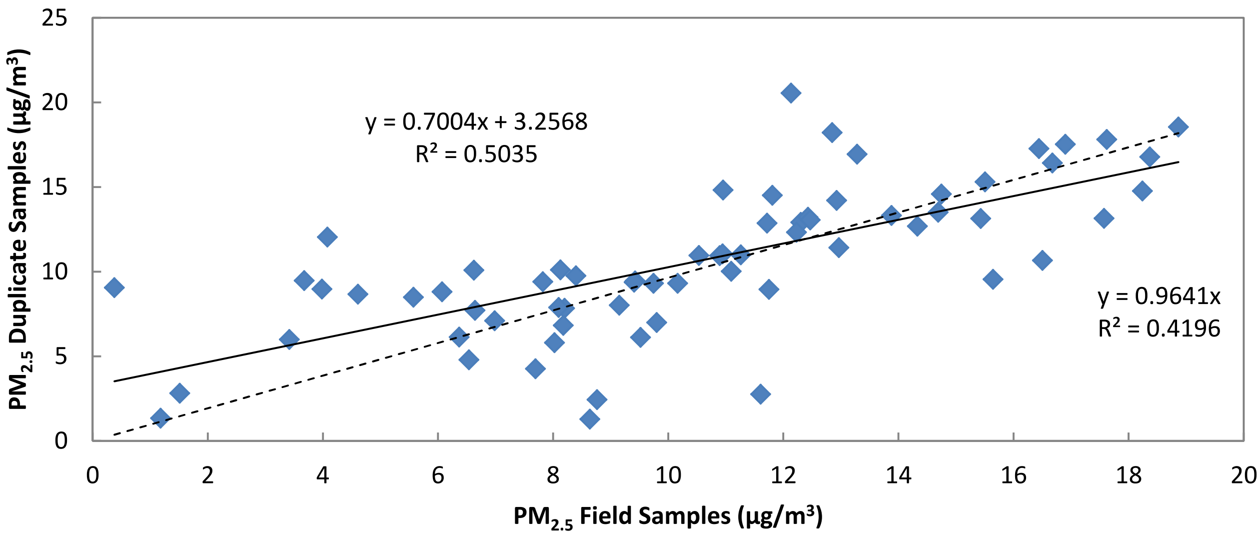


Figure 5.1: Indoor and outdoor $PM_{2.5}$ paired duplicate samples (N = 67)

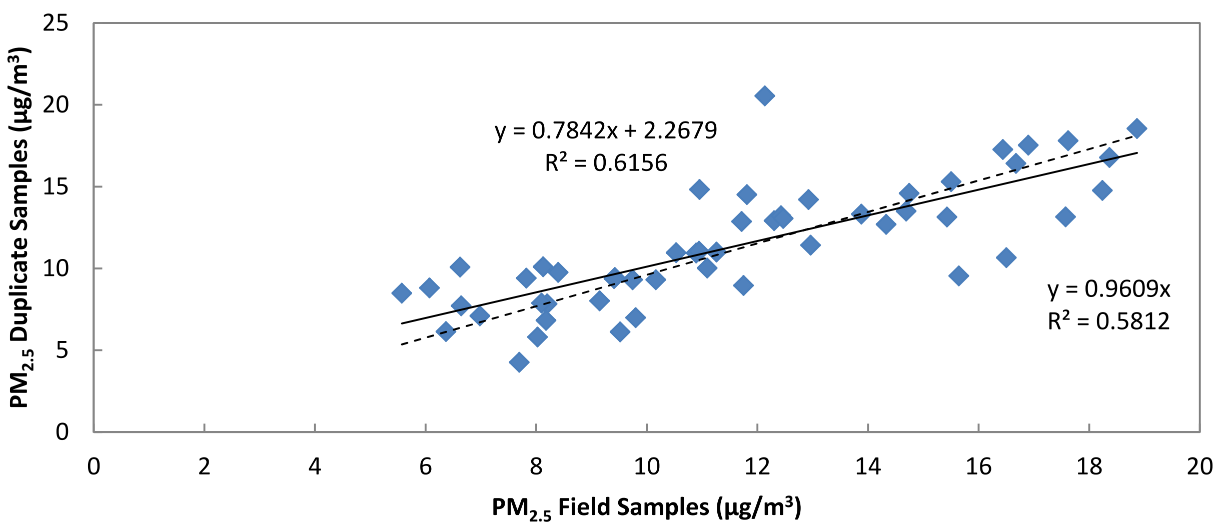


Figure 5.2: Indoor and outdoor $PM_{2.5}$ paired duplicate samples above the LOD (N = 55)

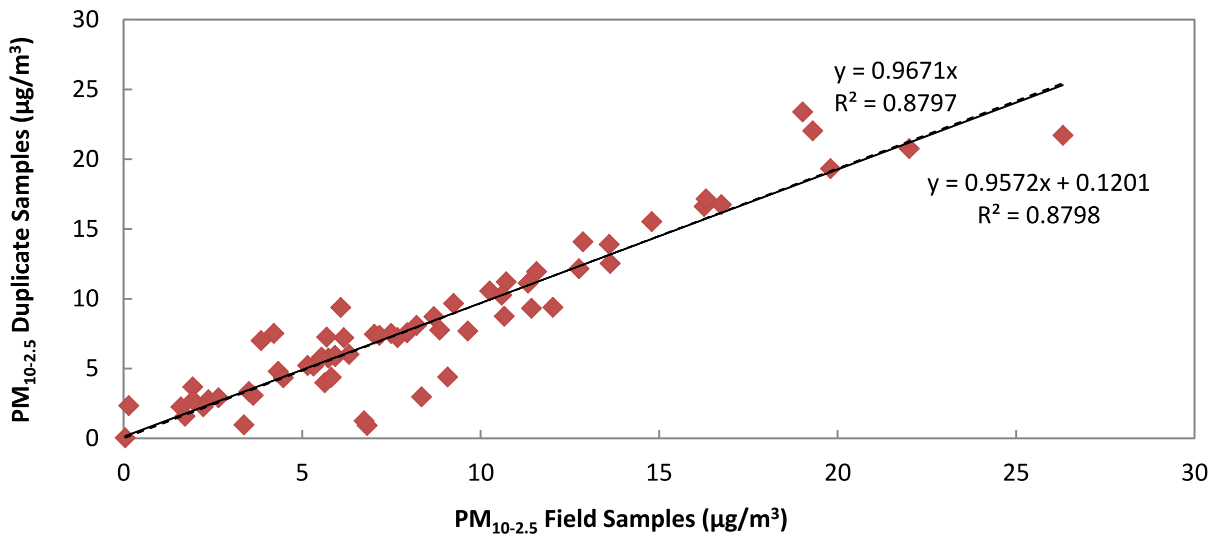


Figure 5.3: Indoor and outdoor $PM_{10\text{-}2.5}$ paired duplicate samples (N = 63)

Table 5.4 below shows basic descriptive statistics per pollutant per sample type (excluding outliers) and the numbers do not indicate extreme differences between the measured concentrations.

Table 5.4: Descriptive statistics for paired duplicates excluding outliers (µg/m^3)

Pollutant	Sample Type	N	Mean	Median	Std. Deviation	Variance	Minimum	Maximum
$PM_{2.5}$	Samples	67	10.51	10.89	4.43	19.61	0.38	18.87
	Duplicates	67	10.62	10.09	4.37	19.11	1.28	20.55
$PM_{10\text{-}2.5}$	Samples	63	8.51	7.16	5.56	30.87	0.04	26.31
	Duplicates	63	8.27	7.38	5.67	32.15	0.03	23.39

To further evaluate the significance of the difference in the means between the duplicates and the samples, a Paired Samples T-Test was conducted and the results are displayed in Table 5.5. Table 5.5 shows that for $PM_{2.5}$, there is no statistically significant difference between the mean of the samples (10.51 µg/m^3) and the mean of the duplicates (10.62 µg/m^3), p-value=0.794; for $PM_{10\text{-}2.5}$, there is no

statistically significant difference between the mean of the samples (8.51 μg/m^3) and the mean of the duplicates (8.27 μg/m^3), p-value=0.331.

Table 5.5: Paired samples t-test between duplicates and samples

Pollutant	Mean Difference	Std. Error Difference	95% CI of Difference		t	p-value
			Lower	Upper		
$PM_{2.5}$	-0.11	3.35	-0.93	0.71	-0.26	0.794
$PM_{10-2.5}$	0.24	1.98	-0.25	0.74	0.98	0.331

Although relative precision values for $PM_{2.5}$ (22.3%) and $PM_{10-2.5}$ (16.7%) were above target precision goal (10%) set for this study, the samples were considered reliable as judged from the correlations obtained in the scatter plots and the results obtained in the paired samples t-test.

5.1.3 Completeness

Completeness, reported as a percentage, is defined as the valid data that was collected compared to the total number of samples that were collected. It is determined by equation (5.3):

$$Completeness = \frac{N_x - N_c}{N_c} x100\% \qquad \text{(Equation 5.3)}$$

Where N_x is the number of valid samples and Nc is the number of expected samples.

The number of valid samples for this project was targeted at 75% (Li, et. al. 2011) and there were a couple of instances when this target value was not met, such as for the indoor school measurements of $PM_{2.5}$ in Zone 2 (67%) and the indoor school measurements of $PM_{10-2.5}$ in Zone 2 (67%). For indoor school measurements of $PM_{2.5}$ at Zone 3, the percentage of valid measurements was just above the target value at 79%. For the rest of the measurements, the percentage of valid samples was above 83%. As mentioned before, many difficulties were encountered during the sampling period

that led to invalidating measurements, including blackouts lasting for a couple of days to weeks, homeowners or school personnel intentionally interrupting the sampling process, children tampering with the instruments, and strong rain or hail that damaged filters. In the case of Zone 3, there was one month worth of lost data (February) due to failure of the equipment to measure the flow rate.

Limits of detection (LOD) were taken from Table 5.1 as 5.2 μg/m^3 for $PM_{2.5}$ and 1.9 μg/m^3 for $PM_{10-2.5}$. The percentages of samples above the LOD were estimated from the valid sample total and as we can see from Table 5.6, for most measurements, the percentage of samples above the LOD was 84% or more. All of the samples under the valid samples column of Table 5.6 were included in the analysis.

Table 5.6: Completeness data for pollutant measurements

Pollutant	Zone	Microenvironment	Site	Samples Collected (N_c)	Valid Samples N_x (%)	Samples ≥ LOD N (%)
$PM_{2.5}$	1	Indoor	School	24	24 (100%)	21 (88%)
			Residence	48	44 (92%)	43 (98%)
		Outdoor	School	12	10 (83%)	10 (100%)
			Residence	48	42 (88%)	41 (98%)
	2	Indoor	School	24	16 (67%)	15 (94%)
			Residence	48	44 (92%)	43(98%)
		Outdoor	School	12	11 (92%)	11 (100%)
			Residence	48	44 (92%)	44 (100%)
	3	Indoor	School	24	19 (79%)	16 (84%)
			Residence	48	40 (83%)	37 (93%)
		Outdoor	School	12	10 (83%)	9 (90%)
			Residence	48	41 (85%)	39 (95%)
$PM_{10-2.5}$	1	Indoor	School	24	24 (100%)	23 (96%)
			Residence	48	45 (94%)	43 (96%)
		Outdoor	School	12	10 (83%)	10 (100%)
			Residence	48	44 (92%)	43 (98%)
	2	Indoor	School	24	16 (67%)	15 (94%)
			Residence	48	44 (92%)	43 (98%)
		Outdoor	School	12	11 (92%)	11 (100%)
			Residence	48	45 (94%)	45 (100%)
	3	Indoor	School	24	20 (83%)	18 (90%)
			Residence	48	41 (85%)	41 (100%)
		Outdoor	School	12	10 (83%)	10 (100%)
			Residence	48	44 (92%)	44 (100%)

5.1.4 Sampling Design

The year-long study in 2010 resulted in week-long results per month per zone. The study started in mid-January and concluded in December. Each zone was monitored for a week during each month, separate weeks were selected for each of the zones. There were some months when data had to be invalidated for certain zones and sites because of prolonged blackouts, school personnel or homeowners intentionally interrupting the sampling process, children tampering with the instruments, and strong rain/hail events that led to filter damage. Table 5.7 shows the months when valid samples were

successfully collected for each zone. Zone 1 did not have valid data for school/outdoor for the months of January and February for $PM_{2.5}$, for the month February and August for $PM_{10-2.5}$ and for the months of January, February, and August for PM_{10}. Zone 2 did not have valid data for school/indoor for September and school/outdoor for April for all pollutants. Zone 3 did not have any valid data for the month of February in any of the microenvironments, no valid data at the school/indoor for the month of December and school/outdoor for the month of May for all pollutants.

Table 5.7: Valid samples collected in the study

Pollutant	Zone	Microenvironment	Site	Available Samples											
				Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
$PM_{2.5}$	1	Indoor	School	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
			Residence	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		Outdoor	School			✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
			Residence	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	2	Indoor	School	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓
			Residence	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		Outdoor	School	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓
			Residence	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	3	Indoor	School	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	
			Residence	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		Outdoor	School	✓		✓	✓		✓	✓	✓	✓	✓	✓	✓
			Residence	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
$PM_{10-2.5}$	1	Indoor	School	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
			Residence	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		Outdoor	School	✓		✓	✓	✓	✓	✓		✓	✓	✓	✓
			Residence	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	2	Indoor	School	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓
			Residence	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		Outdoor	School	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓
			Residence	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	3	Indoor	School	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	
			Residence	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		Outdoor	School	✓		✓	✓		✓	✓	✓	✓	✓	✓	✓
			Residence	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
PM_{10}	1	Indoor	School	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
			Residence	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		Outdoor	School			✓	✓	✓	✓	✓	✓		✓	✓	✓
			Residence	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	2	Indoor	School	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓
			Residence	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		Outdoor	School	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓
			Residence	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	3	Indoor	School	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	
			Residence	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		Outdoor	School	✓		✓	✓		✓	✓	✓	✓	✓	✓	✓
			Residence	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

5.2 Data Analysis

5.2.1 Indoor Samples

Weekly $PM_{2.5}$ Samples

Table 5.8 shows descriptive statistics for $PM_{2.5}$ (µg/m^3) seven-day school and residential indoor measurements. At the school, as expected, the high exposure zone, (Zone 2) had the highest mean (SD) 14.7 (15.6) while Zone 3 (low exposure) and Zone 1 (medium exposure) had similar means 10.8 (8.9) and 10.6 (4.9) µg/m^3. At the residential sites, indoor concentrations were almost twice as high as those measured at the schools with Zone 1 (medium exposure) having the highest mean 29.0 (30.5) followed by Zone 2 (high exposure) 20.8 (10.4) and Zone 3 (low exposure) 19.3 (14.6) µg/m^3. These observations are comparative to the results by Raysoni, et al. (2011) where 48-hr $PM_{2.5}$ mean indoor concentrations at two schools in El Paso, TX (US) followed the pattern of high and low traffic exposures at 9.6 (6.3) and 7.5 (3.3) µg/m^3 respectively, while the schools in Ciudad Juárez, (México) did not follow the high low traffic exposures at concentration levels of 21.5 (11.6) and 29.4 (19.3) µg/m^3 respectively. Residential indoor microenvironments have $PM_{2.5}$ contributors (e.g. cooking), other than traffic emissions infiltrated from outdoor, causing the pre-defined exposure patterns to be altered.

Table 5.8: Descriptive statistics for indoor $PM_{2.5}$ measurements (µg/m^3)

Statistics	Schools Indoor			Residential Indoor		
	Z1	Z2	Z3	Z1	Z2	Z3
N	24	16	19	44	44	40
Mean	10.6	14.7	10.8	29.0	20.8	19.3
Geom. Mean	10.1	11.0	10.1	25.0	20.0	16.5
Median	10.6	11.0	8.4	18.1	17.5	14.3
SD	4.9	15.6	8.8	30.5	10.4	14.6
Geom. SD	1.4	1.6	1.8	1.8	1.3	1.8
Minimum	0.4	4.1	3.0	4.4	4.7	3.1
Maximum	18.3	72.1	44.2	149.8	45.1	64.0

Figures 5.4 and 5.5 show monthly averages of $PM_{2.5}$ at school indoor and residential indoor, respectively. The school monthly averages are estimated from two seven-day samples measured at each zone each month, while residential monthly averages are estimated from four samples collected at four different residences per zone each month. At the schools, for all 3 zones, the averages ranged from 5-20 $\mu g/m^3$ for most of the year, except in June when Zone 2 experienced a high peak at 42 $\mu g/m^3$ (school indoor) and in January when Zone 3 experienced a high peak at 44 $\mu g/m^3$ (school and residential). The January wind rose (Figure A.1) for Zone 3 (Los Chillos) show a high percentage of winds blowing from the east that were possibly carrying emissions from the textile industry located to the east of Zone 3. According to the 2011 emission inventory, the textile industry has significant levels of PM emissions (*Secretaría de Ambiente,* 2011). At Zone 2, there were no unusual events recorded for the June monitoring period, so the peak is probably a result of an unusually high volume of traffic activity and meteorological conditions. At the residences, Figure 5.5 also shows Zone 1 having the highest concentrations during the months of April, July, August, and October, with levels ranging from 38-68 $\mu g/m^3$. $PM_{2.5}$ peaks at the residential indoor microenvironments can be attributed to many factors, but for this particular location, cooking could be the activity having the strongest effect on $PM_{2.5}$ concentrations. Two of the peaks observed at the residential sites in Zone 1 coincide with the summer break (June and July) and could be attributed to increased activity at home because the children are on vacation, including the increase in cooking. For the rest of the year, concentrations across the three zones vary between 5-30 $\mu g/m^3$.

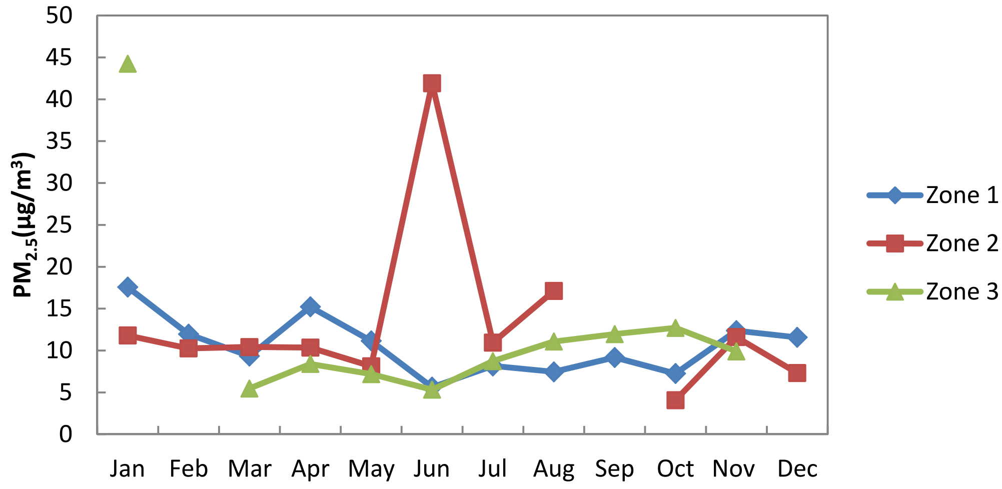


Figure 5.4: $PM_{2.5}$ monthly averages at school/indoor

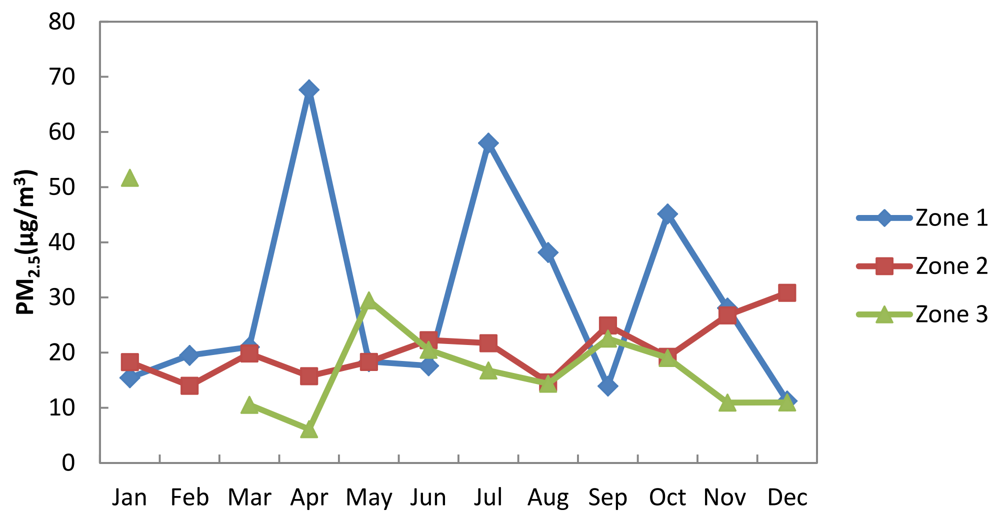


Figure 5.5: $PM_{2.5}$ monthly averages at residence/indoor

Weekly $PM_{10\text{-}2.5}$ Samples

Table 5.9 shows descriptive statistics for school indoor and residential indoor $PM_{10\text{-}2.5}$ seven-day samples (μg/m^3). The concentration levels obtained in our pre-defined exposure zones were different

from what was expected. Zone 1 (medium exposure) had the highest mean 16.1 (11.6) followed by Zone 3 (low exposure) 9.1 (6.0) and Zone 2 (high exposure) 5.73 (2.8) μg/m^3. At the residential sites, Zone 1 (medium exposure) and Zone 3 (low exposure) both had similar mean levels 16.4 (10.2) and 16.9 (21.1) respectively and Zone 2 (high exposure) had the lowest mean at 12.4 (7.9) μg/m^3. Again, as with $PM_{2.5}$, $PM_{10-2.5}$ indoor concentrations at the residences are greater than indoor concentrations at the schools, although the difference for $PM_{10-2.5}$ is not as significant as the differences for $PM_{2.5}$. $PM_{10-2.5}$ levels are more uniform throughout the zones because the most significant source for coarse PM is the resuspension of dust, which can be more uniform throughout the city than emission from combustion sources. Zones 1 and 3 are located closer to the outskirts of the urban limits of the Quito Metropolitan District (or in the case of Zone 3, outside of the urban limits), being subject to greater exposure from unprotected surfaces, such as unpaved roads (especially north of Quito, close to Zone 1), quarry and cement plant resuspension of dust, and soil erosion. Results are consistent with the 48-hr school indoor averages measured by Raysoni, et al. (2011) in Ciudad Juárez, (México) where the low exposure school, mean 42.2 (18.0) had a higher mean than the high exposure school, mean 24.7 (10.0) μg/m^3, citing that even though the low exposure school was located near a low traffic area, higher $PM_{10-2.5}$ concentrations were a result of fugitive dust from unpaved road surfaces.

Table 5.9: Descriptive statistics for indoor $PM_{10-2.5}$ measurements (μg/m^3)

Statistics	Schools Indoor			Residential Indoor		
	Z1	Z2	Z3	Z1	Z2	Z3
N	24	16	20	45	44	41
Mean	16.1	5.7	9.1	16.4	12.4	16.9
Geom. Mean	13.9	5.4	8.2	14.8	11.9	12.3
Median	16.5	5.6	9.1	16.5	11.2	9.4
SD	11.6	2.8	6.0	10.2	7.9	21.1
Geom. SD	1.8	1.6	1.6	1.8	1.5	2.3
Minimum	0.4	1.6	0.1	0.6	1.8	2.0
Maximum	39.2	12.6	23.2	41.6	45.7	117.5

Figures 5.6 and 5.7 shows monthly school and residential indoor averages for $PM_{10-2.5}$. At the school, Zone 1 shows the highest averages for most of the year, with the exception of July, August, and

September. The highest value was seen in the month of January at 32 μg/m^3 and its lowest in the month of August at 5 μg/m^3. The monthly wind rose at Zone 1 (Cotocollao) for August shows less winds coming from the northeast as compared to the rest of the year, signaling that most of the coarse PM ($PM_{10-2.5}$) is coming from the north of the area, in addition to the fact that children are on summer break during that month, therefore there is less no resuspension of dust from children's activity. School/indoor monthly averages for Zone 2 remained constant and the lowest from all three zones, for most of the year with values ranging from 4 μg/m^3 in March to 13 μg/m^3 in February. Zone 2 is located right in the center of the Quito metropolis and resuspension of dust from unprotected surfaces such as unpaved roads is very unlikely. Zone 3 concentrations remained between 4-15 μg/m^3 with a slightly higher concentration in January (19 μg/m^3), as compared to the rest of the year due to the significant amount of winds coming from the east, as previously explained in the $PM_{2.5}$ section. Summer break took place starting in the last part of June and lasted until September 4th, so we would expect reduced PM concentrations for that part of the year, especially for larger particles such as $PM_{10-2.5}$. At the residences (Figure 5.7) has the three zones displaying a high degree of variability throughout the whole year: for the months of January, May, September, and October, Zone 3 has the highest monthly averages with a higher-than-usual level in January, while Zone 1 has the highest monthly averages in the months of February, April, June-August, and November. Overall and throughout the year, concentrations range across the three zones between 5-30 μg/m^3. During the sampling period, field staff noted few unpaved roads close to the residential sites, but they also noted construction activities taking place inside or outside the homes, so higher levels of coarse PM can be expected at the residential sites because of resuspension of dust from construction activities. Occupancy at the homes and household activities such as cleaning were also contributing factors to high elevations of $PM_{10-2.5}$.

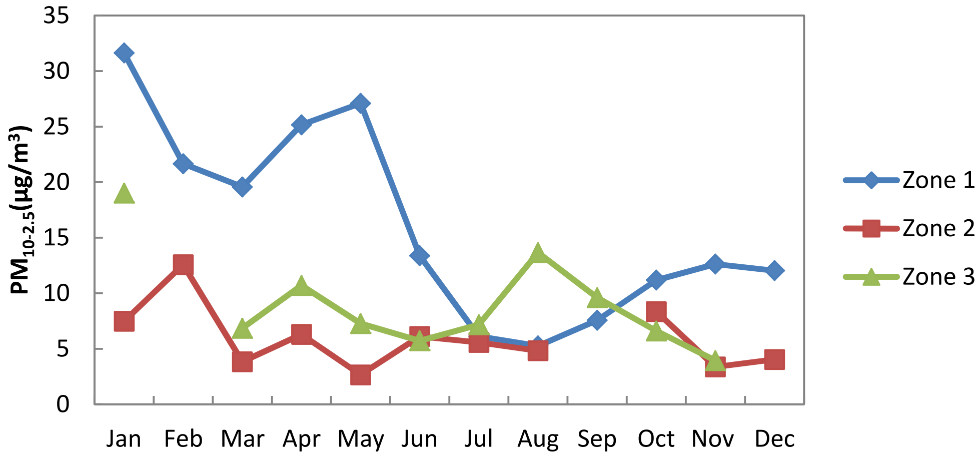


Figure 5.6: $PM_{10\text{-}2.5}$ monthly averages at school/indoor

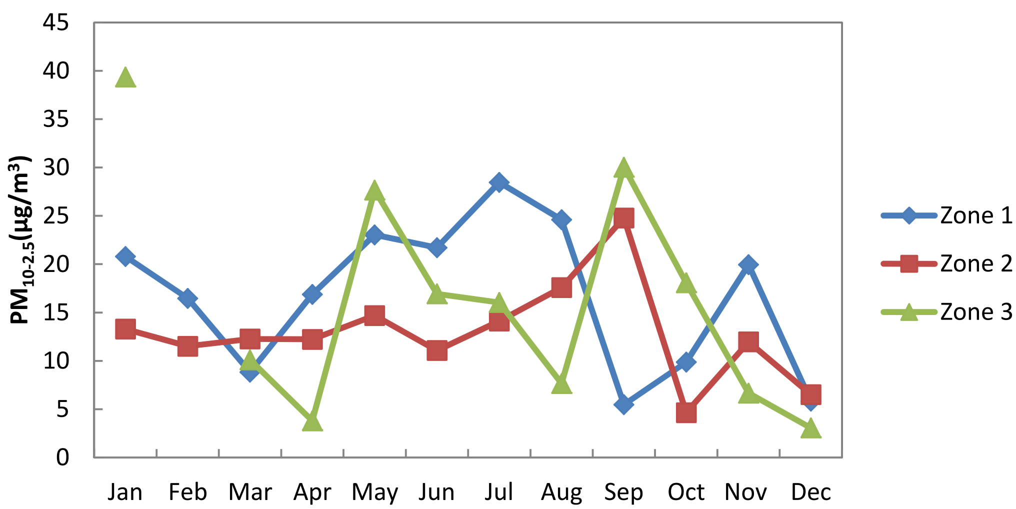


Figure 5.7: $PM_{10\text{-}2.5}$ monthly averages at residence/indoor

Weekly PM_{10} Samples

Table 5.10 gives descriptive statistics for school and residential indoor PM_{10} seven-day measurements. At the school Zone 1 (medium exposure) had the highest mean value 26.7 (15.9) followed by Zone 2 (high exposure) 20.4 (16.0) and Zone 3 (low exposure) 19.6 (13.6) µg/m^3. At the residences, Zone 1 (medium exposure) had the highest mean level 45.3 (34.8) followed by Zone 3 (low exposure) 36.4 (34.0) and Zone 2 (high exposure) 33.1 (14.5) µg/m^3. Composition of PM_{10} will include

both coarse and fine fractions, reflecting a combination of emissions from combustions sources (e.g. traffic emissions) as well as geologic material from dust resuspension. Even though Zone 1 does not have the highest traffic flows from the three exposure zones, it still gets a significant amount of traffic from private and public vehicles affecting its $PM_{2.5}$ levels and adding significant contributions from dust resuspension coming from the north, resulting in the high PM_{10} concentrations that we observed at both the school and residential microenvironments.

Table 5.10: Descriptive statistics for indoor PM_{10} measurements (µg/m3)

Statistics	Schools Indoor			Residential Indoor		
	Z1	**Z2**	**Z3**	**Z1**	**Z2**	**Z3**
N	24	16	19	44	44	40
Mean	26.7	20.4	19.6	45.3	33.1	36.4
Geom. Mean	24.5	17.3	18.9	41.4	32.8	29.6
Median	28.9	16.4	15.7	36.5	32.7	27.5
SD	15.9	16.0	13.6	34.8	14.5	34.0
Geom. SD	1.5	1.5	1.7	1.7	1.2	2.0
Minimum	2.4	10.8	7.7	8.1	10.0	5.6
Maximum	57.4	78.5	67.5	168.3	83.0	181.5

Figures 5.8 and 5.9 show the schools and residences indoor monthly averages for PM_{10}. Concentrations between Zones 2 and 3 range between 10-30 µg/m^3 with a high average at Zone 2 in June (50 µg/m^3). Zone 1 shows the highest averages from February to May and in November and December between 50-30 µg/m^3. Consistent with $PM_{2.5}$ and $PM_{10-2.5}$, Zone 3 shows an unusually high concentration in the month of January at 68 µg/m^3, which as mentioned previously, can be attributed to easterly winds blowing in emission from the textile factory. At the residences, Figure 5.9 shows Zone 1 with the highest monthly averages for most of the year (February, April, July, August, October, and November) between 60-80 µg/m^3. The high concentrations for Zone 1 during the months of July and August could be due to a combination of increased activity at home because the children are in summer break along with outside sources, that as mentioned before, include traffic emissions and resuspension of coarse particles coming from geologic material. Zone 3 has the highest monthly averages in January, May, and September, with an unusual high concentration in January. Zone 2 concentrations remain

uniform (between 20-40 μg/m^3) as compared to the other two zones because even though traffic flow is more significant in the area contributing to high $PM_{2.5}$ concentrations, its low coarse particulate matter fraction ($PM_{10-2.5}$) allows the PM_{10} levels to remain steady and between Zones 1 and 3.

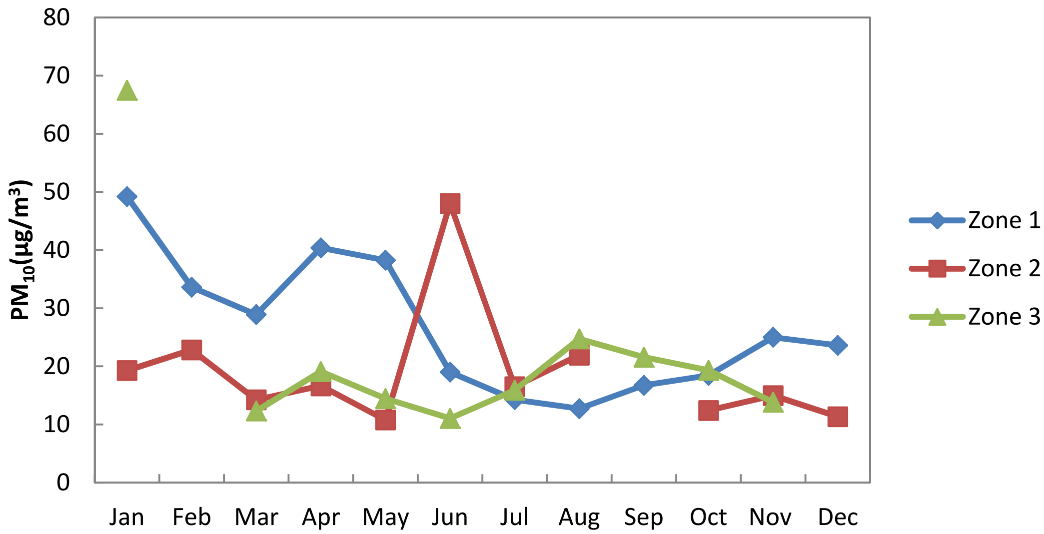


Figure 5.8: PM_{10} monthly averages at school/indoor

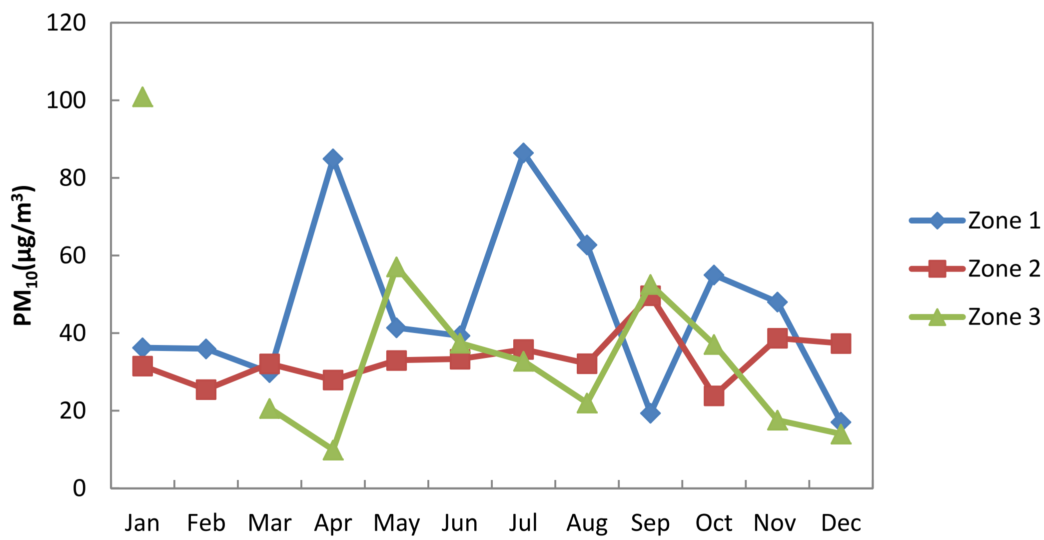


Figure 5.9: PM_{10} monthly averages at residence/indoor

5.2.2 Outdoor Samples

Weekly $PM_{2.5}$ Samples

Table 5.11 shows descriptive statistics for school and residential outdoor seven-day $PM_{2.5}$ samples. School outdoor mean averages are consistent across the three zones, with the highest average at Zone 2 (high exposure) 13.2 (3.5) followed by Zone 3 (low exposure) 13.0 (8.7) and Zone 1 (medium exposure) 10.9 (3.2) $\mu g/m^3$. The same pattern was followed at the residences with Zone 2 (high exposure) having the highest mean 14.3 (10.1) followed by Zone 3 (low exposure) 13.5 (7.2) and Zone 1 (medium exposure) 12.5 (4.6) $\mu g/m^3$. Again, as with the indoor concentrations, outdoor residential concentrations are higher than outdoor school concentrations. However, the difference between residence and school concentrations is smaller for outdoor than for indoor microenvironments. Outdoor sources are more consistent when compared to indoor sources. Residential indoor sources can include smoking, cooking, and are dependent on ventilation rates, resuspension of dust from movement around the house, while at school, indoor sources can be limited to ventilation rates, blackboard usage, and resuspension of dust. Cooking and smoking will (usually) not take place in the classrooms. On the other hand consistency of outdoor sources, within a zone, is more common. Slightly higher concentrations observed at Zone 3 as compared to Zone 1 can be attributed to common northerly winds (Figures A.1-A.12) at Zone 3 bringing in vehicle emissions from the urbanized zone, while Zone 1, located north of the urban limits, has very little winds blowing from the south. Concentrations in Quito were lower than the outdoor $PM_{2.5}$ weekly average for schools within 400-m located in the Netherlands at 20.5 (2.2) $\mu g/m^3$ (Janssen et al, 2001) and lower than the 48-hr outdoor concentrations reported by Raysoni in El Paso, TX (US) at 14.5 (7.8) and 8.3 (4.1) at high and low traffic areas respectively and in Ciudad Juárez (México) at 26.2 (22.9) and 34.6 (22.9) $\mu g/m^3$ also at low and high traffic areas respectively.

Table 5.11: Descriptive statistics for school and residential outdoor $PM_{2.5}$ measurements ($\mu g/m^3$)

Statistics	Schools Outdoor			Residential Outdoor		
	Z1	Z2	Z3	Z1	Z2	Z3
N	10	11	10	42	44	41
Mean	10.9	13.2	13.0	12.5	14.3	13.5
Geom. Mean	10.4	12.7	10.9	11.9	13.6	12.7
Median	10.1	12.2	11.0	12.4	12.6	11.6
SD	3.2	3.5	8.7	4.6	10.1	7.2
Geom. SD	1.3	1.3	1.8	1.2	1.4	1.3
Minimum	6.1	6.6	4.0	2.1	8.0	3.2
Maximum	16.5	18.9	34.6	34.2	76.1	28.4

Figures 5.10 and 5.11 shows the school and residential $PM_{2.5}$ monthly averages as well as ambient monthly averages for Zones 1 and 2. Both ambient averages and site averages (school and residential) outdoor levels are reported to local conditions temperature and pressure conditions. Figure 5.10 shows the school/outdoor $PM_{2.5}$ monthly averages very consistent across all three zones, ranging from 5-20 $\mu g/m^3$, except for the month of January, in Zone 3 when the average is at 35 $\mu g/m^3$. The peak in Zone 3 is consistent with the high concentration levels observed at this zone at the school indoor. Figure 5.11 shows the residence/outdoor monthly averages with values ranging from 5-20 $\mu g/m^3$ for most of the year with a few exceptions. During the month of December, Zone 2 had a peak at 35 $\mu g/m^3$. It was expected for Zone 3 to have a high concentration during the month of January in order to follow the same pattern as with the other microenvironments (school/indoor, residence/indoor, and school/outdoor), however, three out of the four samples collected were eliminated and only the sample from one residence was taken into account. The location of this residence could have been a factor in not capturing the peak concentration levels captured at the other monitors. Hourly ambient concentrations from central monitors in zones 1 and 2 were also collected and averaged to match the time period when the sampling took place. Monthly averages at Zone 1 ambient monitor were similar, or in some cases, less than the values monitored in the school or residential sites. Monthly averages collected at Zone 2 central monitor were higher than levels collected at school and residential sites. However, ambient

concentrations seem to follow similar (up-and-down) trends as the concentration levels sampled at the schools and at the residences.

In Zone 1 (medium exposure), the values at the central monitor were usually the same or less than those collected at the school or residences. For Zone 2 (high exposure), the values at the central monitor were usually higher than those collected at the school or residences. For Zone 1, the central monitor and the school are located in close proximity to each other, within one-tenth of a mile and residences are located in all directions surrounding the monitor, whereas for Zone 2, the central monitor is to the north while the residences and the school are to the south and east of the monitor only. It seems that the central monitor from Zone 2 is downwind from the center of Quito and therefore prone to pick up traffic and other emissions generated in this area (see Figure 3.1), showing the importance of the location of the central monitor. The fact that at Zone 1, residences are farther spread out from the central monitor and in Zone 2 they are in closer distance to the central monitor shows that $PM_{2.5}$ levels at Zone 2 will show greater variation due to greater amount of traffic, while Zone 1 traffic may be more evenly spread out.

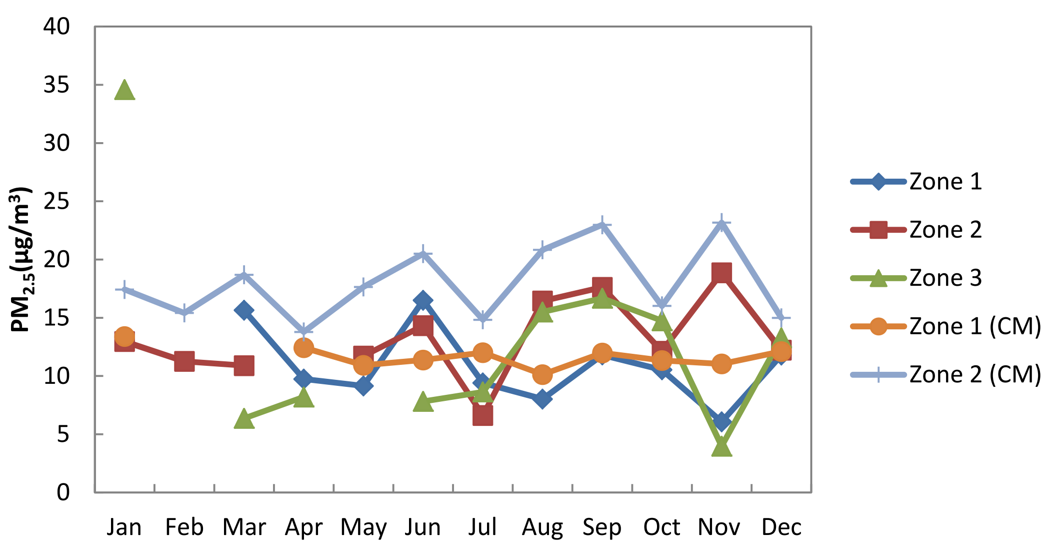


Figure 5.10: $PM_{2.5}$ monthly averages at school/outdoor and central monitors (CM)

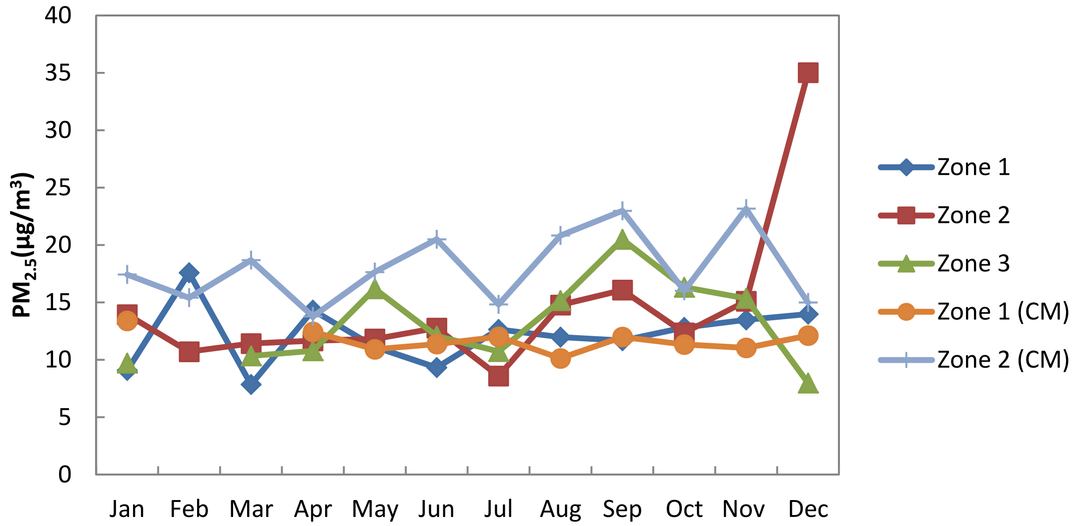


Figure 5.11: $PM_{2.5}$ monthly averages at residence/outdoor and central monitors (CM)

Weekly $PM_{10\text{-}2.5}$ Samples

Table 5.12 shows descriptive statistics for school and residences seven-day outdoor measurements of $PM_{10\text{-}2.5}$. At the schools, Zone 3 (low exposure) had the highest mean 11.2 (5.4) followed closely by Zone 1 (medium exposure) 10.5 (3.8) and Zone 2 (high exposure) 7.9 (2.2) $\mu g/m^3$. A similar pattern is followed at the residential sites, with Zones 3 and 1 having the highest means 11.6 (6.6) and 11.6 (3.1) respectively, and Zone 2 following closely with a mean of 8.2 (2.4) $\mu g/m^3$. The difference between residential and school levels is indistinguishable for $PM_{10\text{-}2.5}$ as compared to the differences for $PM_{2.5}$. Consistency of outdoor coarse PM levels is expected within each zone because of its geologic nature. Contrastingly, the large difference between the 48-hr mean concentrations measured by Raysoni et al. (2011) in the high and low exposure areas in Ciudad Juárez (México) at 37.5 (19.4) and 57.9 (21.6) $\mu g/m^3$ is a reflection of the different fugitive dust sources in both Latin American cities. Ciudad Juárez coarse PM comes mainly from a significant network of unpaved roads, while most of Quito's road network is paved and coarse PM levels across the different zones is likely to be consistent attributed to dust of the region.

Table 5.12: Descriptive statistics for school and residential outdoor $PM_{10\text{-}2.5}$ measurements ($\mu g/m^3$)

Statistics	Schools Outdoor			Residential Outdoor		
	Z1	Z2	Z3	Z1	Z2	Z3
N	10	11	10	44	45	44
Mean	10.5	7.9	11.2	11.6	8.2	11.6
Geom. Mean	9.9	7.6	9.9	11.6	8.0	10.9
Median	11.0	8.7	10.2	11.0	8.3	10.5
SD	3.8	2.2	5.4	3.1	2.4	6.6
Geom. SD	1.4	1.4	1.7	1.3	1.3	1.5
Minimum	6.1	4.5	3.8	0.1	3.4	2.5
Maximum	19.0	10.7	19.8	20.6	12.4	34.5

Figures 5.12 and 5.13 show monthly $PM_{10\text{-}2.5}$ averages for outdoor school and residence levels, as well as ambient monitors (CM). Concentrations for $PM_{10\text{-}2.5}$ at central monitors is not directly measured, but it was obtained by subtracting the $PM_{2.5}$ monthly average from the PM_{10} (reflecting local conditions). For school outdoor levels, Zone 3 shows the highest monthly averages out of the three zones for the months of August, September, and October at ranging between 15-20 $\mu g/m^3$. The month of January has unusually high concentrations for Zone 1 (19 $\mu g/m^3$) and Zone 3 (17 $\mu g/m^3$). For the rest of the year, concentrations stay constant across all three zones, ranging in values from 5-15 $\mu g/m^3$. At the residences/outdoor (Figure 5.13), it can be seen that May, July, August, September, and October Zone 3 has the highest monthly averages while Zone 1 has the highest monthly averages in January, February, March, June, November, and December. However, in general, the values across the three zones and throughout the year stay below 20 $\mu g/m^3$. As with $PM_{2.5}$, ambient concentrations for $PM_{10\text{-}2.5}$ in Zone 1 are equal or less than school/residential concentrations. At Zone 2, ambient concentrations for $PM_{10\text{-}2.5}$ are slightly higher than levels collected at school and residential sites. Closer agreement between the concentrations captured by the central monitor and residential/school sites is evidence that coarse $PM_{10\text{-}2.5}$ concentrations are more uniform because they consist of resuspension from geologic material.

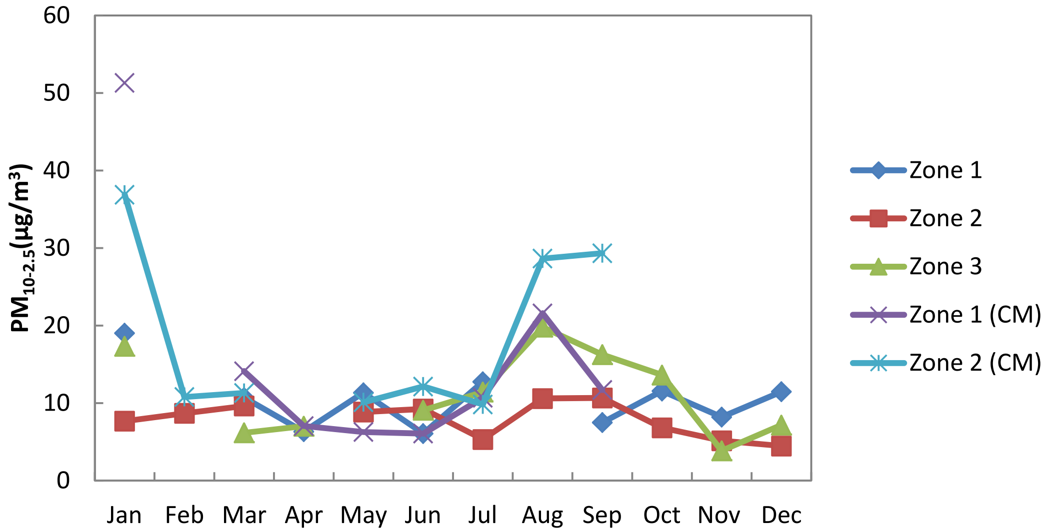


Figure 5.12: $PM_{10\text{-}2.5}$ monthly averages at school/outdoor and central monitors (CM)

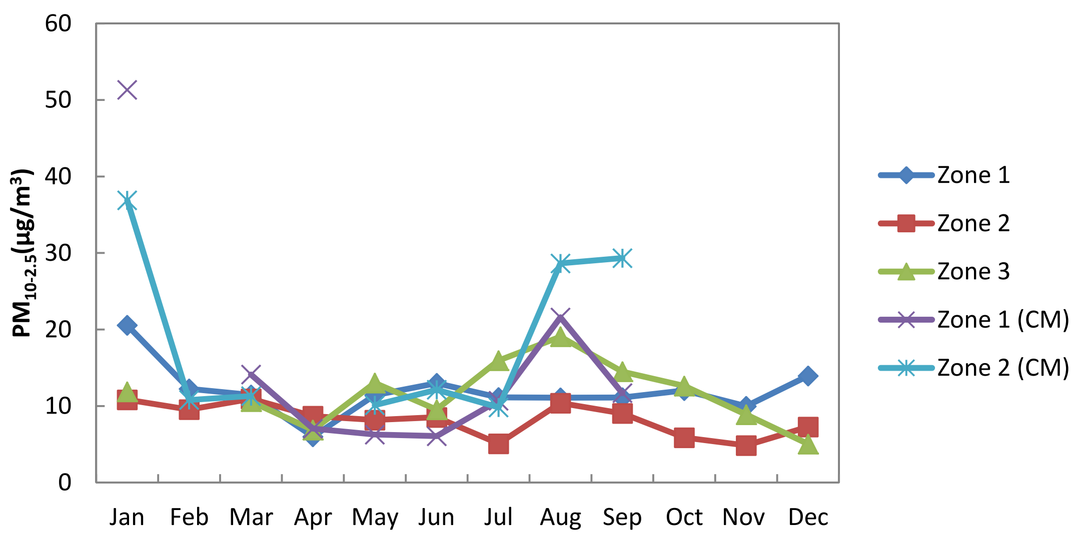


Figure 5.13: $PM_{10\text{-}2.5}$ monthly averages at residence/outdoor and central monitors (CM)

Weekly PM_{10} Samples

Table 5.13 shows descriptive statistics for PM_{10} school and residential outdoor seven-day measurements. At the schools, Zone 3 (low exposure) had the highest mean value 24.2 (13.1) followed by Zone 2 (high exposure) 21.1 (4.6) and Zone 1 (medium exposure) 20.7 (3.7) µg/m^3. At the residences, Zone 3 had the highest mean value 25.1 (13.2) followed by Zone 1 24.5 (7.3), and Zone 2

21.1 (7.3) μg/m^3. The difference between school and residential concentrations is almost indistinguishable because, whereas indoor PM sources can greatly vary from place to place within a zone, measurements from outdoor sources are affected by the same local sources at the same level, within a certain area (in this case, within the zones), regardless of where you take the measurement.

Table 5.13: Descriptive statistics for school and residential outdoor PM_{10} measurements (μg/m^3)

Statistics	Schools Outdoor			Residential Outdoor		
	Z1	Z2	Z3	Z1	Z2	Z3
N	9	11	10	42	43	41
Mean	20.7	21.1	24.2	24.5	21.1	25.1
Geom. Mean	20.4	20.6	21.1	24.1	20.7	23.9
Median	22.1	20.6	20.3	24.1	21.2	21.1
SD	3.7	4.6	13.1	7.3	4.5	13.2
Geom. SD	1.2	1.3	1.7	1.1	1.2	1.3
Minimum	14.3	11.9	7.8	5.6	12.4	7.6
Maximum	26.4	28.3	51.9	52.7	36.3	60.3

Figures 5.14 and 5.15 show monthly PM_{10} averages for school and residential outdoor concentrations respectively as well as ambient concentrations from central monitors (CM). Zone 3 ambient concentrations are included for PM_{10}. Both ambient and site concentrations were made to local temperature and pressure conditions. Fine ($PM_{2.5}$) and coarse ($PM_{10-2.5}$) were not collected in Zone 3. At central monitors, PM_{10} was collected as 24-hour averages every six days. The monthly averages are a reflection of four to six 24-hour averages taken approximately 6-days apart over that month. Figure 5.14 shows the monthly averages at the school/outdoor with Zone 3 having an unusual high average for the month of January and the highest averages from the three zones for the period of August-October. Overall, across the three zones, monthly averages ranged between 10 and 35 μg/m^3. Figure 5.15 (residences/outdoor) shows Zone 1 with the highest monthly averages for January. Zone 3 has the highest monthly averages for the months of May and July-October. As with the school outdoor averages, monthly averages for residences also vary between 10 and 35 μg/m^3. Ambient concentrations for Zones 1 and 3 are similar or lower than site concentrations, whereas ambient concentrations for Zone 2 are slightly higher than school/residential concentrations, because of central monitor location and the way

the residences were distributed from the central monitor. Both Zones 1 and 3 have residences spread out in all directions from the central monitor, while at Zone 2 the residences are closer to the central monitor. However, the central monitor for Zone 2 seems to be capturing the fine fraction of PM emissions from the traffic to the north, contributing to higher PM_{10} concentrations.

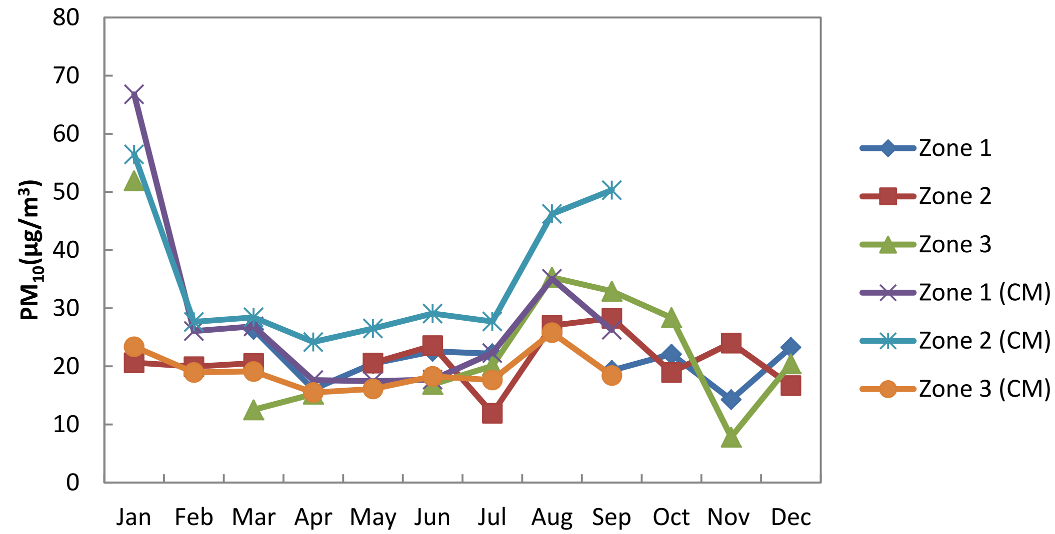


Figure 5.14: PM_{10} monthly averages at school/outdoor and central monitors (CM)

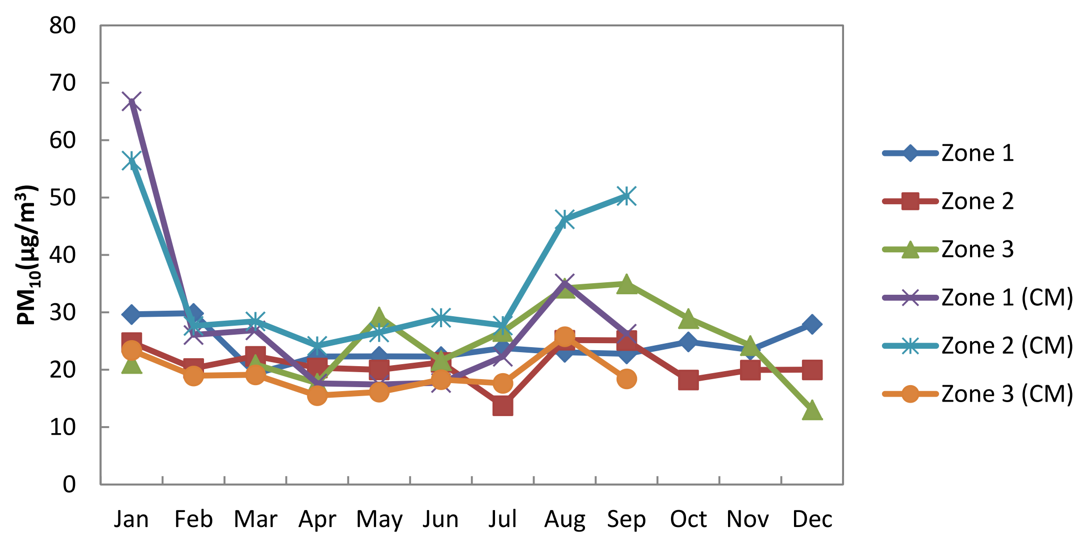


Figure 5.15: PM_{10} monthly averages at residence/outdoor and central monitors (CM)

5.2.3 School Indoor/Outdoor Variations

Indoor/outdoor (I/O) ratios are important indicators for the influence of outdoor concentrations on indoor levels. They are also important indicators for building characteristics' where the measurements are taking place, including air tightness and ventilation (Massey, et al. 2012). Ratios are close to zero for most airtight buildings with little to no indoor sources of pollution, while, for more permeable buildings, I/O increases with decreasing air-tightness, which means that indoor concentrations reflect outdoor concentrations (Blondeau, et al. 2005). Higher indoor/outdoor ratios may also be indicative of additional sources in indoor environments (Massey, et al. 2012). Indoor exposure to air pollutants will be affected by the penetration of outdoor pollutants, wall absorption, emissions from furniture and other materials, emissions from activities such as cooking or cleaning, occupancy, quality of ventilation, and the depositional characteristics of particles (Fromme, et al. 2007, Mejia, et al. 2011 and Massey, et al. 2012). The presence of central heating, refrigerated air, and evaporative coolers for thermal comfort will also have an influence on I/O ratios that will depend mostly on the amount of air exchange by each system. Most houses in the developing world and with climates such as the one seen in Quito, (Ecuador) are naturally ventilated, allowing for the penetration of outdoor particles through given spaces and cracks in the structure (Massey et al. 2012).

Weekly $PM_{2.5}$ Indoor-Outdoor Ratios

The time series and descriptive statistics for the school $PM_{2.5}$ I/O ratios are shown in Figure 5.16 and Table 5.14 respectively. Boxplots are shown in Figure 5.17. For Zone 1, mean I/O was 1.0 (0.50), 1.1 (0.74) at Zone 2, and 1.1 (0.56) at Zone 3. The values indicate similar concentrations indoor and outdoor at the schools because of good ventilation. Schools did not rely on central heating, refrigeration, or evaporative coolers, but on natural ventilation for thermal comfort. Classroom doors were opened, as needed, to allow for circulation of air. No major sources of indoor $PM_{2.5}$ were noted at the schools during the study, so most of the $PM_{2.5}$ detected indoors will be from the outdoor. In another study (Raysoni et al, 2013) were schools rely on evaporative coolers with 100% fresh make-up air for cooling,

mean $PM_{2.5}$ I/O at two schools in El Paso, TX (US) are also close to unity at 1.0 (0.44-2.56) for the school in the low traffic area and at 1.19 (0.75-2.26) for the school in the high traffic area. In the same study, I/O ratios at two schools with refrigerated air and high traffic exposure were much lower at 0.70 (0.40-1.33) and 0.68 (0.32-1.17). The presence of refrigerated air clearly reduces outdoor-to-indoor infiltration rates, whereas the use of evaporative coolers still allow for greater infiltration of outdoor air. Median I/O at another Latin American city (Ciudad Juárez, México) were also close to unity at 0.86 (0.486-1.69) and 0.91 (0.26-1.37) for low and high traffic zones respectively (Raysoni et al, 2011). In this case, the schools also relied on natural ventilation with windows and doors commonly open during the summer, but shut during the winter. Still, in a study conducted in Thailand (Tippayawong et al, 2009), I/O ratios were kept well below 1 ranging from 0.69 to 0.88, even when natural ventilation was common. At 7 schools in Athens (Diapouli et al, 2008), I/O ratios were between 1 and 2 for the classrooms and much higher at an office environment where smoking was a common practice. Although the Athens schools also relied on natural ventilation, the measurements were made during the winter period, when probably doors and windows were kept closed to reduce cold drafts. At the schools in Quito, the temperatures allow for ventilation practices to be kept uniform throughout the year and this practice has an impact on the I/O ratio. Findings from this and other studies (Goyal and Khare, 2009) corroborate that at the school indoor microenvironment $PM_{2.5}$ sources are not significant (including occupancy and resuspension), unless smoking is present, and $PM_{2.5}$ indoor concentrations are likely a reflection of outdoor infiltration from traffic and other sources.

Table 5.14: Descriptive statistics for school $PM_{2.5}$ I/O ratios

Statistics	Schools		
	Z1	Z2	Z3
N	10	10	9
Mean	1.0	1.1	1.1
Median	0.90	0.91	0.86
SD	0.50	0.74	0.56
Minimum	0.34	0.34	0.68
Maximum	2.0	2.9	2.5

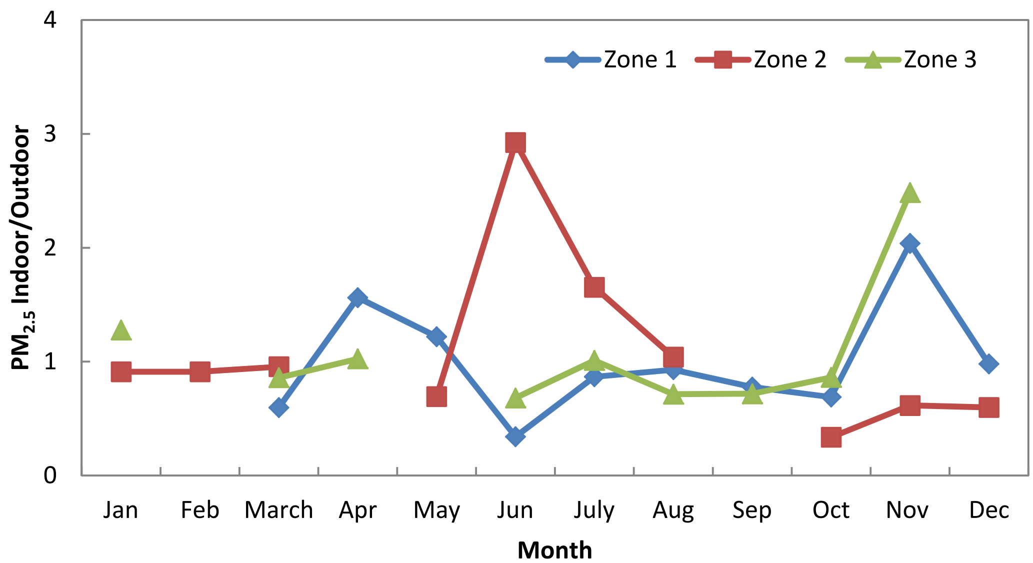


Figure 5.16: $PM_{2.5}$ Indoor/outdoor ratios for the monthly averages at the schools

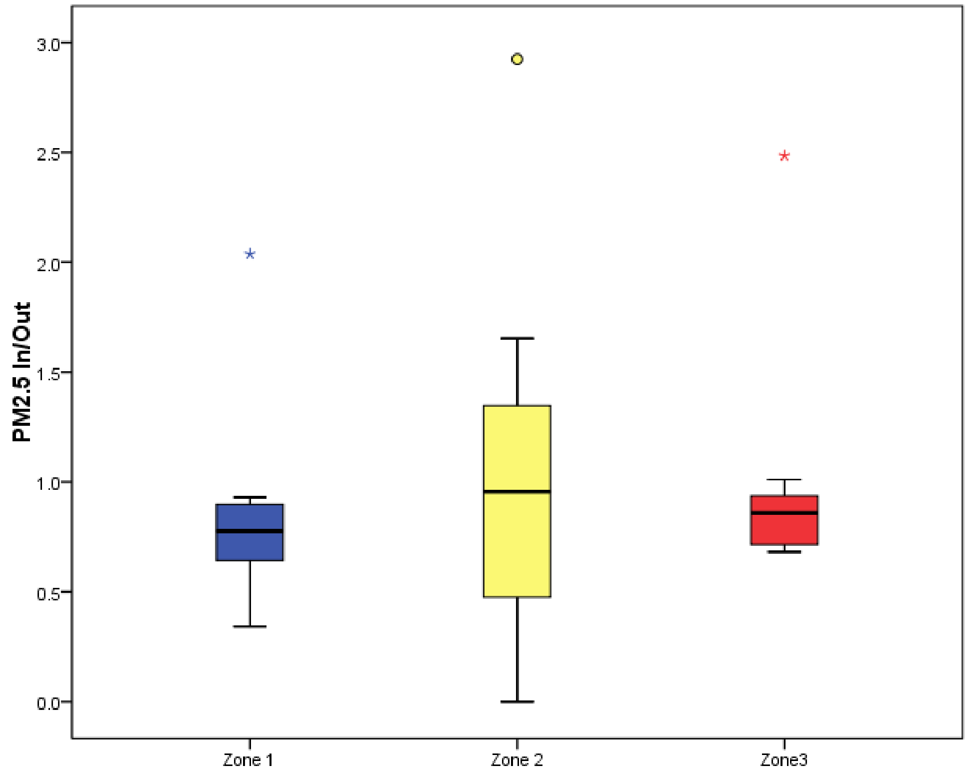


Figure 5.17: $PM_{2.5}$ Indoor/outdoor boxplots at the schools

Weekly $PM_{10\text{-}2.5}$ Indoor-Outdoor Ratios

The time series, descriptive statistics, and boxplots for the $PM_{10\text{-}2.5}$ school I/O ratios are shown in Figure 5.18, Table 5.15, and Figure 5.19 respectively. Mean I/O ratios for Zone 1 were the highest at 1.7 (1.0) followed by Zone 3 0.9 (0.3), and Zone 2 0.8 (0.4). Coarse particles have usually lower penetration efficiency and are removed by means of gravitational settling. Occupancy will also have an influence on the re-suspension of previously deposited particles (Blondeau et al, 2005 and Branis et al, 2009). For coarse particles, such as $PM_{10\text{-}2.5}$ ventilation and heating/cooling systems as well as occupancy will greatly influence I/O ratios. Indoor samples at the school in Zone 1 were taken at two classrooms located in the first and third floor, which were probably occupied most of the school-day, hence an I/O of 1.7. Zone 2 had some samples measured at a classroom and others at a conference room for students. Zone 3 had its samples taken at a computer classroom, director's office, and a regular classroom. The

conference room, computer classroom, and director's office probably experienced less student traffic/activity during the day than the classrooms. Although few studies have measured coarse PM exclusively ($PM_{10-2.5}$), the results are consistent with those found by Raysoni et al, (2011) for two schools located in Juárez, (México) with median I/O ratios of 0.80 (0.13-1.25) and 0.67 (0.28-2.88), where the 0.80 was obtained from classroom measurements, subjected to increased student activity and the 0.67 was obtained from measurements at the library. At the same study, the two schools located in El Paso, TX (US) with evaporative coolers had ratios below one at 0.89 (0.38-1.57) and 0.39 (0.09-0.86), with the measurements taken at a computer classroom and library respectively. In another study (Raysoni et al, 2013) $PM_{10-2.5}$ I/O ratios at four schools in El Paso, TX (US) were 0.83 (0.23-2.04) at a computer classroom and 1.09 (0.40-2.38), 0.46 (0.16-1.32), and 0.38 (0.14-1.21) at three libraries. It is evident that coarse particulate matter concentrations vary within the schools and occupancy will have an effect on indoor $PM_{10-2.5}$ levels. Branis et al, (2009) found that $PM_{10-2.5}$ was associated with the number of exercising pupils (correlation coefficient 0.77) at a school gymnasium, indicating that human activity is the main source.

Table 5.15: Descriptive statistics for school $PM_{10-2.5}$ I/O ratios

Statistics	Schools		
	Z1	Z2	Z3
N	10	10	9
Mean	1.7	0.81	0.86
Median	1.6	0.78	0.69
SD	1.0	0.38	0.34
Minimum	0.48	0.30	0.49
Maximum	4.0	1.5	1.5

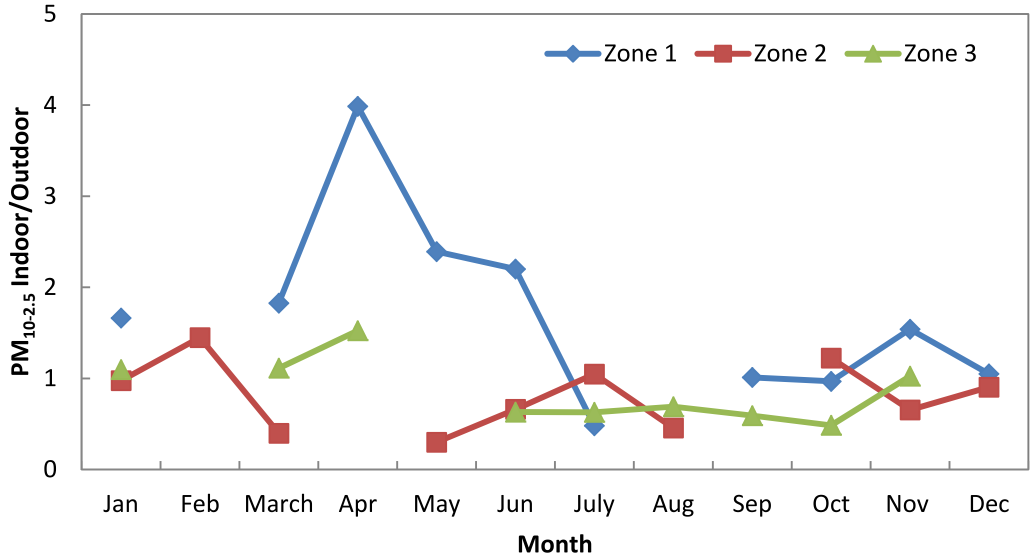


Figure 5.18: $PM_{10-2.5}$ Indoor/outdoor ratios for the monthly averages at the schools

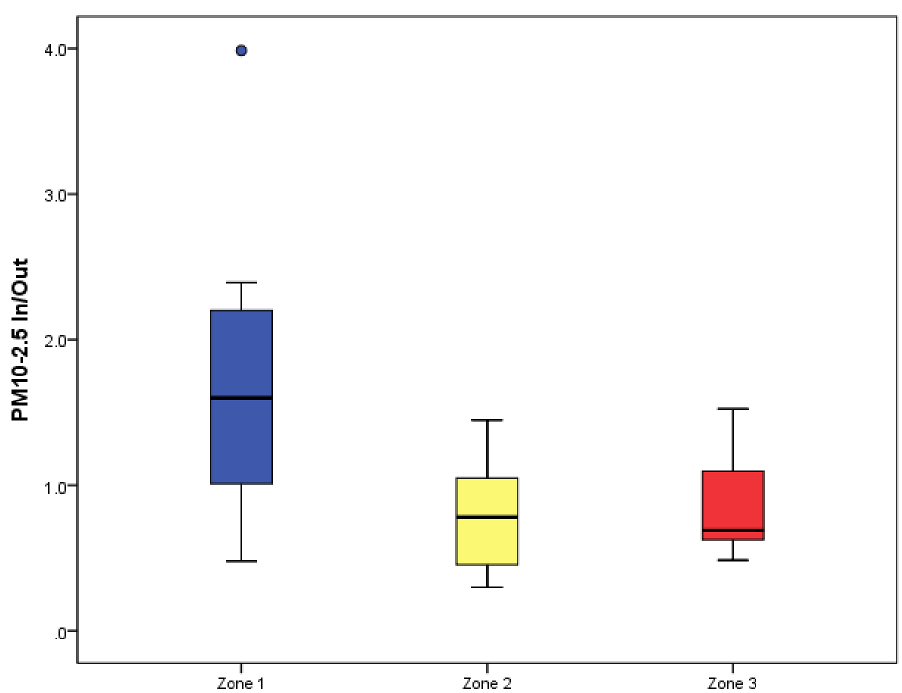


Figure 5.19: $PM_{10-2.5}$ Indoor/outdoor boxplots at the schools

Weekly PM_{10} Indoor-Outdoor Ratios

Table 5.16 and Figures 5.20 and 5.21 display descriptive statistics, time series and boxplots for the school PM_{10} I/O ratios. The highest mean I/O ratio was for Zone 1 at 1.3 (0.63) followed by Zone 3 at 0.98 (0.39) and Zone 2 at 0.95 (0.46). Again, as with $PM_{10-2.5}$, sampling location had an influence on the I/O values for PM_{10} with Zone 1 reflecting greater student activity throughout the day because most of the indoor sampling was conducted at classrooms, while Zones 2 and 3 locations reflect decreased student activity because sampling locations included the director's office, computer classroom, and conference room. However, occupancy and sampling location does not have a strong effect on I/O PM_{10} ratios as it did with $PM_{10-2.5}$ ratios. Other studies reflect similar situations. Raysoni et al, (2011) reported median PM_{10} I/O ratios for the schools in El Paso, TX (US) of 0.89 (0.48-2.05) at the computer classroom and 0.47 (0.26-0.90) at the library, while I/O ratios for the schools in Juárez (México) were 0.77 (0.17-1.15) at the classroom and 0.81 (0.41-2.26) at the library. At a second study in El Paso, TX (US) (Raysoni et al, 2013) I/O ratios were 0.91 (0.33-1.71) at a computer classroom and 1.12 (0.55-2.21), 0.54 (0.23-1.16), and 0.49 (0.22-1.20) at the libraries from three different schools. At a study conducting PM_{10} measurements in Athens, I/O ratios varied between 1 and 2 at the classrooms, 2.46 at a school gymnasium, 1.1 at a computer classroom, and 0.53 at the library, with the library experiencing significant construction activity outside (Diapouli et al, 2008). Monthly average I/O PM_{10} ratios at a school in Delhi, India (Goyal and Khare, 2009) were between 2 and 5 during weekdays and between 1 and 1.5 during the weekends, suggesting that occupancy as well as building envelop will have an influence on indoor PM_{10} concentrations. Indoor PM_{10} concentrations are likely a combination of outdoor sources (infiltrating indoors) and occupancy (causing resuspension).

Table 5.16: Descriptive statistics for school PM_{10} I/O ratios

Statistics	Schools		
	Z1	Z2	Z3
N	9	10	9
Mean	1.3	0.95	0.98
Median	1.0	0.75	0.79
SD	0.63	0.46	0.39
Minimum	0.64	0.52	0.65
Maximum	2.5	2.0	1.8

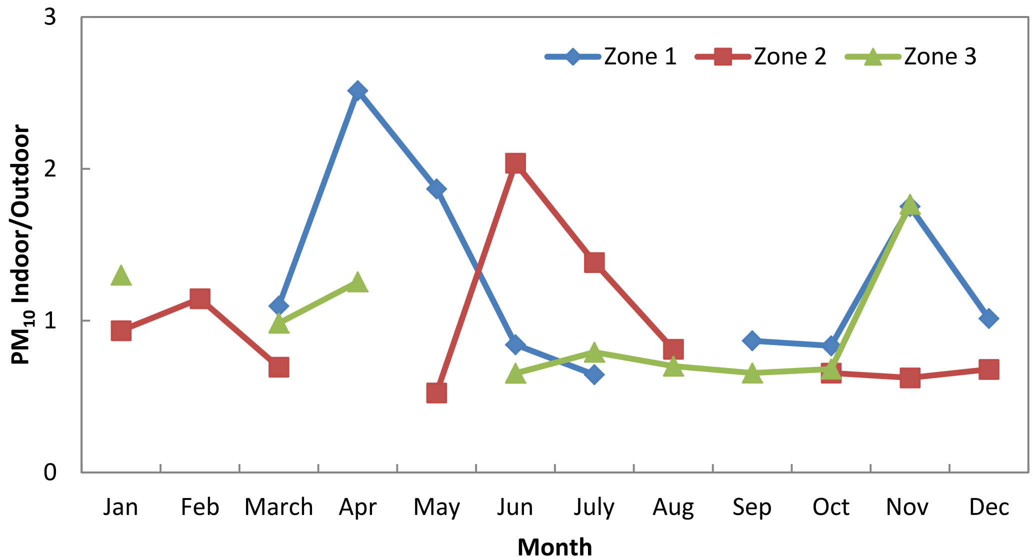


Figure 5.20: PM_{10} Indoor/outdoor ratios for the monthly averages at the schools

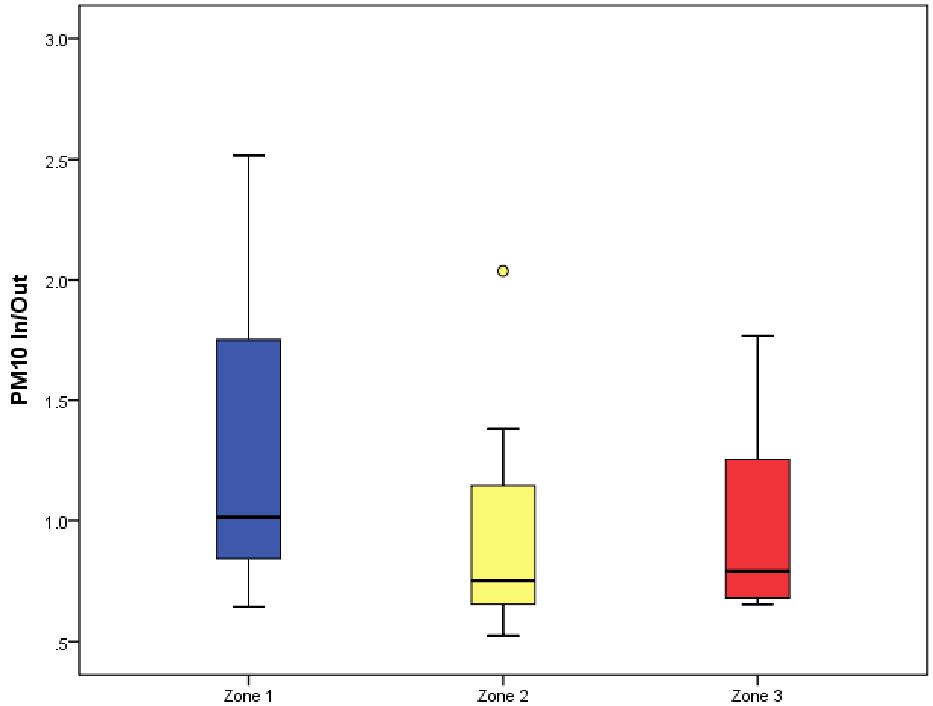


Figure 5.21: PM_{10} Indoor/outdoor box plots at the schools

5.2.4 Residential Sites Indoor/Outdoor Variations

Residential I/O ratios are expected to be larger than school I/O ratios because of a larger number of direct indoor sources at home. Both environments will be influenced by ventilation and building envelop, but at the schools, the most important indoor source will be the resuspension of dust generated by the students and teachers and janitorial activities, whereas at homes indoor pollutant sources include cooking, cleaning, and sweeping, the presence of pets, and resuspension of dust generated by the household's occupants. It is important to note that for this study residences with smokers were excluded.

Weekly $PM_{2.5}$ Indoor-Outdoor Ratios

Table 5.17 and Figures 5.22 and 5.23 shows descriptive statistics, time series, and boxplots for $PM_{2.5}$ I/O residential ratios. Mean residential ratios were the highest for Zone 1 at 2.4 (1.3) followed by

Zone 3 1.6 (1.3), and Zone 2 1.5 (0.43). Residential I/O ratios are higher than school ratios because indoor concentrations at the homes were higher than at the schools. Residential indoor concentrations were also higher than residential outdoor concentrations. Cooking, burning of candles, family activity, household activities, among many other factors are common sources of particulate matter. Although values such as this are not uncommon, they were greater than values encountered in Hong Kong and England. Cao et al, (2005) estimated 24-hr I/O average ratios at 6 homes in Hong Kong between 0.9 and 1.6. A study conducted in 28 homes in Huddersfield, England (Kingham et al, 2000) estimated mean $PM_{2.5}$ I/O ratios much closer to unity at 0.91 ± 1.01. At a study conducted in 7 homes in Birmingham, England (Jones et al, 2000) $PM_{2.5}$ was measured at one home only and the average I/O ratio was 1.0 ± 1.3. Morawska et al, (2001) found average $PM_{2.5}$ I/O ratios at 16 homes in suburban Australia to be 1.08 (1.55-0.76), while Abdel-Salam (2013) found average I/O ratios of 0.84 ± 0.27 at 17 homes in Alexandria, Egypt. It is evident that $PM_{2.5}$ indoor sources at Quito had a greater influence and increased concentrations than $PM_{2.5}$ indoor sources elsewhere.

Table 5.17: Descriptive statistics for residential $PM_{2.5}$ I/O ratios

Statistics	Residences		
	Z1	Z2	Z3
N	12	12	11
Mean	2.4	1.5	1.6
Median	2.0	1.6	1.2
SD	1.3	0.43	1.3
Minimum	0.80	0.88	0.57
Maximum	4.7	2.5	5.3

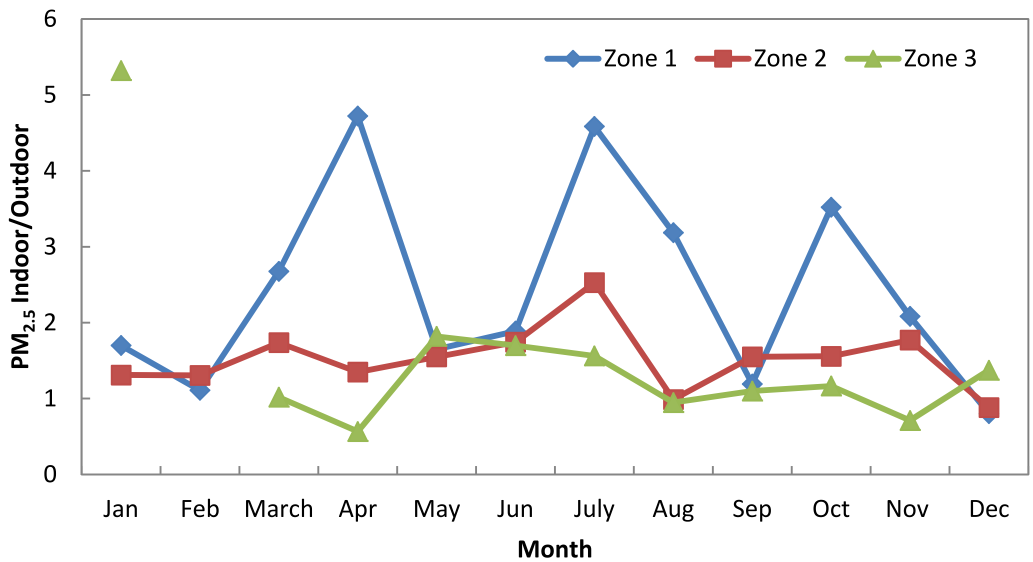


Figure 5.22: $PM_{2.5}$ Indoor/outdoor ratios for the monthly averages at the residences

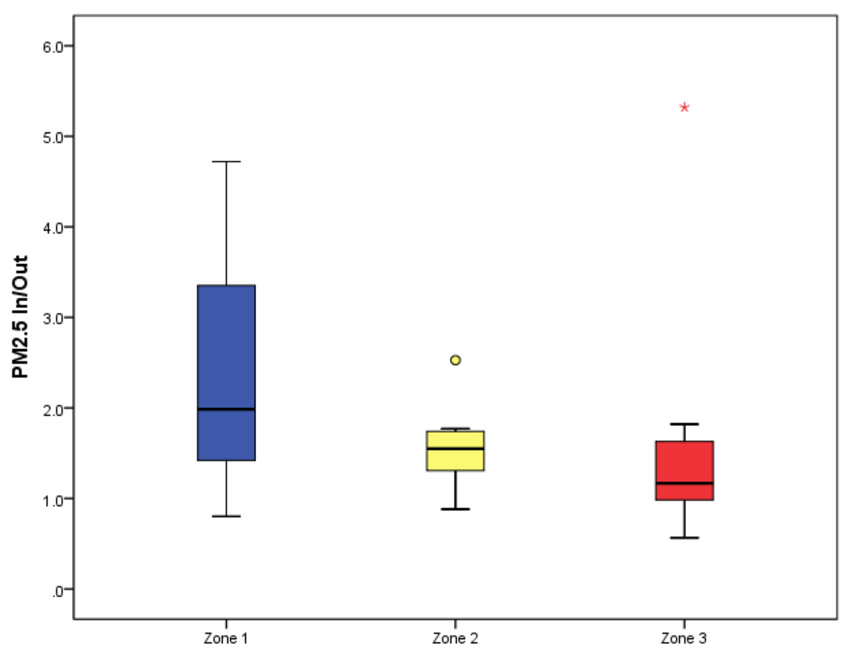


Figure 5.23: $PM_{2.5}$ Indoor/outdoor boxplots at the residences

Weekly $PM_{10\text{-}2.5}$ Indoor-Outdoor Ratios

Table 5.18 and Figures 5.24 and 5.25 show descriptive statistics, time series, and boxplots for $PM_{10\text{-}2.5}$ residential I/O ratios. The mean ratios across the zones are consistent with Zone 2 having the highest mean at 1.6 (0.7), Zone 1 at 1.5 (0.8), and Zone 3 at 1.4 (0.9). Indoor sources for residential coarse PM ($PM_{10\text{-}2.5}$) are less than for fine PM ($PM_{2.5}$) and will be more affected by the family's cleaning and general movements/activity causing resuspension of coarse particles (Jones et al, 2000 and Abdel-Salam 2013). In general, residential I/O ratios for $PM_{2.5}$ were larger than for $PM_{10\text{-}2.5}$, indicating larger concentrations of indoor $PM_{2.5}$ due to infiltration or indoor combustion sources. This result is consistent with the results by Abdel-Salam, 2013 and by Kingham et al, 2000 where they measure $PM_{2.5}$ and PM_{10} only (not $PM_{10\text{-}2.5}$), and they mention that average I/O ratios of $PM_{2.5}$ were higher, indicating the presence of more fine-mode particles indoors coming from combustion-related sources such as cooking.

Table 5.18: Descriptive statistics for residential $PM_{10\text{-}2.5}$ I/O ratios

Statistics	Residences		
	Z1	**Z2**	**Z3**
N	12	12	11
Mean	1.5	1.6	1.4
Median	1.5	1.4	1.0
SD	0.82	0.69	0.89
Minimum	0.42	0.79	0.40
Maximum	2.8	2. 8	3.3

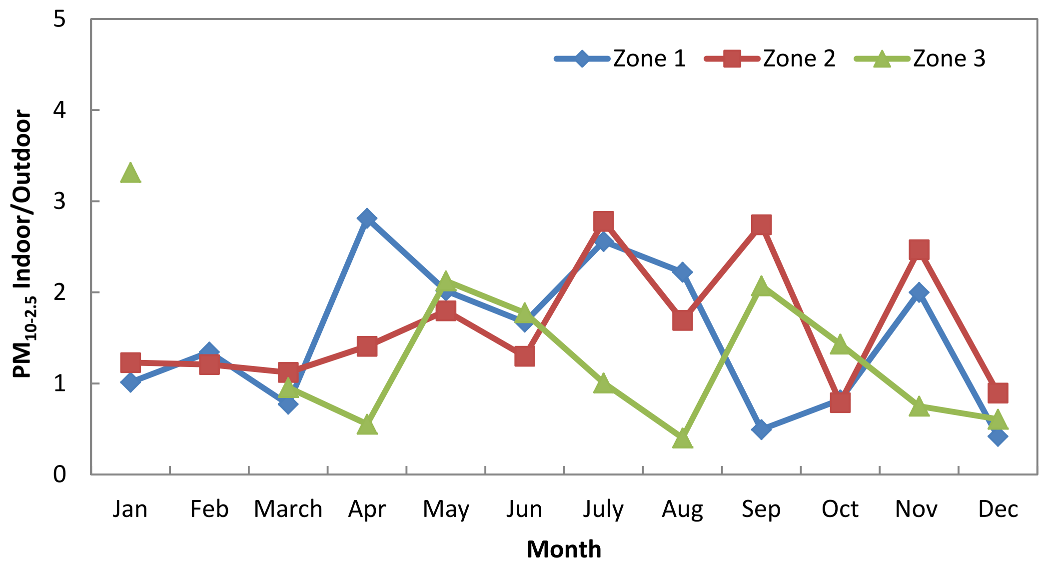


Figure 5.24: $PM_{10-2.5}$ Indoor/outdoor ratios for the monthly averages at the residences

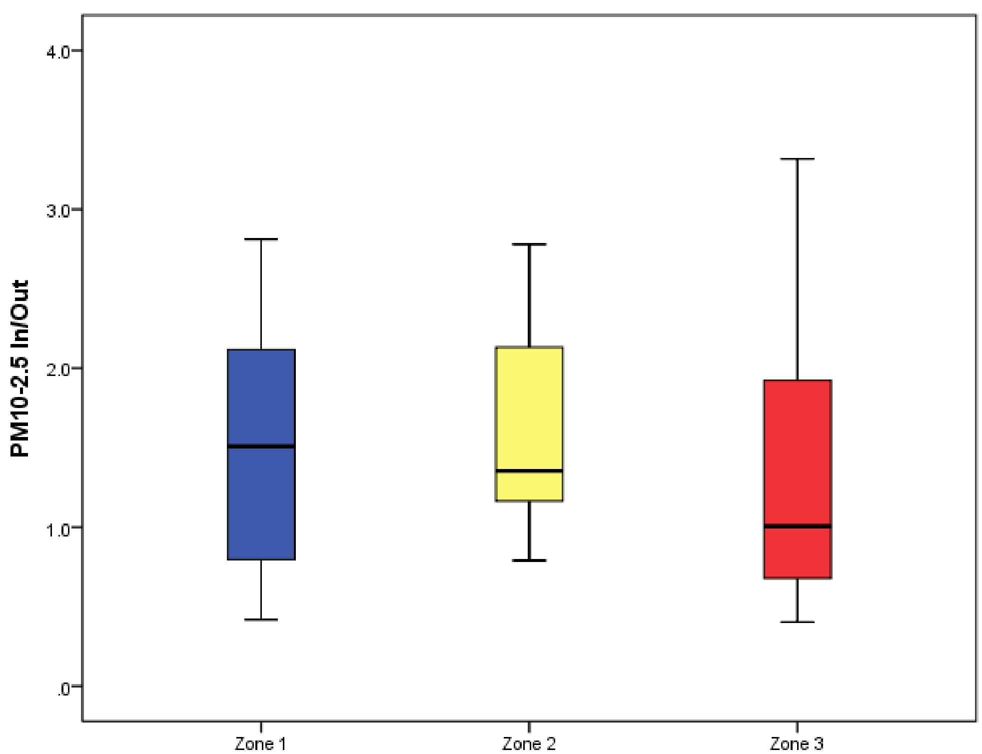


Figure 5.25: $PM_{10-2.5}$ Indoor/outdoor boxplots at the residences

Weekly PM_{10} Indoor-Outdoor Ratios

Table 5.19 and Figures 5.26 and 5.27 show descriptive statistics, time series, and boxplots respectively for residential PM_{10}. Zone 1 had the highest mean I/O ratio 2.0 (1.0), followed by Zone 2 at 1.6 (0.4), and Zone 3 at 1.5 (1.2). As stated in the $PM_{10-2.5}$ size fraction, indoor coarse PM will be strongly influenced by the activity of its occupants, more so than fine PM. Wallace (1996) estimated that the penetration of outdoor PM_{10} and $PM_{2.5}$ indoors is similar, but because of the higher settling velocity, the I/O ratio for PM_{10} is expected to be smaller than for $PM_{2.5}$. For this study, I/O ratios for PM_{10} are smaller than I/O ratios for $PM_{2.5}$. However, I/O ratios for PM_{10} are larger than I/O ratios for $PM_{10-2.5}$, because PM_{10} contains the $PM_{2.5}$ size fraction and $PM_{10-2.5}$ does not. Kingham et al, (2000) found I/O PM_{10} ratios of 1.04 ± 0.81 at 27 homes in Huddersfield, England. Monn et al, (1997) found PM_{10} I/O ratios varying between 0.67-2.07 at 17 homes in Switzerland. In Alexandria, Egypt (Abdel-Salam, 2013) average PM_{10} I/O ratio was much lower than at Quito, Huddersfield, or Switzerland at 0.65 ± 0.18. Jones et al, (2000) found mean PM_{10} I/O ratios at 11 homes between 1.0 and 3.9. Indoor/outdoor PM_{10} ratios from Quito were similar to those found in Switzerland, were the homes were all naturally ventilated similar to Quito. The presence of people (occupancy) and housework activities will likely have a stronger influence in the resuspension and indoor concentration of particles greater than 2.5 µm (Jones et al, 2000 and Abdel-Salam, 2013).

Table 5.19: Descriptive statistics for residential PM_{10} I/O ratios

Statistics	Residences		
	Z1	Z2	Z3
N	12	12	11
Mean	2.0	1.6	1.5
Median	1.8	1.5	1.2
SD	1.0	0.41	1.2
Minimum	0.61	1.3	0.56
Maximum	3.8	2.6	4.8

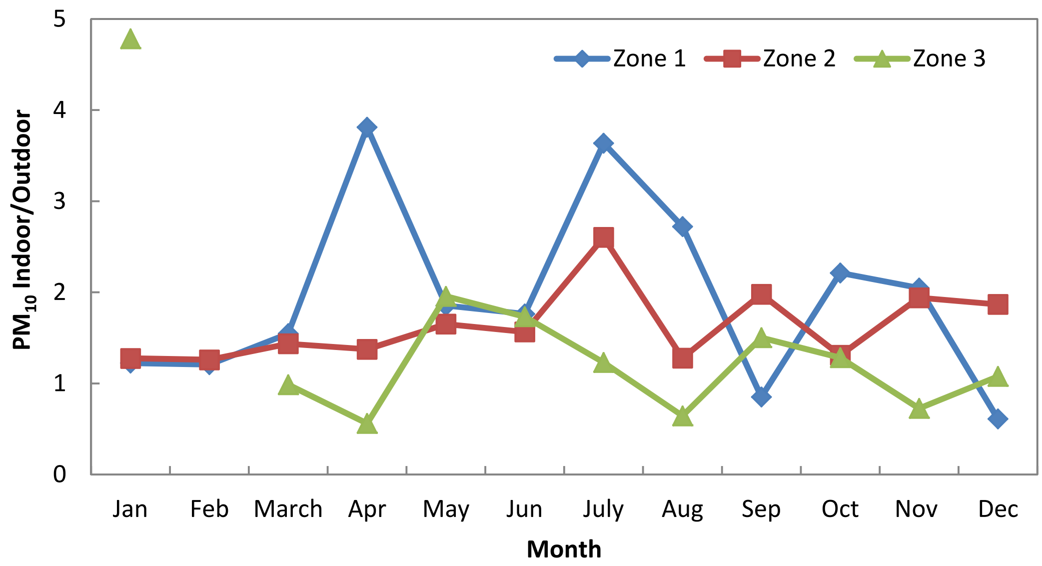


Figure 5.26: PM_{10} Indoor/outdoor ratios for the monthly averages at the residences

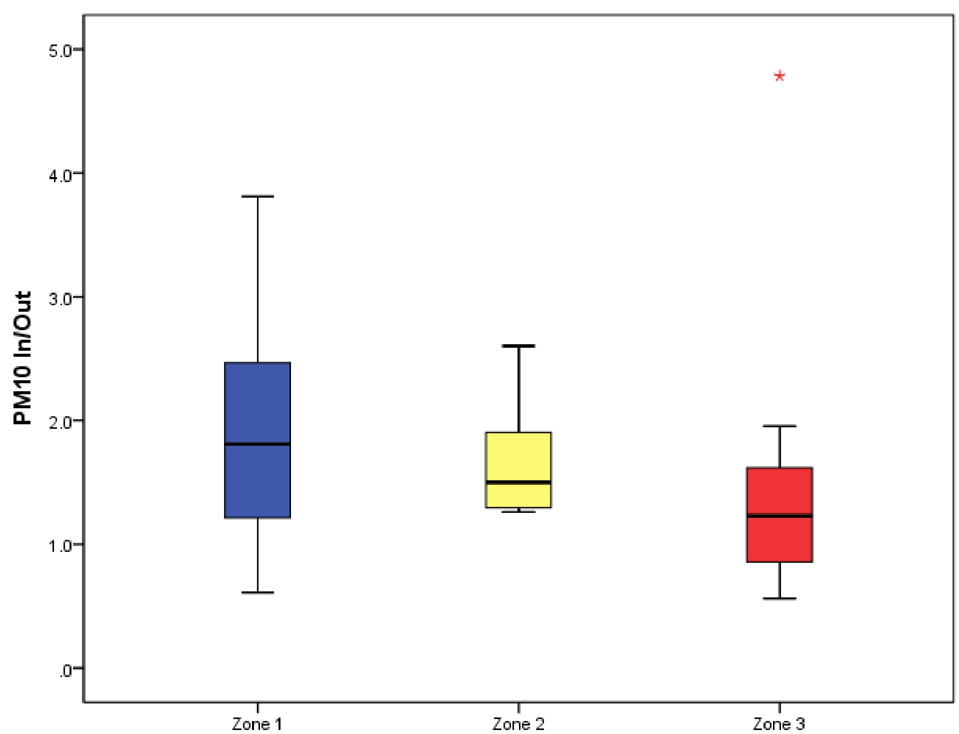


Figure 5.27: PM_{10} Indoor/outdoor boxplots at the residences

5.2.4 School Indoor-Outdoor Pollutant Correlations

Correlations between paired indoor-outdoor data at the schools are computed to inspect the linear relationship between both microenvironments. Figures 5.28, 5.29, and 5.30 represent $PM_{2.5}$, $PM_{10-2.5}$, and PM_{10} respectively and each contain three graphs, one for each zone. Each graph also has a dashed line representing 1:1 relationship (zero intercept). The R^2 values for $PM_{2.5}$ range from the weakest in Zone 2 (0.076) to the strongest in Zone 3 (0.87). For $PM_{10-2.5}$ R^2 values are 0.016 for Zone 2 and 0.50 for Zone 3. For PM_{10}, R^2 values ranged from 0.08 in Zone 1 to 0.74 in Zone 3. Indoor-to-outdoor concentrations were better correlated for Zone 3 (low exposure) than for Zones 1 and 2 in part because the outdoor samplers for Zone 3 were placed right outside of the classroom that was being sampled.

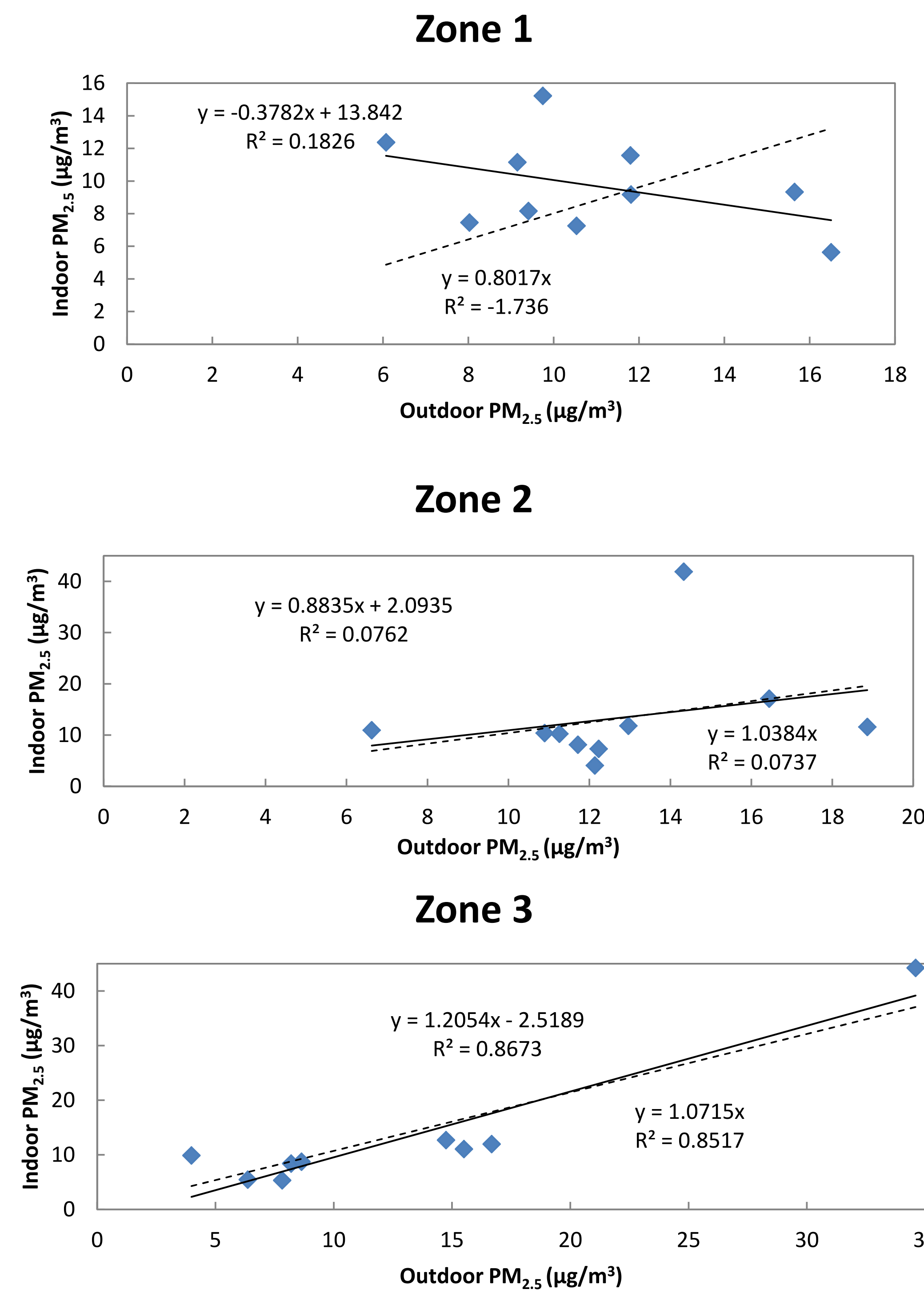
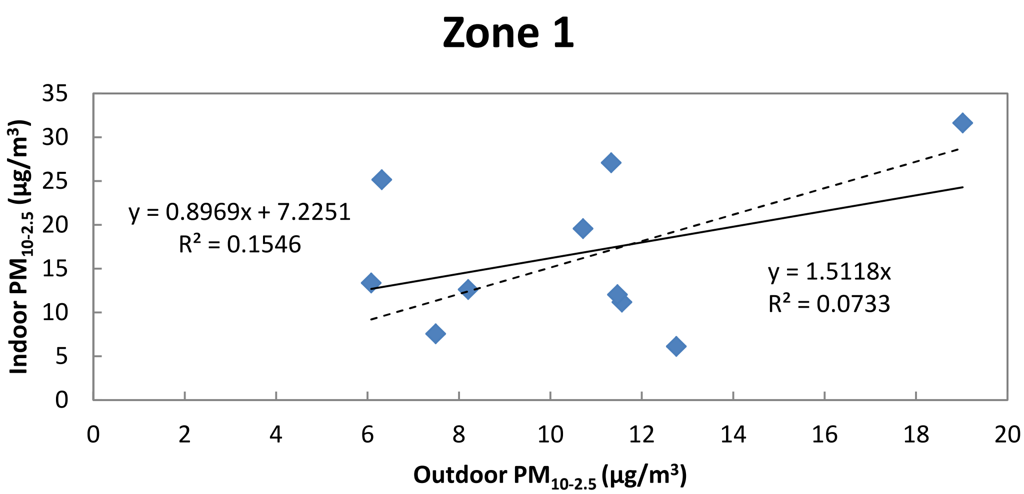
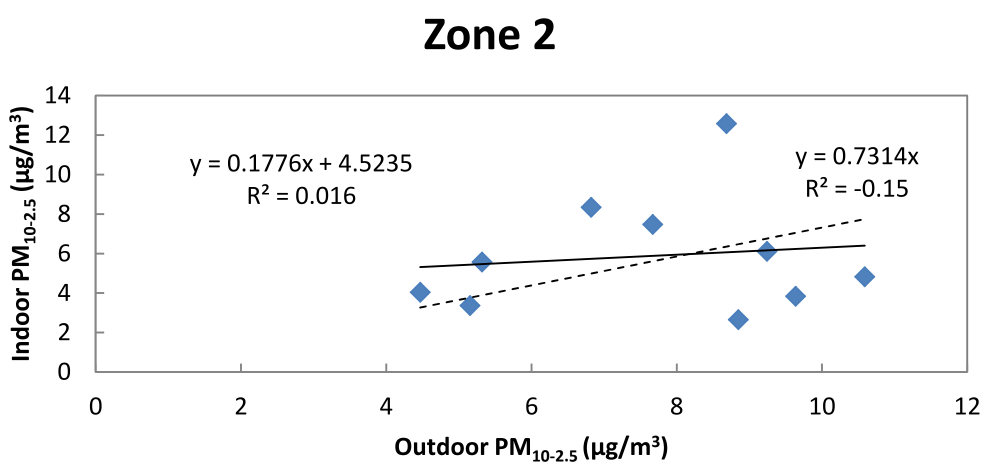


Figure 5.28: School indoor concentrations as a function of outdoor concentrations for $PM_{2.5}$





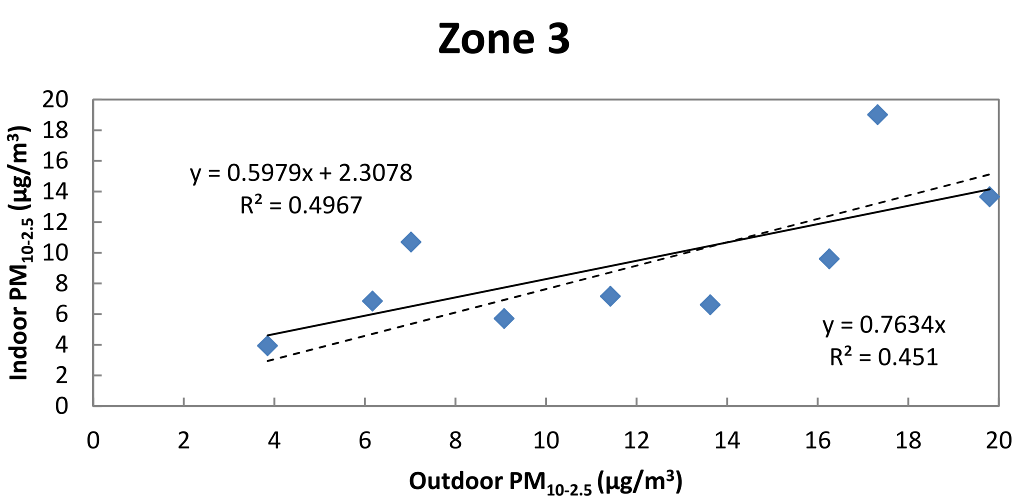


Figure 5.29: School indoor concentrations as a function of outdoor concentrations for $PM_{10-2.5}$

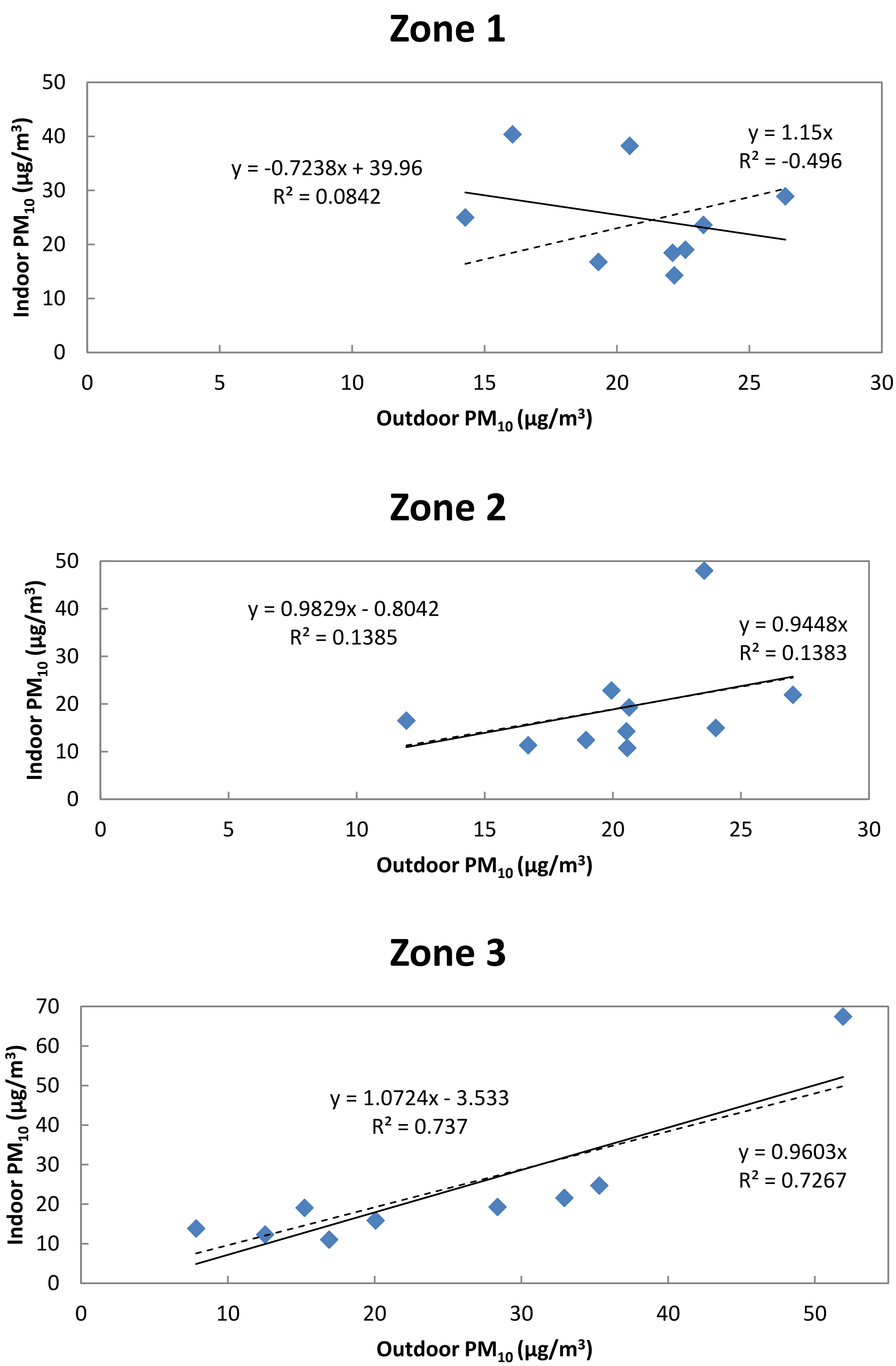


Figure 5.30: School indoor concentrations as a function of outdoor concentrations for PM_{10}

5.2.5 Residential Indoor-Outdoor Pollutant Correlations

Indoor-outdoor residential correlations are shown in Figures 5.31, 5.32, and 5.33 for $PM_{2.5}$, $PM_{10-2.5}$, and PM_{10}, each figure containing three graphs, one per zone. Note that although the indoor-outdoor measurements were conducted within the same zone concurrently, they were not conducted right outside the same residence all the time. Each graph also has a dashed line representing 1:1 relationship (zero intercept). The R^2 values for indoor-outdoor $PM_{2.5}$ ranged from 0.0014 in Zone 3 to 0.48 in Zone 2. For $PM_{10-2.5}$ R^2 values ranged from 0.0002 in Zone 1 to 0.13 in Zone 3. For PM_{10}, R^2 values ranged from 0.05 in Zone 3 to 0.06 in Zone 2. Less consistency was found across the correlations at the residences when compared to the school correlations, but this would be expected since the indoor-outdoor locations varied at the residences but were kept the same at the school, and there is just greater variability among the pollutant levels at the residences than at the schools, indoor pollutant levels at the residences were usually much higher and influenced by many different factors and sources (cooking, cleaning, ventilation, among others), than their outdoor counterparts.

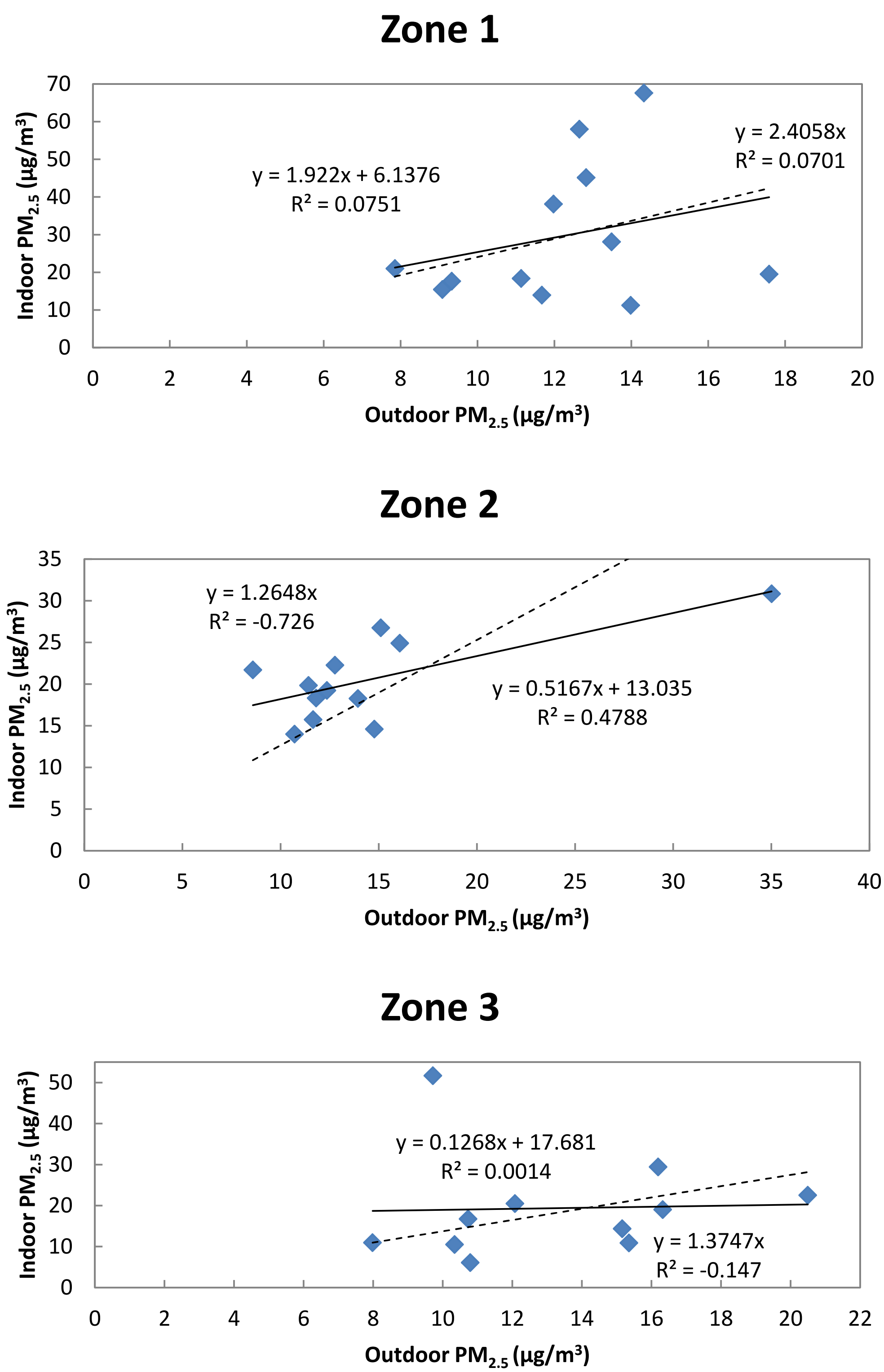
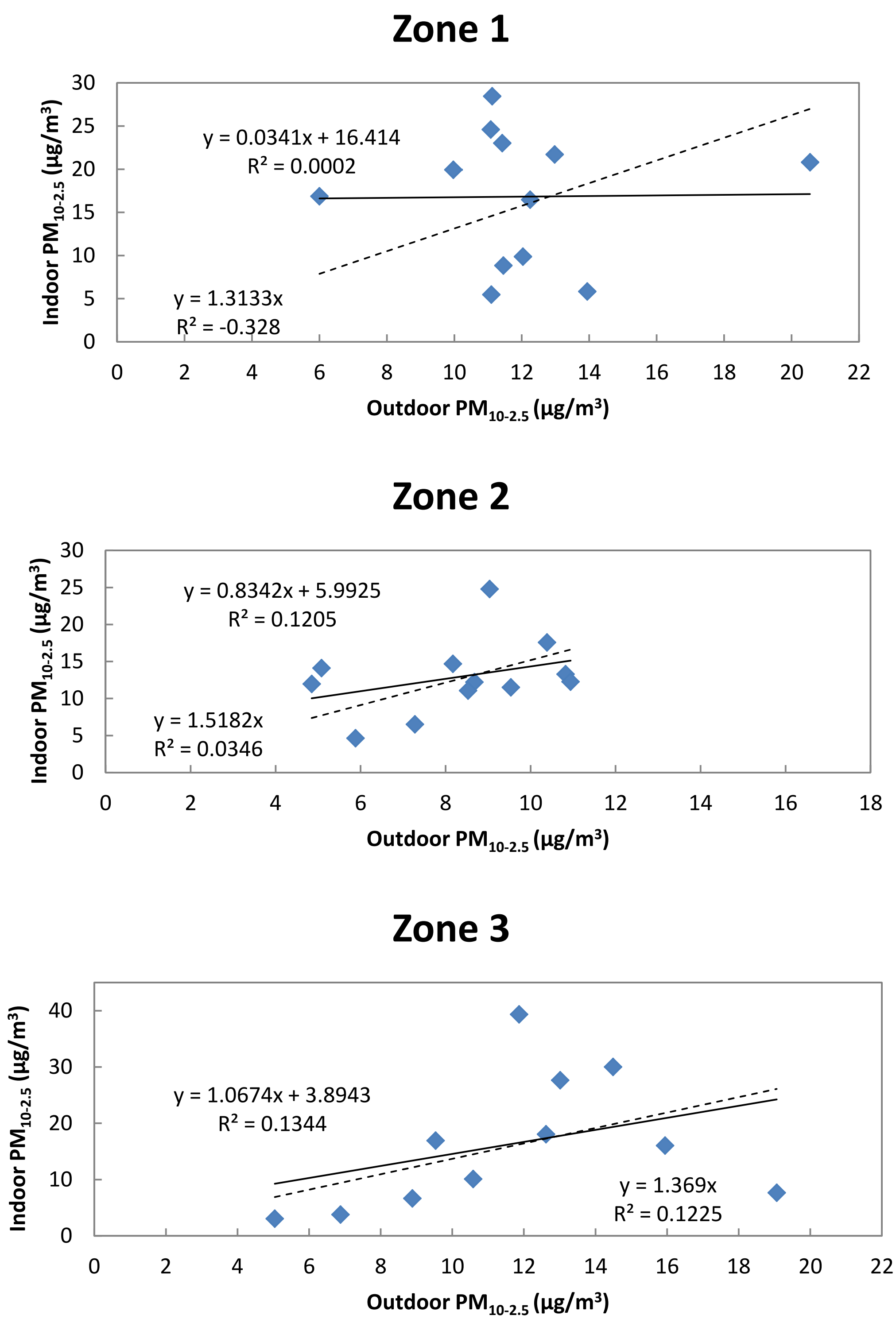
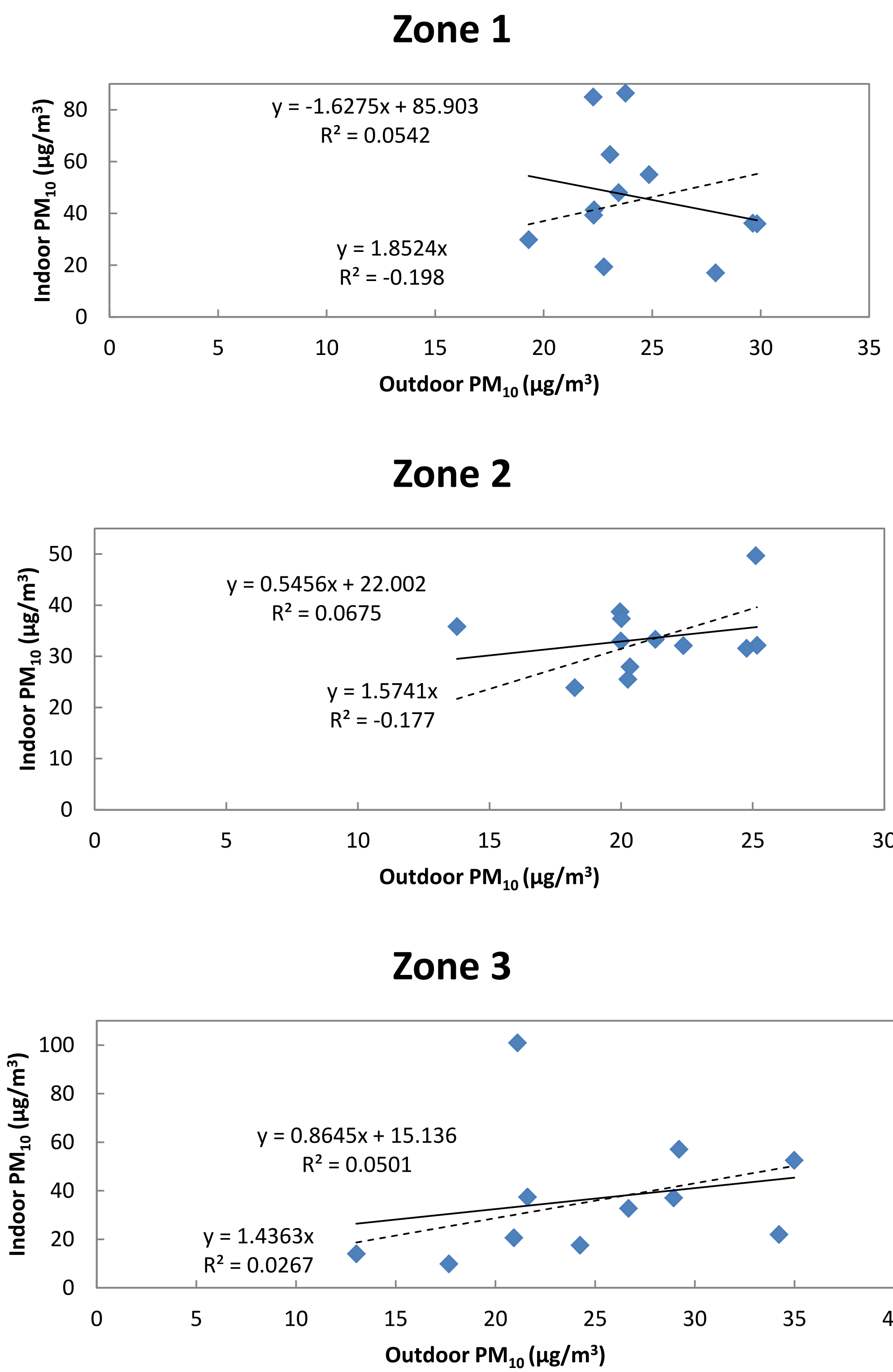


Figure 5.31: Residences indoor concentrations as a function of outdoor concentrations for $PM_{2.5}$



Figures 5.32: Residences indoor as a function of outdoor concentrations for $PM_{10\text{-}2.5}$



Figures 5.33: Residences indoor concentrations as a function of outdoor concentrations for PM_{10}

5.2.6 Spatial and Temporal Variability between the Sites

Spatial variability in this research was assessed by pairwise coefficients of divergence (COD) and by Spearman correlations. A small COD (r < 0.2) indicates similar concentrations between two sites, whereas a value approaching one indicates spatial non-uniformity between the sites (Pinto et al, 2004; Sarnat et al, 2010). COD has been used as a complementary measure to correlation analysis to characterize spatial patterns of particulate matter in several multi-site comparative analyses (Sarnat, et al. 2010). The COD provides degree of uniformity between simultaneously sampled sites, j and k by using the following equation:

$$COD_{i,k} = \sqrt{\frac{1}{n}\sum_{i-1}^{p}\left[\frac{x_{i,j}- x_{i,k}}{x_{i,j}+ x_{i,k}}\right]^2} \qquad \text{(Equation 5.5)}$$

where $x_{i,j}$ is the concentration measured at site j over the sampling period and n is the number of observations.

Correlation coefficients reflect temporal similarity of paired sites, whether the concentrations vary at the same rate (Pinto et al., 2004, Wilson et al., 2005, Raysoni, 2011). Correlation coefficients range between -1 and +1, with a +1 indicating a perfect direct relationship between two variables, meaning that they increase or decrease proportionally while a -1 indicates a perfect indirect relationship, meaning that as one variable increases, the other one decreases. Spearman correlations were computed to analyze the relationship between the indoor-outdoor measurements and school-residences measurements.

Coefficients of Divergence

Tables 5.20 and 5.21 show the results from the COD calculations. Focusing on the CODs for the schools/indoor, there was slight intra-city spatial variability between Zone 1 and Zone 3 for both $PM_{2.5}$ (0.23) and PM_{10} (0.28); greater heterogeneity was seen in that location and microenvironment between Zones 1-2, and Zones 3- 2, with CODs ≥ 0.30 for all pollutants. There was very slight intra-city spatial

variability for the measurements at the schools outdoors across all pollutants where COD were between 0.20 and 0.30 for all zones and pollutants, except for PM_{10} between Zone 1 and 2 where the COD = 0.17. Indoor microenvironments, even at the schools where no major indoor PM sources are present (except for student/teacher traffic, ventilation practices), are expected to have greater variability because of the many factors that can vary from place to place and will have an influence on particulate matter concentrations, whereas outdoor microenvironments within a certain zone are expected to be influenced by similar factors.

Looking at the CODs for the residences/indoor, greater spatial variability was seen across all pollutants and between all the zones with CODs ≥ 0.30, except for $PM_{2.5}$ at Zone 1 and Zone 2 (COD = 0.29). Slight to no spatial variability was observed at the residences outdoor, with CODs < 0.26. As with the schools, greater spatial variability was seen indoors than outdoors. This is expected due to the variability in residential indoor particulate matter sources. Residence/outdoor COD values were mostly below 0.2, indicating slight spatial variability between the zones, expected in the outdoor microenvironment. However, for the most part COD values were greater than 0.2 indicating the existence of intra-city spatial variability across all pollutants and zones in the city of Quito, Ecuador.

Table 5.21 shows the COD comparing PM levels measured at the schools and at the residences within the same zone. Indoor COD are all greater than 0.2 indicating heterogeneity at the indoor environments within each zone. Indoor microenvironments at the residential sites will have greater amount of PM sources (cooking, cleaning, vacuuming, among others) than indoor microenvironments at the schools. However, outdoor COD between school and residences are less than or very close to 0.2, indicating homogeneity within each zone. Outdoor sources at schools and residences, within the same zone, are less likely to vary between each other.

Table 5.20: Coefficients of divergence (CODs) for the monitored pollutants

		Schools		Residences	
Pollutant	**Zone**	**Indoor**	**Outdoor**	**Indoor**	**Outdoor**
$PM_{2.5}$	**Z1-Z2**	0.30	0.24	0.33	0.19
	Z1-Z3	0.23	0.24	0.44	0.16
	Z2-Z3	0.39	0.30	0.30	0.21
$PM_{10-2.5}$	**Z1-Z2**	0.49	0.29	0.29	0.24
	Z1-Z3	0.39	0.22	0.40	0.20
	Z2-Z3	0.30	0.27	0.36	0.26
PM_{10}	**Z1-Z2**	0.35	0.17	0.30	0.13
	Z1-Z3	0.28	0.20	0.41	0.16
	Z2-Z3	0.30	0.27	0.31	0.17

Table 5.21: Coefficients of divergence between school and residence concentrations

Pollutant	**Indoor**			**Outdoor**		
	Z1S-R	**Z2S-R**	**Z3S-R**	**Z1S-R**	**Z2S-R**	**Z3S-R**
$PM_{2.5}$	0.47	0.37	0.33	0.21	0.16	0.29
$PM_{10-2.5}$	0.33	0.42	0.42	0.14	0.10	0.18
PM_{10}	0.37	0.35	0.36	0.12	0.06	0.24

Indoor-Outdoor Spearman Correlations

Spearman correlations were computed to determine the relationships between indoor-outdoor concentrations as shown in Table 5.22. Significant correlations at the p=0.05 level are shown in bold. Significant correlations at the p=0.01 level are shown bold and italicized. Significant correlations were found for the school at Zone 3 for $PM_{2.5}$ (r=0.767, p<0.05), $PM_{10-2.5}$ (r=0.700, p<0.05), and PM_{10} (r=0.850, p<0.01) indicating that at the school in Zone 3 indoor and outdoor PM levels were strongly correlated. This was also observed in the linear relationships presented in Figures 4.28-4.30, that could

be in part to the close proximity between the indoor and outdoor microenvironment. Indoor-outdoor correlations for the rest of the zones and environments (schools or residences) were weak.

Table 5.22: Spearman correlation coefficients between indoor-outdoor concentrations

	School						**Residences**					
	Z1		**Z2**		**Z3**		**Z1**		**Z2**		**Z3**	
	r	**p**	**r**	**p**	**r**	**p**	**r**	**p**	**r**	**p**	**r**	**p**
$PM_{2.5}$	-0.345	0.328	0.503	0.138	**0.767**	**0.016**	0.315	0.319	0.517	0.085	0.282	0.401
$PM_{10-2.5}$	-0.055	0.881	-0.006	0.987	**0.700**	**0.036**	-0.168	0.602	0.357	0.255	0.536	0.089
PM_{10}	-0.183	0.637	0.394	0.260	***0.850***	***0.004***	-0.140	0.665	0.007	0.983	0.536	0.089

School-Residences Spearman Correlations

Spearman correlations were also computed to determine the relationships between concentrations measured at the schools and residences and are shown in Table 5.23. Significant correlations were found outdoors in Zone 2 across all pollutants ($r=0.836$, $p<0.01$ for $PM_{2.5}$; $r=0.682$, $p<0.05$ for $PM_{10-2.5}$ and PM_{10}) and at Zone 3 for $PM_{10-2.5}$ ($r=0.745$, $p<0.05$). Outdoor exposures for zone 1 (across all PM) and for zone 3 (for $PM_{2.5}$ and PM_{10}) correlations were weak, indicating that PM exposures outdoor schools vary differently (increase and decrease differently) from PM exposures outside the homes, even though spatial variability (concentration levels, as indicated in Table 5.21) is similar. Indoor correlations across all the zones were weak, indicating that PM exposures inside the schools are very different from PM exposures inside the home, concurrent with the results from Table 5.21, that is, not only are PM levels different inside schools and residences (as indicated by the COD), but they also vary differently (as indicated by the Spearman Correlation).

Table 5.23: Spearman correlation coefficients between school-residences concentrations

	Indoor						Outdoor					
	Z1		Z2		Z3		Z1		Z2		Z3	
	r	p	r	p	r	p	r	p	r	p	r	p
$PM_{2.5}$	-0.105	0.746	-0.009	0.979	0.345	0.328	-0.430	0.214	***0.836***	***0.001***	0.055	0.881
$PM_{10-2.5}$	-0.021	0.948	-0.391	0.235	0.236	0.511	0.479	0.162	**0.682**	**0.021**	**0.745**	**0.013**
PM_{10}	-0.196	0.542	-0.200	0.555	0.309	0.385	0.000	1.000	**0.682**	**0.021**	0.406	0.244

5.3 Conclusion

This chapter presented the analysis conducted on the field samples and a discussion of the results obtained. It presents the work done under research task No. 2 (Describe and quantify exposure levels at three different zones in Quito utilizing data collected from the monitoring phase of the study). The points from this analysis are the following:

- Concentration levels for the different size fraction of particulate matter did not always agree with our pre-defined exposure zones. Pre-defined exposure zones were based on central monitor data and traffic patterns. Higher traffic and higher ambient (central monitor) concentrations meant higher exposure. However, the location of the central monitor does not necessarily reflect true exposure, it will be dependent upon the type of pollutant, ventilation rates (for indoor exposure), meteorology, season, and local sources (Raysoni et al, 2013; Sarnat et al, 2000; Sarnat et al, 2010; Rodes et al, 2010; Mejia et al, 2011).
- Indoor and outdoor concentrations and magnitude of the differences across the zones were found to be strongly dependent on the size fraction being studied and microenvironment. Within a zone, concentration levels at the residential sites were higher than concentration levels at the schools, signaling that the higher exposure for children is occurring at the home level. The difference between school and residential concentrations was larger at the indoor

microenvironment and for fine particulate matter ($PM_{2.5}$) more so than for coarse particulate matter ($PM_{10-2.5}$).

- Although indoor PM levels can vary significantly because of the particular activities taking place, sources present, amount of ventilation, among others, outside sources still played a strong role in explaining the concentration levels collected at each microenvironment.
- Zone 2 usually had the highest levels for $PM_{2.5}$ at both indoor and outdoor microenvironments. However, Zones 1 or 3 usually had the highest levels for $PM_{10-2.5}$, evidence that Zone 2 is dominated by the fine PM fraction ($PM_{2.5}$) because of its high amount of traffic, whereas Zones 1 and 3 have moderate to low traffic, but are strongly influenced by higher levels of coarse PM fraction ($PM_{10-2.5}$) a result of dust resuspension from unprotected surfaces including unpaved roads ad quarries. In the case of PM_{10} exposure levels were altered because of the nature of the pollutant, meaning that PM_{10} combines both fine and coarse fraction, having the influence of both traffic emissions and dust resuspension.
- I/O ratios were close to unity at the schools showing the strong influence of outdoor sources to indoor concentrations, attributable to minimal indoor sources, lack of central heating and air conditioning, and weather that allowed for similar ventilation patterns all year long. I/O ratios were between 1-2 for residential sites indicating the presence of indoor sources including cooking, cleaning, presence of pets, and resuspension of dust because of other activities. When comparing I/O ratios of the residential sites in Quito, from the residential sites in other parts of the world, Quito's were among the largest, taking into account that smoking was not included in the residences, implies that traditions and way of life creates the strongest exposure for Ecuadorian children inside their home.
- This chapter analyzed part of the second hypothesis posted in this study stating that indoor PM exposure for children both at school and home is associated with PM collected outdoors. Indeed, in an environment such as Quito's with uniform temperatures throughout the year and ventilation, outdoor sources will influence indoor sources, especially at school. However, in

places with significant indoor sources, such as residential sites, outdoor measurements will not act as good surrogates for indoor exposures.

Chapter 6: Central Monitoring and Site Monitoring

Central monitoring is used widely as a way to measure exposure levels of air pollutants in a community and especially to evaluate compliance with established air pollutant standards. Quito's current central monitoring network initialized its operation since 2003. In 2008, the U.S. EPA published a document reviewing Quito's air quality network saying that "the monitoring system was accurate and well-implemented" and that the network appeared to have been operating successfully for the last five years (USEPA, 2008). However, central monitors are not always the best method to measure personal exposures (Sarnat et al., 2000; Sarnat, et al., 2005; Janssen, et al., 2000; Williams, et al., 2003; Brown, et al., 2009; Rodes, et al., 2010; Raysoni et al, 2011; Mejia et al, 2011) and strong associations between personal exposures and ambient data will depend on the geographical location, meteorology, season, particle cut-size, and local sources. Well-ventilated indoor environments will show stronger associations between ambient concentrations and personal exposures (Sarnat et al, 2000). Quito's yearlong cool, spring-like weather allows for the use of natural ventilation throughout the entire year. Residential sites reported having windows open for an average of 2-hours each day. School's particulate matter I/O ratios were very close to unity, indicating similar concentration levels in both microenvironments. However, Quito's topography will have a strong influence on concentration levels recorded from one site to another. In addition, it is important to evaluate the role of meteorology and co-pollutant data on particulate matter concentration levels. Strong correlations among pollutants will become important when determining their relative contribution to a specific health risk, as they may have confounding effects between each other, so it becomes important to recognize and account for this effect to accurately describe if a specific pollutant poses a health risk (Sarnat et al, 2005).

This chapter presents the analysis between central monitoring and site (school and residences) data. The analysis includes an evaluation between particulate matter data collected in both ambient and site monitors, as well as an evaluation of the influence between meteorological and co-pollutant data collected at a central monitor with particulate matter levels collected from site monitors. The first section presents the correlation analysis between meteorological factors and co-pollutants collected from central monitors and particulate matter site monitoring. Section 6.2 presents the spatial variation

between particulate matter collected at central monitors and at the sites. Section 6.3 presents inter-zone variations among the residential sites. The discussion in this chapter will help us understand the role of central monitors in representing true exposure of the population in Quito. Particulate matter levels collected from central monitors and site monitors are reported to local conditions.

6.1 Correlation Analysis

Hourly meteorological and co-pollutant data collected from ambient monitors were averaged to match the 7-day monitoring periods (in each zone and each month) and correlated with particulate matter measurements at the indoor and outdoor microenvironments. Results are separated by site (school vs. residence). Significant Spearman correlations at the α=0.05 are shown in bold; significant correlations at the α=0.01 are shown in bold and italicized. Correlation coefficients do not reflect spatial variability, but rather temporal similarity between the sites. A correlation coefficient close to +1 indicates a direct relationship between two variables, meaning that they increase or decrease proportionally while a -1 indicates an indirect relationship, meaning that as one variable increases, the other one decreases. A high temporal correlation between two sites indicates that changes in concentrations at one site may be estimated from data collected at another site (EPA Vol. I).

6.1.1 Indoor PM Measurements and Ambient Monitors

School Indoor and Ambient Monitors

Table 6.1 shows the Spearman correlation coefficients of the school indoor measurements and ambient meteorology and co-pollutant measurements. For the most part, no significant correlations were found between $PM_{2.5}$ data and meteorological factors and only one significant correlation was found between $PM_{2.5}$ and SO_2 (r=0.66). Sarnat et al. (2002) demonstrated that because indoor microenvironments lack sulfur sources, indoor sulfur concentrations were strongly associated with outdoor levels and sulfur compounds have been used to estimate $PM_{2.5}$ of outdoor origin. Most of the school indoor $PM_{2.5}$ at Quito can be attributed to outdoor infiltration because of lack of indoor sources.

For $PM_{10-2.5}$ and PM_{10}, significant correlations were found at Zone 1 with temperature (r=0.69 and r=0.62) and solar radiation (r=0.60 and r=0.59). This effect can be attributed to thermal diffusion, with higher outside temperatures, pollutants are pushed indoors, while the vice versa takes place with a lower outdoor temperature (Chan 2002). Correlation between the rest of the school indoor parameters and co-pollutant data measured by a central monitor were weak. Even though traffic is a common source for some of the co-pollutants listed (e.g. CO and NO_2) and $PM_{2.5}$, the level of traffic emissions collected by the ambient monitor is different from the levels collected by the school indoor monitors.

Table 6.1: Spearman correlations between school indoor PM levels and ambient measurements

School Indoor Msmts.	Zone	Central Monitors									
		WV	T	RH	SR	P	$PM_{2.5}$	CO	NO_2	SO_2	O_3
$PM_{2.5}$	Z1	-0.04	0.25	0.12	0.34	0.06	0.54	0.42	0.0	0.13	-0.31
	Z2	-0.21	-0.01	-0.12	0.11	-0.02	0.55	0.18	0.06	**0.66**	-0.13
	Z3	0.47	-0.02	-0.41	0.55	-0.37	-	-	-	-	0.45
$PM_{10-2.5}$	Z1	0.15	**0.69**	-0.24	**0.60**	-0.50	0.36	0.42	-0.49	0.05	-0.33
	Z2	0.38	0.35	-0.18	0.45	-0.43	-0.46	-0.10	-0.60	-0.26	-0.05
	Z3	0.39	0.31	-0.30	0.12	0.24	-	-	-	-	0.29
PM_{10}	Z1	0.12	**0.62**	-0.11	**0.59**	-0.37	0.46	0.46	-0.47	0.08	-0.30
	Z2	0.09	0.34	-0.34	0.25	-0.46	0.14	0.05	-0.40	0.50	-0.24
	Z3	0.58	0.15	-0.47	0.44	-0.16	-	-	-	-	0.40

Residence Indoor and Ambient Monitors

Significant correlations were found at Zone 2 between $PM_{2.5}$ concentrations and temperature (r=-0.73), $PM_{2.5}$ and relative humidity (r=0.59), and $PM_{2.5}$ and precipitation (r=0.71). Significant correlations were also found between $PM_{10-2.5}$ and relative humidity (r=-0.68). The relationships between PM residence indoor measurements and meteorological factors were similar to those found at Chennai, India were PM concentrations were higher during winter, associated with low temperatures (20-25C), high humidity (80-90%), high pressure, and low wind speed (below 1 m/s) conditions (Srimuruganandam and Nagendra 2011). Lower temperatures present in the morning are also an

indication of thermal inversions, and as the day progresses, the temperature increases, dissipating the inversion and the stagnation of pollutants. As far as co-pollutants, significant correlations were found between $PM_{2.5}$ and NO_2 (r=0.73) and PM_{10} and NO_2 (r=0.69) at Zone 2. Residential sites at Zone 2 are closer to the ambient monitor as compared to the distributions in the other two zones.

Table 6.2: Spearman correlations between residence indoor PM levels and ambient measurements

Residence Indoor Msmts.	Zone	Central Monitors									
		WV	T	RH	SR	P	$PM_{2.5}$	CO	NO_2	SO_2	O_3
$PM_{2.5}$	**Z1**	-0.12	-0.07	0.47	-0.38	0.38	-0.15	-0.22	-0.16	0.44	-0.01
	Z2	-0.51	***-0.73***	**0.59**	-0.49	**0.71**	0.28	0.45	***0.73***	0.08	-0.19
	Z3	0.43	0.30	-0.60	0.31	-0.30	-	-	-	-	-0.07
$PM_{10-2.5}$	**Z1**	-0.35	0.13	-0.19	-0.33	-0.19	-0.33	-0.17	-0.07	0.57	-0.35
	Z2	0.31	0.34	**-0.68**	0.50	-0.20	0.33	-0.29	0.04	-0.12	0.54
	Z3	0.30	0.38	-0.52	0.21	-0.15	-	-	-	-	-0.12
PM_{10}	**Z1**	-0.33	-0.15	0.33	-0.52	0.20	-0.21	-0.36	0.02	0.47	-0.11
	Z2	-0.40	-0.54	0.21	-0.36	0.53	0.46	0.34	**0.69**	0.18	-0.06
	Z3	0.35	0.41	-0.58	0.24	-0.17	-	-	-	-	-0.07

6.1.2 Outdoor PM Measurements and Ambient Monitors

School Outdoor and Ambient Monitors

Although no significant correlations were found between $PM_{2.5}$ and any of the meteorological factors, a strong association was observed between the $PM_{2.5}$ at the school outdoor and the $PM_{2.5}$ from the ambient monitor (r=0.77) in Zone 2. Significant correlations were found between outdoor $PM_{10-2.5}$ measurements and wind velocity (r=0.65), relative humidity (r=-0.82), solar radiation (r=0.65), and precipitation (r=-0.75) at Zone 2. At Zone 3, significant correlations were found between outdoor $PM_{10-2.5}$ and wind velocity (r=0.82), relative humidity (r=-0.76), and solar radiation (r=0.67). Resuspension of coarse particulate matter ($PM_{10-2.5}$) is expected with increasing wind velocities, whereas higher humidity and precipitation levels will lead to settlement. Finally, for PM_{10}, significant correlations were found

with wind velocity (r=0.71) and solar radiation (r=0.66) at Zone 3, again the coarse fraction of PM_{10} increases with increasing wind velocity. Also, a significant correlation was found between PM_{10} and $PM_{2.5}$ recorded from the central station (r=0.93) at Zone 2, attributed to the fine fraction portion of PM_{10}.

Table 6.3: Spearman correlations between school outdoor PM levels and ambient measurements

School Outdoor Msmts.	Zone	Central Monitors									
		WV	**T**	**RH**	**SR**	**P**	**$PM_{2.5}$**	**CO**	**NO_2**	**SO_2**	**O_3**
$PM_{2.5}$	**Z1**	0.10	0.13	-0.20	0.41	-0.28	0.53	0.40	-0.22	-0.30	0.17
	Z2	0.08	-0.45	0.05	0.12	0.17	***0.77***	0.24	0.52	0.15	0.11
	Z3	0.62	0.28	-0.54	0.58	-0.22	-	-	-	-	0.46
$PM_{10-2.5}$	**Z1**	0.26	0.08	-0.22	0.39	-0.43	0.25	-0.12	-0.22	-0.13	-0.03
	Z2	**0.65**	0.55	***-0.82***	**0.65**	***-0.75***	0.54	-0.46	-0.13	-0.01	0.60
	Z3	***0.82***	0.52	**-0.76**	**0.67**	-0.28	-	-	-	-	0.54
PM_{10}	**Z1**	0.36	0.40	-0.55	0.60	-0.52	0.24	0.33	-0.36	0.05	-0.24
	Z2	0.30	0.05	-0.42	0.42	-0.23	***0.93***	0.02	0.25	0.21	0.35
	Z3	**0.71**	0.41	-0.61	**0.66**	-0.26	-	-	-	-	0.39

Residence Outdoor and Ambient Monitors

No significant correlations were found between meteorological factors and $PM_{2.5}$, except with relative humidity (r=0.72). A significant correlation was also observed between $PM_{2.5}$ and NO_2 (r=0.68) at Zone 2, attributed to close proximity between residential sites and monitor and common traffic source among both pollutants. For $PM_{10-2.5}$, significant correlations were found with wind velocity (r=0.62), temperature (r=0.73), relative humidity (r=-0.70), and solar radiation (r=0.66) at Zone 2, attributed to higher dispersion with increasing wind speeds and increased settlement with increased relative humidity. For PM_{10}, significant correlations were found with relative humidity (r=-0.63) and solar radiation (r=0.62) at Zone 2 and with relative humidity (r=-0.68) at Zone 3.

Table 6.4: Spearman correlations between residence outdoor PM levels and ambient measurements

Residence Outdoor Msmts.	Zone	Central Monitors									
		WV	T	RH	SR	P	$PM_{2.5}$	CO	NO_2	SO_2	O_3
$PM_{2.5}$	Z1	-0.29	-0.28	***0.72***	0.01	0.39	0.10	-0.14	-0.11	-0.26	0.03
	Z2	0.08	-0.57	0.22	0.01	0.42	0.52	0.33	**0.68**	-0.12	0.24
	Z3	-0.05	-0.32	-0.24	-0.25	-0.03	-	-	-	-	0.69
$PM_{10-2.5}$	Z1	0.48	0.29	-0.43	***0.76***	***-0.81***	0.32	0.27	-0.47	-0.40	0.05
	Z2	**0.62**	***0.73***	**-0.70**	**0.66**	-0.57	0.13	-0.05	-0.32	0.05	**0.58**
	Z3	0.58	0.32	***-0.82***	0.36	-0.12	-	-	-	-	0.62
PM_{10}	Z1	0.22	-0.18	0.06	0.41	-0.25	0.27	-0.06	-0.14	-0.48	0.26
	Z2	0.57	0.41	**-0.63**	**0.62**	-0.44	0.42	-0.04	0.00	0.09	0.56
	Z3	0.34	-0.04	**-0.68**	0.10	-0.11	-	-	-	-	0.71

6.2 Spatial variability between site measurements and central monitors

Coefficients of divergence show the spatial variability between measurements at two sites to see if concentration levels in two sites are homogeneous. In this analysis, coefficients of divergence were estimated between PM measurements at the schools and residential sites and those measured at the ambient monitors, again to evaluate if central monitoring can be used to represent true exposure for the population.

6.2.1 $PM_{2.5}$

Table 6.5 shows values that represent the CODs between the $PM_{2.5}$ levels that were measured at the school and residences and the $PM_{2.5}$ levels measured at the central monitors. Zone 3 is not included because its ambient monitor does not measure $PM_{2.5}$. Low spatial variability was exhibited between the measurements of Zone 2 central monitor and indoor residence levels (COD<0.2). Residential sites were closer together in Zone 2 and so measurements collected at the central site can be more representative of the true levels of exposure. Central monitor and outdoor residence levels and school indoor and outdoor levels at Zone 1 also exhibited small spatial variability (COD < 0.2). High spatial variability was exhibited at school indoor microenvironment in Zone 2 and at the indoor residential sites at Zone 1

(COD > 0.2), because of the influence of site sources in $PM_{2.5}$ concentrations, especially at the indoor residential sites in Zone 1.

Table 6.5: CODs between $PM_{2.5}$ site and central monitor measurements

$PM_{2.5}$	Schools		Residences	
	Indoor	**Outdoor**	**Indoor**	**Outdoor**
Z1	0.16	0.14	0.44	0.09
Z2	0.31	0.19	0.13	0.22

6.2.2 PM_{10}

For PM_{10}, (Table 6.6) indoor concentrations at the school sites in the three zones exhibited spatial variability (COD > 0.20). Outdoor school concentrations exhibited low spatial variability at Zone 1 (COD < 0.2), but some spatial variability at Zones 2 and 3 (COD > 0.2). At the residences, indoor microenvironments showed spatial heterogeneity for Zones 1 and 3, while outdoor microenvironments showed slight spatial heterogeneity for Zone 2. Indoor PM_{10} concentrations will greatly depend on sources for both fine and coarse particles, that includes cooking, occupancy and the amount of activity causing resuspension of particles, and infiltration from outdoor sources, while outdoor concentrations should be more consistent, dependent upon common sources such as soil erosion, resuspension from unpaved roads, quarry emissions, among others.

Table 6.6: CODs between PM_{10} site and central monitor measurements

PM_{10}	Schools		Residences	
	Indoor	**Outdoor**	**Indoor**	**Outdoor**
Z1	0.27	0.09	0.38	0.17
Z2	0.32	0.27	0.13	0.25
Z3	0.21	0.21	0.39	0.18

6.3 Inter-zone Analysis

Figures 6.1 to 6.3 grouped residential sites within zones and averaged particulate matter concentrations at the indoor and outdoor microenvironments (where available) to see if there were any differences among the concentration levels recorded within a zone. Figure 6.1 shows the grouping for Zone 1 based on longitudinal distribution (north vs. south). The houses to the north showed lower mean concentrations for indoor $PM_{2.5}$ than the houses in the south (19.2 and 38.3 μg/m^3) respectively, while coarse PM ($PM_{10-2.5}$) levels were similar (16.8 and 18.0 μg/m^3 for the north and south respectively). High indoor $PM_{2.5}$ levels at the residences are driven by the specific activities in that particular home, whether it is cooking, smoking, or others. Mean outdoor $PM_{2.5}$, $PM_{10-2.5}$, and PM_{10} concentrations were doubled in the north. Annual wind rose for Zone 1 shows a significant percentage of winds coming from the Northwest (Figure 3.6), and the outdoor residential sites are downwind and capturing the higher concentrations.

The residences inside the circle of Figure 6.2 are south of the central monitor approximately within 1 km, while the rest are further apart. The group of residences outside of the 1 km range did not have any measurements for outdoor concentrations. However, mean indoor levels of PM are within 5 μg/m^3. Concentration levels may not vary significantly amongst the residential sites in Zone 2 because they are very close to each other, as opposed to the residential sites in the other two zones.

Finally Figure 6.3 shows the residential sites divided by a north and south aggrupation. The residential sites grouped in the southern portion of the zone did not have any measurements for outdoor concentrations. However, indoor concentrations for residential sites outside of the circle and to the north were greater than average concentrations of residences to the south, with approximately doubling for $PM_{2.5}$ (24.9 and 11.3 μg/m^3 for the north and south respectively), almost tripling for the $PM_{10-2.5}$ concentrations (24.1 and 9.1 μg/m^3 at north and south) and also more than doubling for PM_{10} at 49.8 and 20.3 μg/m^3 respectively. Although pollutant levels at residential indoor microenvironments are going to be dependent on the sources, traditions, and activity patterns of the occupants, infiltration, especially with ventilation at the homes will cause outdoor local sources to have an effect on PM concentrations.

Annual wind rose for this region shows wind directions (Figure 3.8) shows predominant winds coming from the North and Northwest, capturing emission coming from the more urbanized region of Quito.

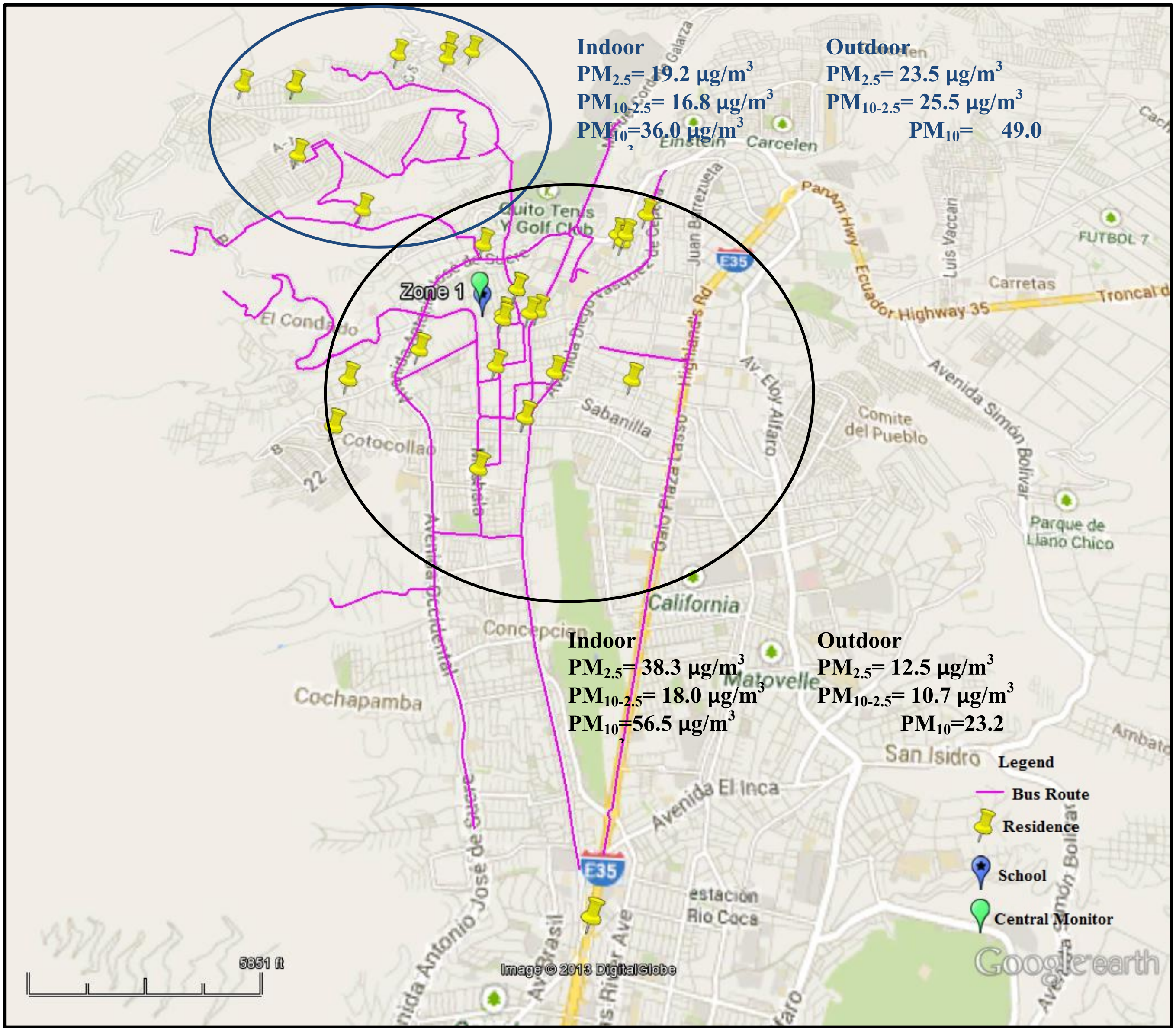


Figure 6.1: Inter-zone analysis between residential sites at Zone 1.

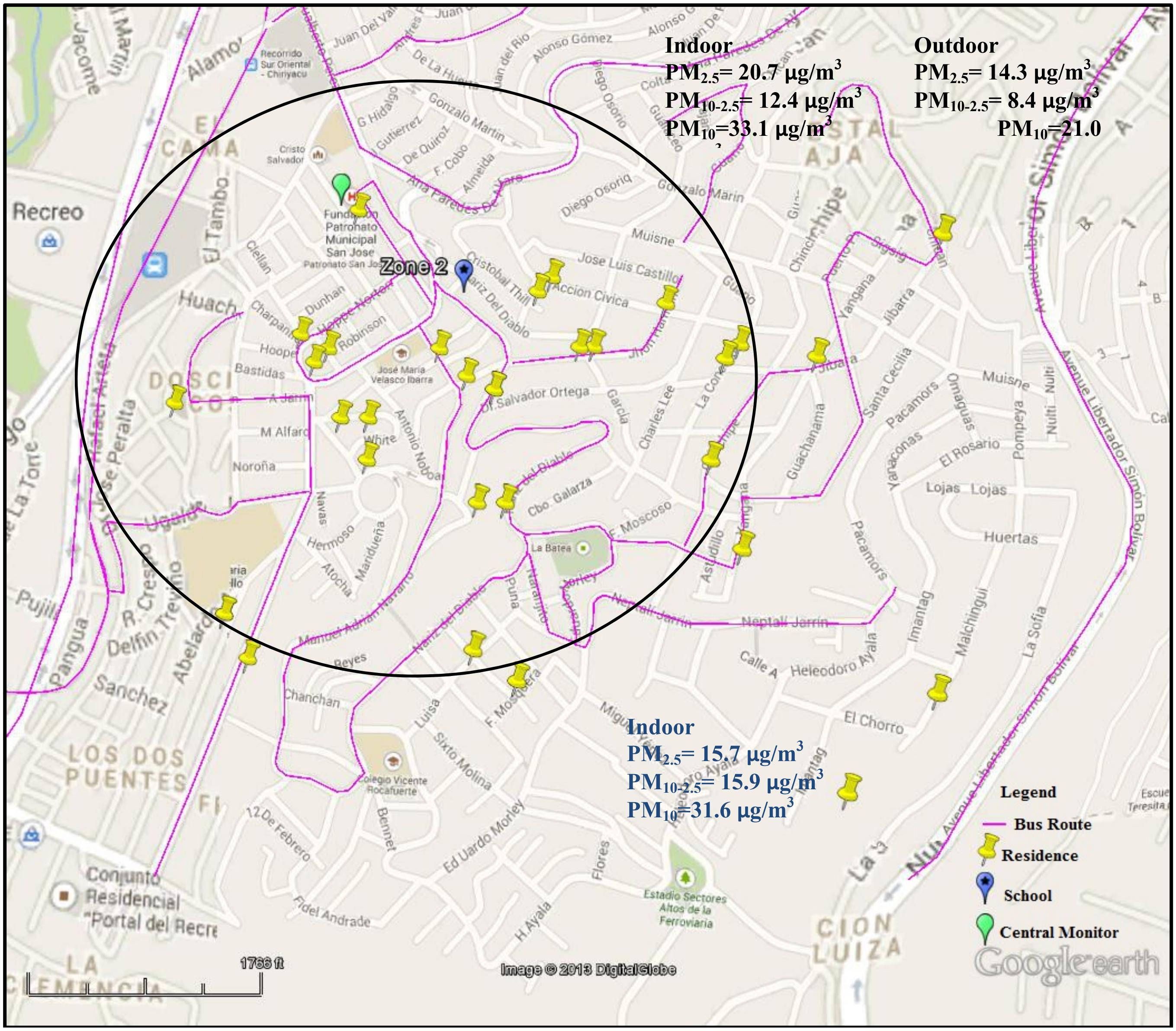


Figure 6.2: Inter-zone analysis between residential sites at Zone 2.

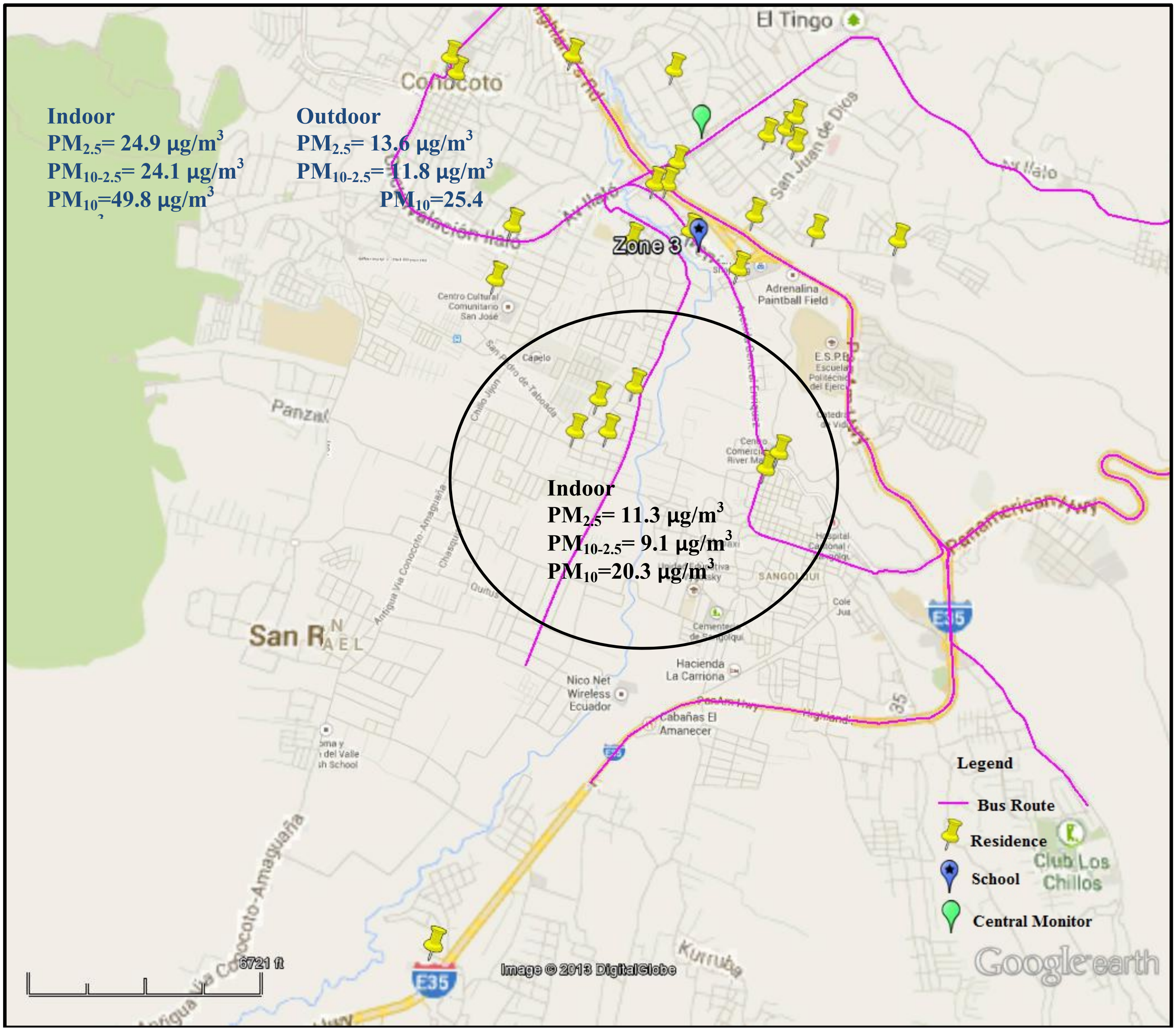


Figure 6.3: Inter-zone analysis between residential sites at Zone 3.

6.4 Conclusion

- Spearman correlation analysis showed weak associations between PM of all size fractions and most co-pollutant levels measured at ambient sites, even $PM_{2.5}$ collected at ambient monitors (with a few exceptions, such as for NO_2). Meteorological factors had stronger correlations, especially for coarse particulate matter ($PM_{10-2.5}$) collected in outdoor microenvironments, especially when the residences were grouped close to the ambient monitor (as in Zone 2).

- In Zone 1, homogeneity between $PM_{2.5}$ levels measured at the ambient monitor and site measurements (except residential indoor) was exhibited with a low COD, due to more uniformity in $PM_{2.5}$ sources at Zone 1, such as emissions from vehicles. In Zone 2 homogeneity was displayed for all microenvironments except school indoor and residences outdoor microenvironment.
- For PM_{10}, spatial heterogeneity was displayed at the indoor microenvironments and homogeneity at the outdoor microenvironments in Zone 1. The coarse PM fraction is strongly dependent on occupancy and activity level in indoor microenvironments, an effect that could not be captured by the central monitor. At Zone 2, indoor residential sites showed spatial homogeneity, possibly due to the closeness of the residences and an increase amount of ventilation amongst the homes. At Zone 3, homogeneity was also displayed in the residential outdoor microenvironment, while the central monitor concentrations differed from school and residential indoor microenvironment.
- One of the hypothesis evaluated in this chapter stated that spatial and temporal variations of outdoor PM concentrations can be associated with meteorological and co-pollutant data at a central monitoring station. This hypothesis was indeed confirmed in this study, although it depends on size fraction. Meteorological factors collected from ambient networks will be better surrogates for increase or decrease in $PM_{10-2.5}$ outdoor concentrations, while co-pollutants collected at the stations are poor predictors of PM behavior. The spatial variability analysis between outdoor PM measurements and central monitors revealed homogeneity for PM_{10} at Zone 1 and for $PM_{2.5}$ at both schools and residential outdoor microenvironments. Exposure in outdoor microenvironments will be better characterized by the central monitoring stations.
- However, the second hypothesis of this dissertation was that indoor PM exposure for children, both at school and home is associated with PM, co-pollutants, and other meteorological factors collected monitoring network. The evaluation provided in this chapter for this hypothesis reveals that meteorological factors collected from ambient networks will be better predictors for outdoor concentrations, while co-pollutant data were just poor predictors of PM exposure at indoor and

outdoor microenvironments. The spatial variability analysis for PM between ambient stations and sites reveals that it will be size dependent and dependent upon the location of the station with respect to the site of interest, as both homogeneous and heterogeneous behavior was captured.

Chapter 7: Conclusion

The outcomes discussed in this dissertation are a result of a 12-month study conducted in the high-altitude city of Quito, Ecuador to evaluate the effect of transient and long-term ambient PM exposure on systemic inflammation, oxidative stress, and atherogenesis in a group of 300 healthy children. Environmental and health data were collected from three exposure zones (high, medium, and low) to investigate the association of transient $PM_{2.5}$ and PM_{10} concentrations with inflammation. This dissertation focused on the environmental PM data ($PM_{2.5}$, $PM_{10-2.5}$, and PM_{10}) that was collected once a month as weekly averages, at a school and a group of residential sites in indoor and outdoor microenvironments at each zone. The results of this study provide important insights into children's PM exposure at a high-altitude city. Although many studies have emphasized the importance of monitoring children's exposure at school, exposure at residential sites has received less attention and this study addresses that limitation. The findings from this research also caution when using data from ambient stations to characterize children's exposure. In particular, this study analyzed two main hypothesis and resulted in the following conclusions,

- Spatial and temporal variations of outdoor PM concentrations can be associated with meteorological data observed at a central monitoring station specifically for the coarse PM fraction ($PM_{10-2.5}$)
- Indoor PM exposure for children both at school and home is not strongly associated with PM, co-pollutants, and other meteorological factors collected from a monitoring network, and will depend upon the size fraction of the PM and the placement of the monitoring station with respect to the sites. However, outdoor measurements of PM concentrations can be good indicators of indoor exposure, especially at places with little to no significant amounts of indoor sources, such as schools and with good ventilation.

In addition to evaluating the three hypothesis presented at the beginning of the document, this dissertation also revealed some interesting points about PM exposure in high-altitude cities and with such distinct topography variations,

- Analyses of meteorological factors characterize Quito as a region with low temperature variations and relatively calm to low wind speeds that can affect stagnation of air pollutants. High humidity levels are present all year long and precipitation is present during the winter season from October to May, while the rest of the year is known as the summer or dry season. Temperature inversions are common occurrences during the months of July through September and November through December.
- The trend of most gaseous air pollutants in Quito has been to decline since 2005 (CO and SO_2) or to remain stable (O_3 and NO_2). The decline in pollutant levels can be attributed to the implementation of programs such as *Revisión Técnica Vehicular, Pico y Placa,* and the lowering of sulfur levels in gasoline. Central monitoring stations located right in the center of Quito and subjected to higher traffic levels, such as El Camal (Zone 2), Belisario, and Centro were also subjected to higher concentrations of CO, NO_2, and SO_2, while stations further north (Cotocollao, Zone 1 and Carapungo) or further south (Guamani) showed lower levels. Ozone levels were closer together amongst the different stations. Pollutant data for 2010 has El Camal (Zone 2) as the station with higher concentrations for most pollutants CO, NO_2, and SO_2, while lower concentrations were observed at Cotocollao (Zone 1).
- The trends for particulate matter are slightly different. In the case of $PM_{2.5}$, we can see similar trends as with the gaseous pollutants, with higher traffic zones having higher $PM_{2.5}$ levels (e.g. El Camal, Belisario, and Centro), while lower traffic zones to the north (Cotocollao and Carapungo) showed lower $PM_{2.5}$ levels. Hourly variations coincide also with rush hour traffic. In terms of annual variations, levels have remained virtually unchanged, for the most part and at most stations. However, in the case of PM_{10}, levels significantly dropped since 2005, attributing this drop to higher precipitation levels. In subsequent years, it went up and down attributed to resuspension of dust from quarries and unpaved roads, soil erosion, and aggravated by lack of precipitation in some years. Although the high traffic zones (El Camal, Belisario, and Jipijapa) still collect higher levels of PM_{10} than the low traffic zones (Guamaní, Los Chillos, and

Cotocollao), the differences between the levels is almost negligible. $PM_{10-2.5}$ data was also plotted and the differences between the stations was almost negligible, more so than with PM_{10}.

- Exceedances are especially a concern for annual $PM_{2.5}$ levels. For PM_{10}, less exceedances were registered between 2005-2010, but still levels are at the borderline. It is important for Quito to keep making efforts into reducing both $PM_{2.5}$ and PM_{10} concentrations.
- Fine particulate matter ($PM_{2.5}$) seems to dominate PM concentration levels (according to the $PM_{2.5}/PM_{10}$) data, especially during the months of the rainy season, while the months of the dry season, $PM_{2.5}/PM_{10}$ ratios were mostly below 0.5, showing the dominance of PM_{10} concentrations.
- Indoor and outdoor concentrations and magnitude of the differences across the zones were found to be strongly dependent on the size fraction being studied and microenvironment. Within a zone, concentration levels at the residential sites were higher than concentration levels at the schools, signaling that the higher exposure for children is occurring at the home level. The difference between school and residential concentrations was larger at the indoor microenvironment and for fine particulate matter ($PM_{2.5}$) more so than for coarse particulate matter ($PM_{10-2.5}$).
- Although indoor PM levels can vary significantly because of the particular activities taking place, sources present, amount of ventilation, among other factors, outside sources still played a strong role in explaining the concentration levels collected at each microenvironment. Indoor-to-outdoor ratios were close to unity at the schools attributable to minimal indoor sources, lack of centralized heating and air conditioning, and weather that allowed for uniform ventilation patterns all year long. At the residential sites, higher I/O ratios indicated presence of PM sources at home due to cooking, cleaning, presence of pets, and resuspension of dust because of other activities (e.g. construction).
- Patterns of exposure across the three zones varied depending on PM size fraction. For fine PM ($PM_{2.5}$) higher exposures occurred in Zone 2, because of its location in the urban center of Quito and high traffic emissions. However, classifying exposure according to coarse PM ($PM_{10-2.5}$)

concentrations would yield the high exposure zones to the north (Zone 1) and south (Zone 3) portions of Quito, away from the urban center and prone to elevated concentrations of coarse PM from resuspension of particles from unprotected surfaces, quarries, and soil erosion, with less traffic flows. In the case of PM_{10}, exposure classification could be misinterpreted because it contains both fine and coarse fractions of particulate matter. It is important to separate exposure by each size fraction because size influences patterns of deposition within the respiratory tract as well as chemical composition. Coarse particles come primarily from mechanical grinding, windblown dust, agricultural activities, while $PM_{2.5}$ is more likely to come from combustion processes. Therefore, using PM_{10} as a proxy for particulate matter exposure in Quito would be misleading. According to direct PM_{10} measurements from the central monitoring network, the high exposure zone would be Zone 2, followed closely by Zone 1 (Figure 4.36). In 2005, the EPA recommended revisions to the NAAQS to add a standard for coarse PM in urban areas in the size range of $PM_{10\text{-}2.5}$, although that recommendation was rejected citing the "limited body of evidence on health effects associated with thoracic coarse particles from studies that use $PM_{10\text{-}2.5}$ measurements" (CRS, 2013). However, this change could have eliminated the duplication in fine particles ($PM_{2.5}$) and isolated measurements for adverse health effects associated with coarse particles only ($PM_{10\text{-}2.5}$) (Ott et al, 2008).

7.1 Recommendations and Future Work

Future studies should focus on characterizing residential exposures at high-altitude cities such as Quito, in particular to gain a deeper understanding on specific factors that lead to high concentrations in PM exposures. The use of a smaller sampling-period will also be beneficial to detect the peaks during the day and associate them with specific activities. Additionally, epidemiological studies investigating effects of coarse PM_{10} should make an effort to isolate health effects for the $PM_{10\text{-}2.5}$ fraction.

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Appendix A: Meteorological Data

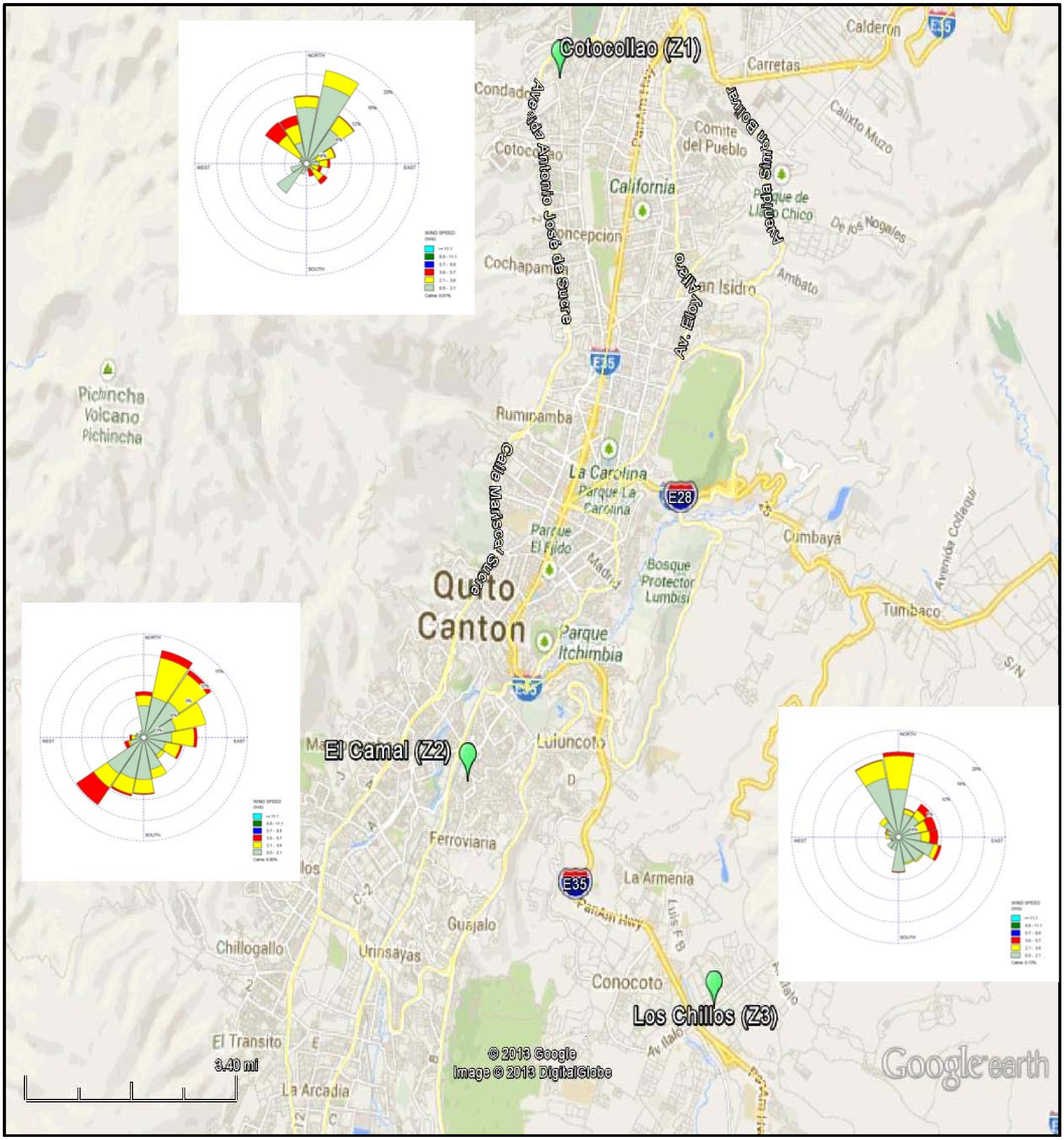

Figure A.1: Wind Roses January 2010

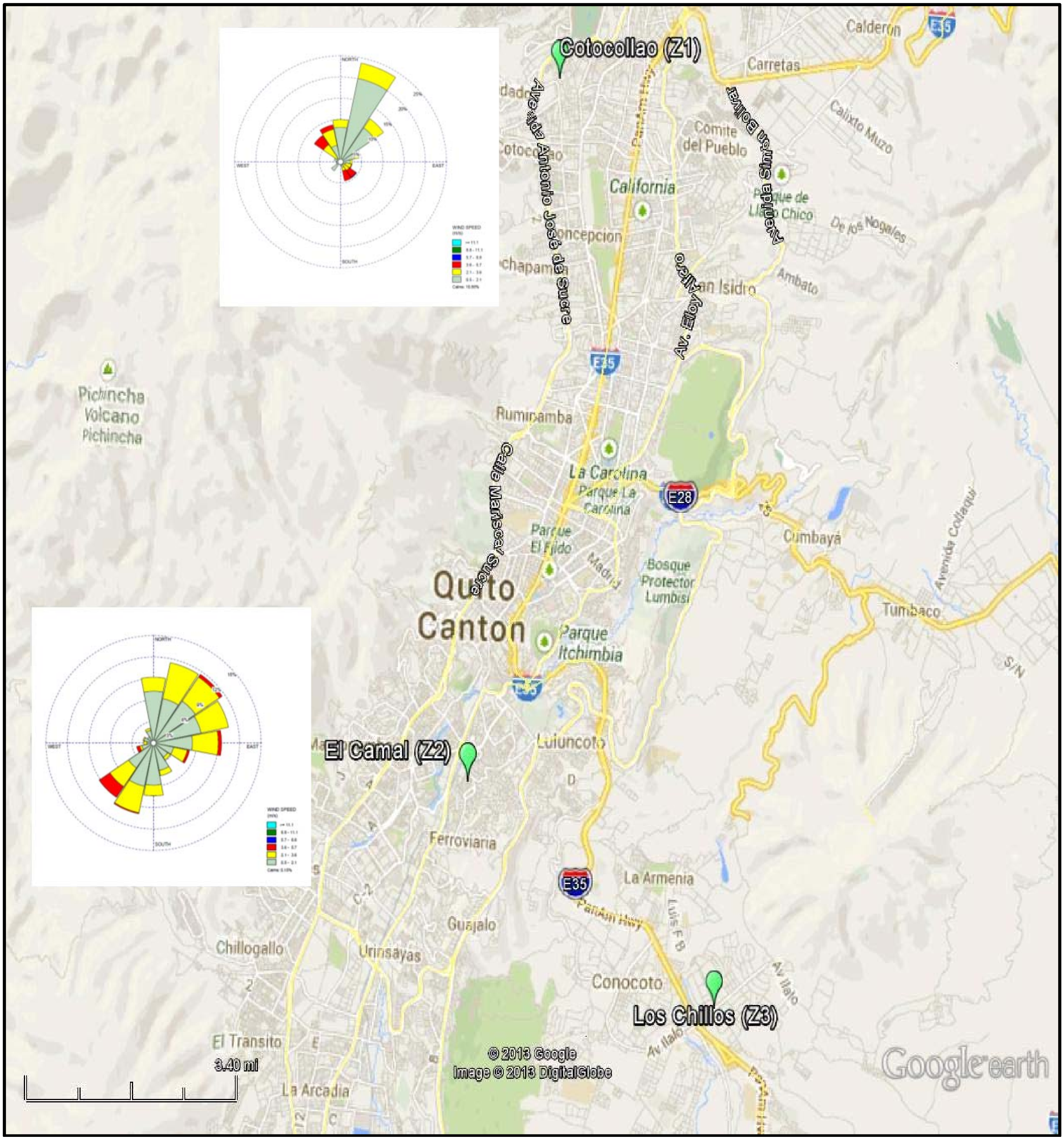

Figure A.2: Wind Roses February 2010

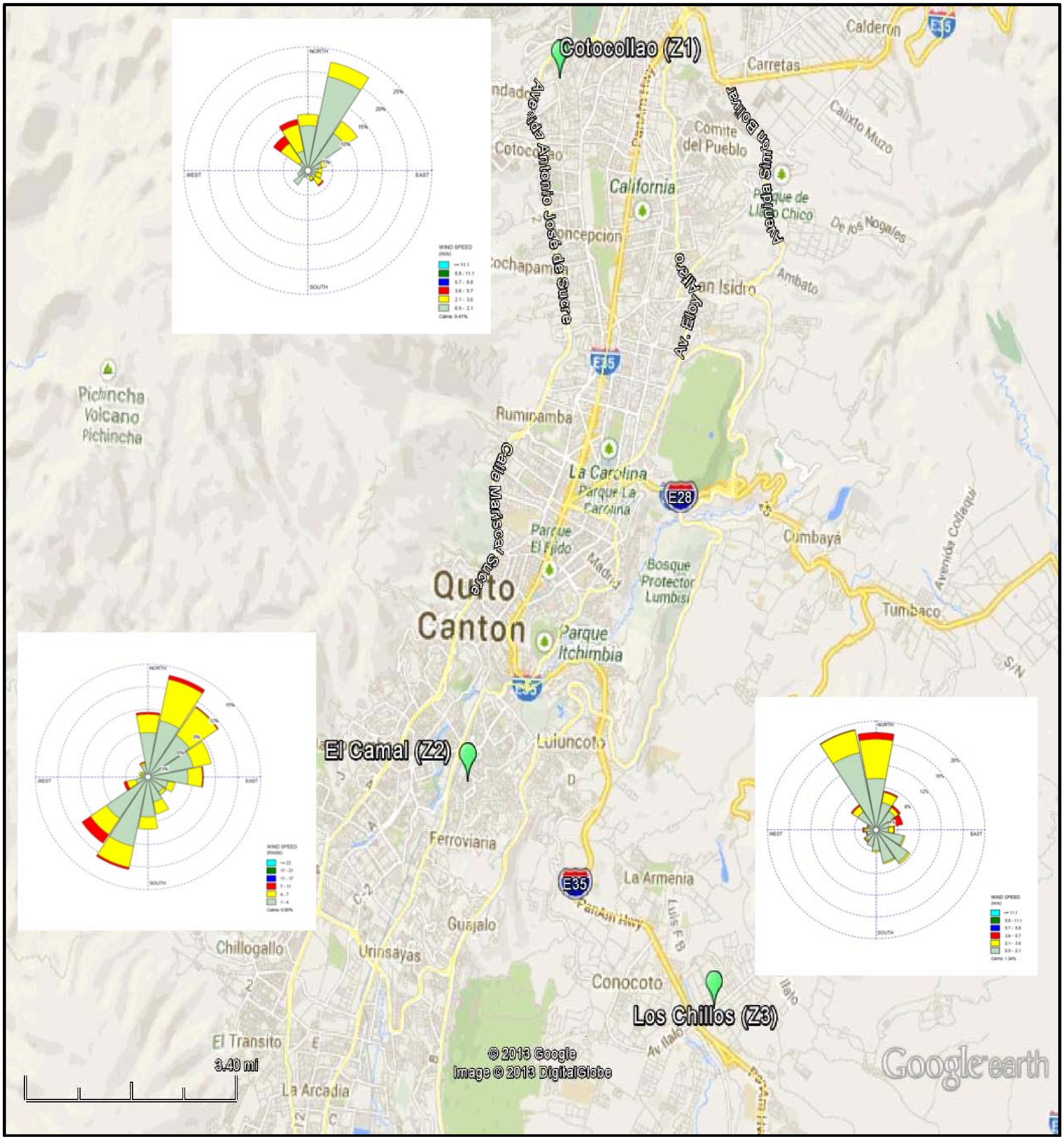

Figure A.3: Wind Roses March 2010

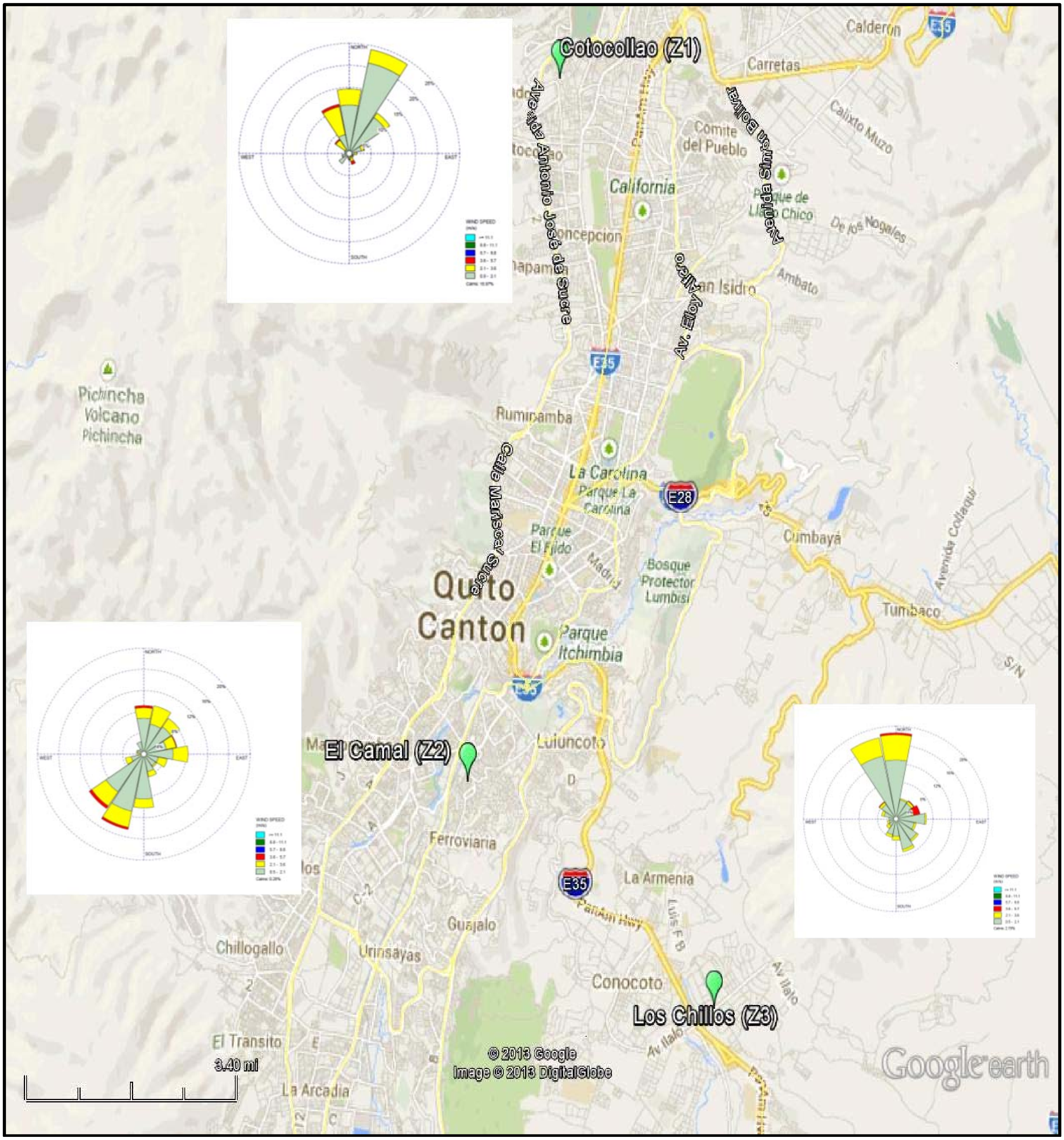

Figure A.4: Wind Roses April 2010

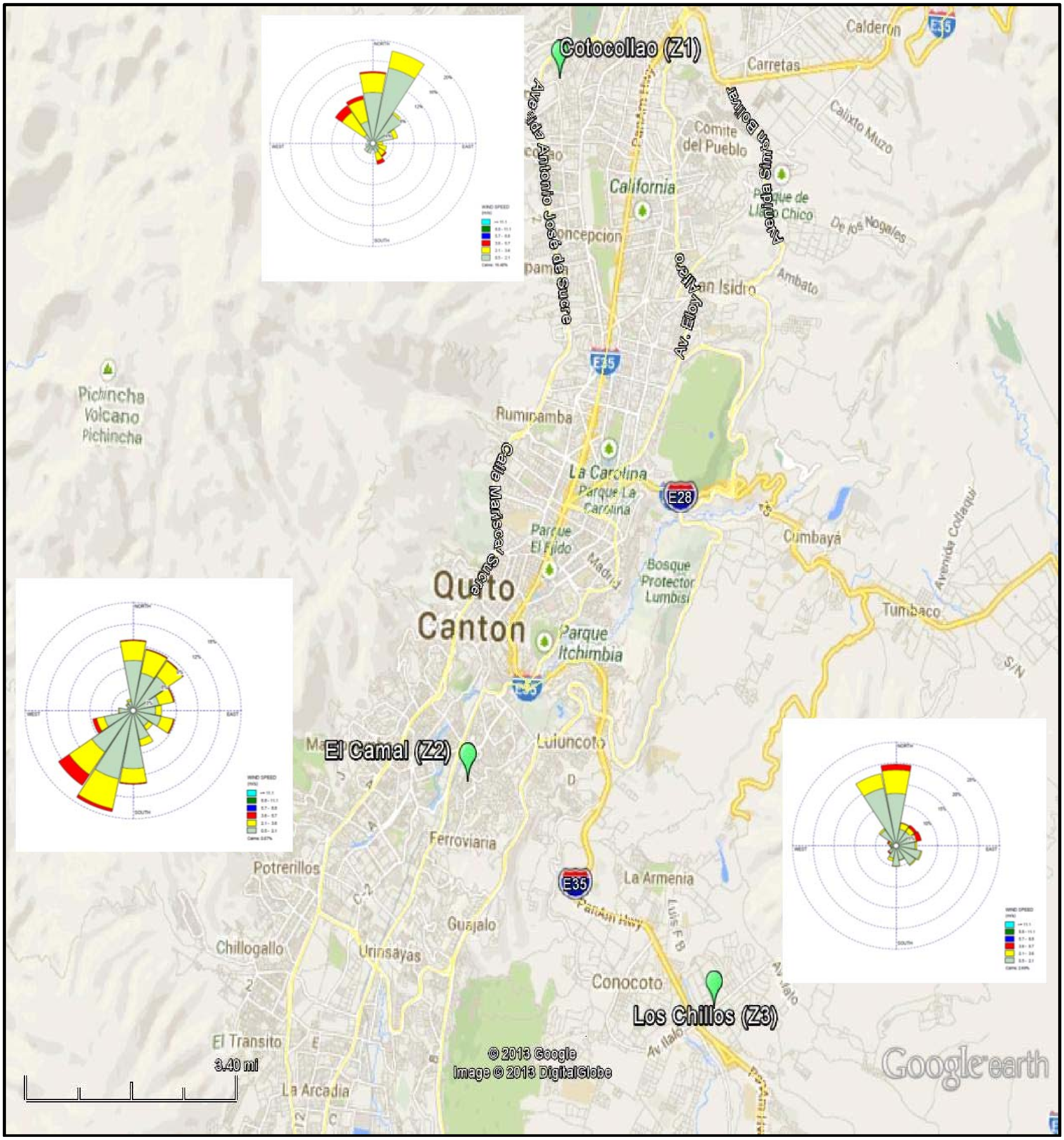

Figure A.5: Wind Roses May 2010

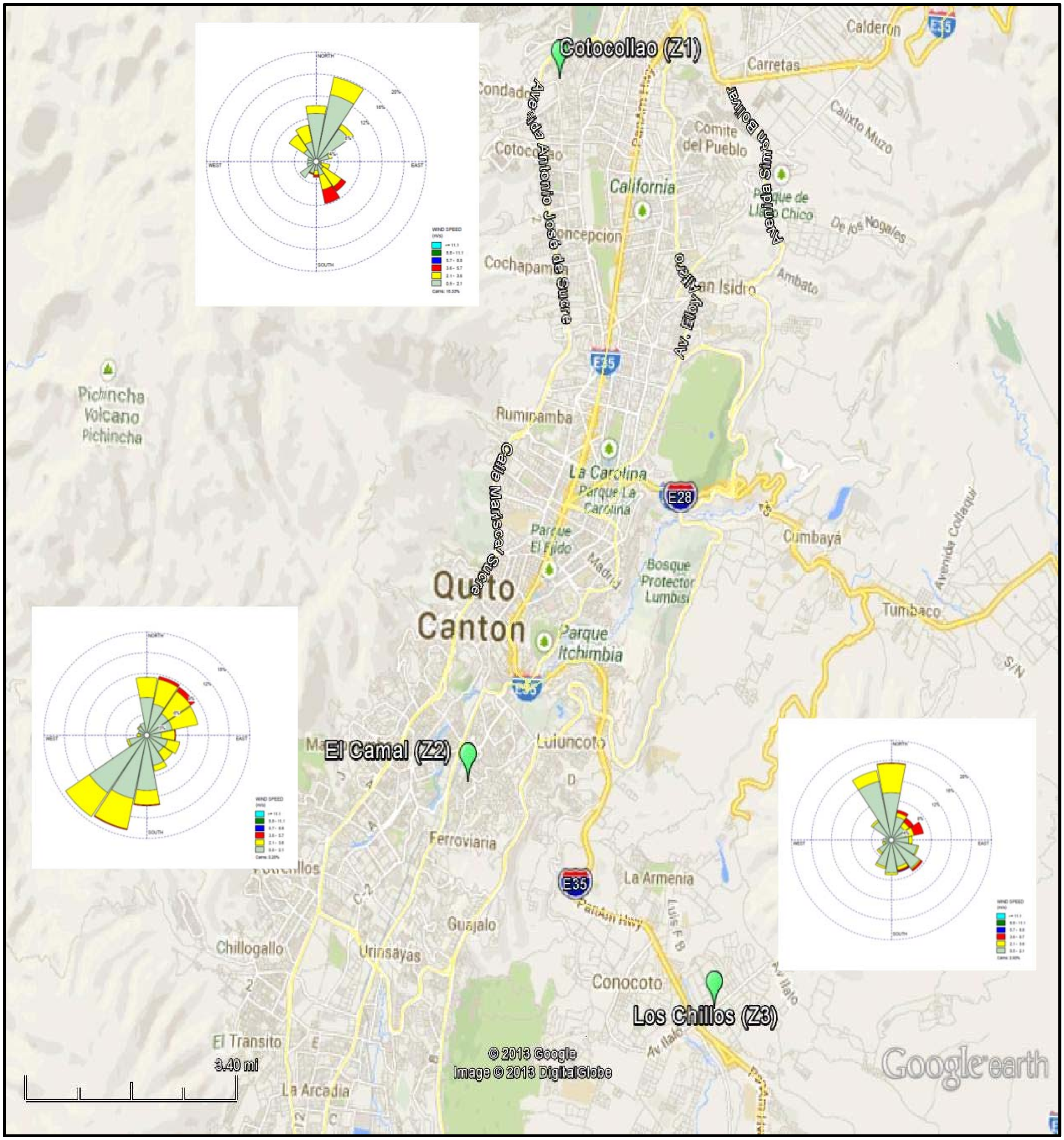

Figure A.6: Wind Roses June 2010

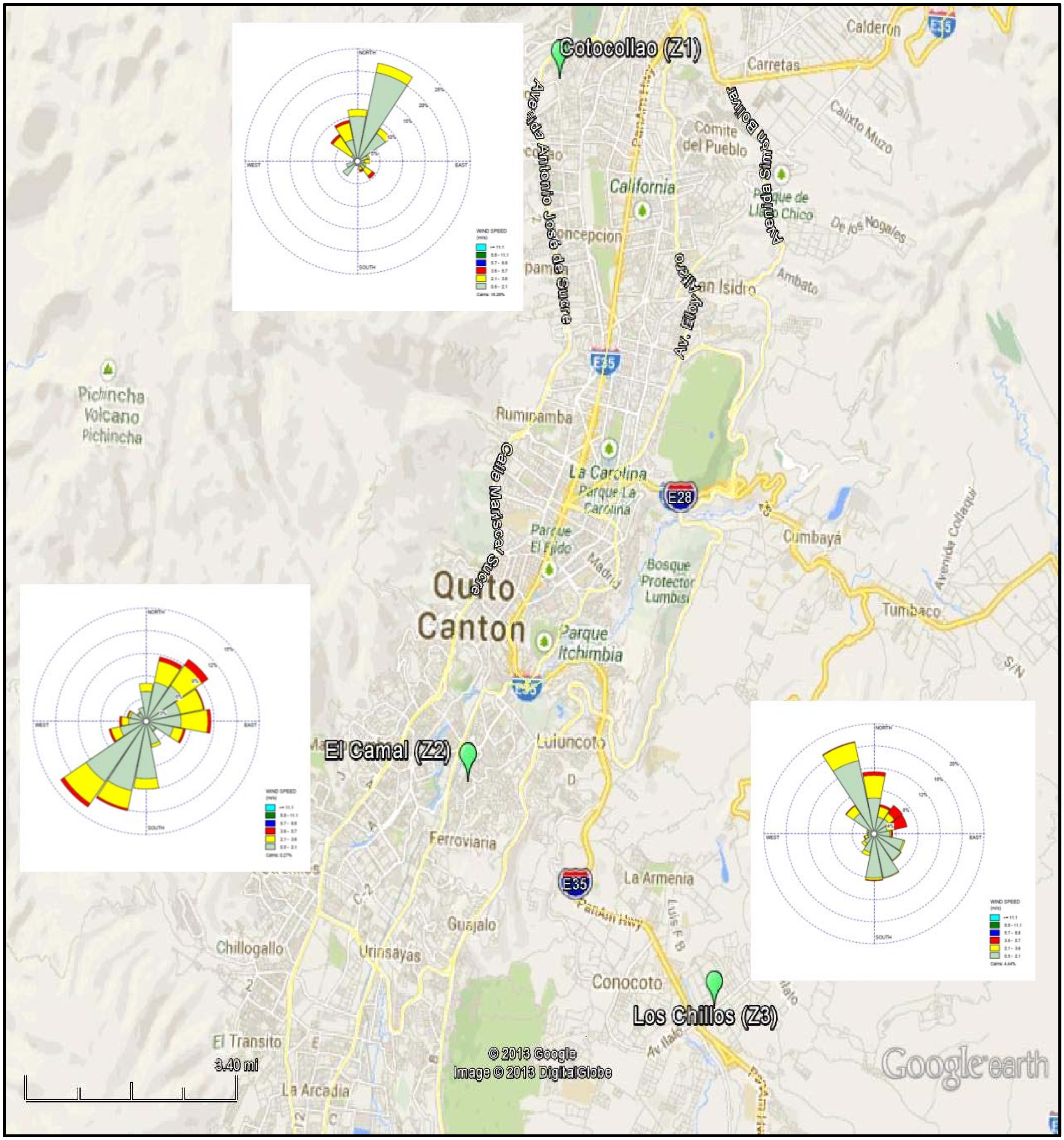

Figure A.7: Wind Roses July 2010

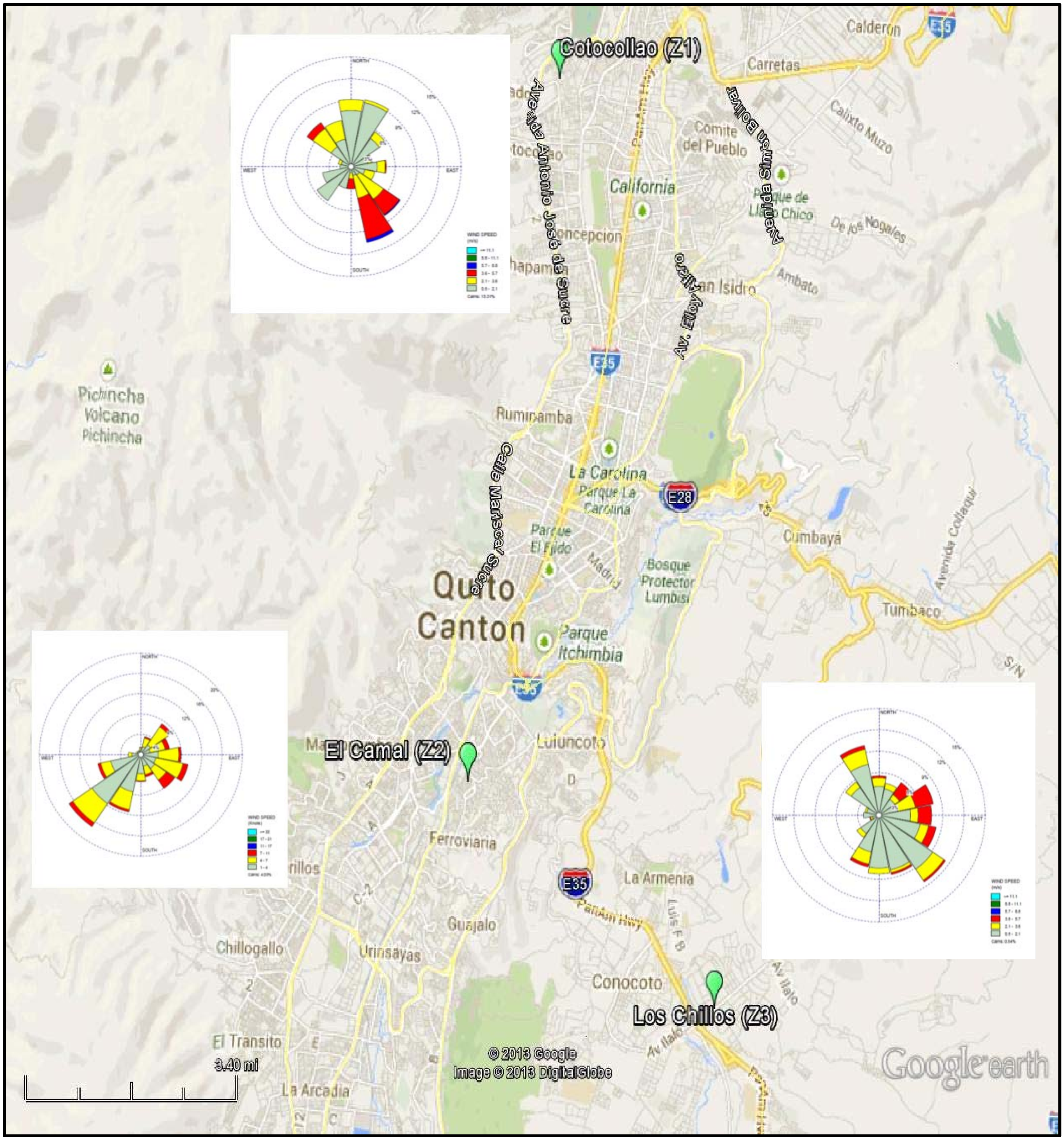

Figure A.8: Wind Roses August 2010

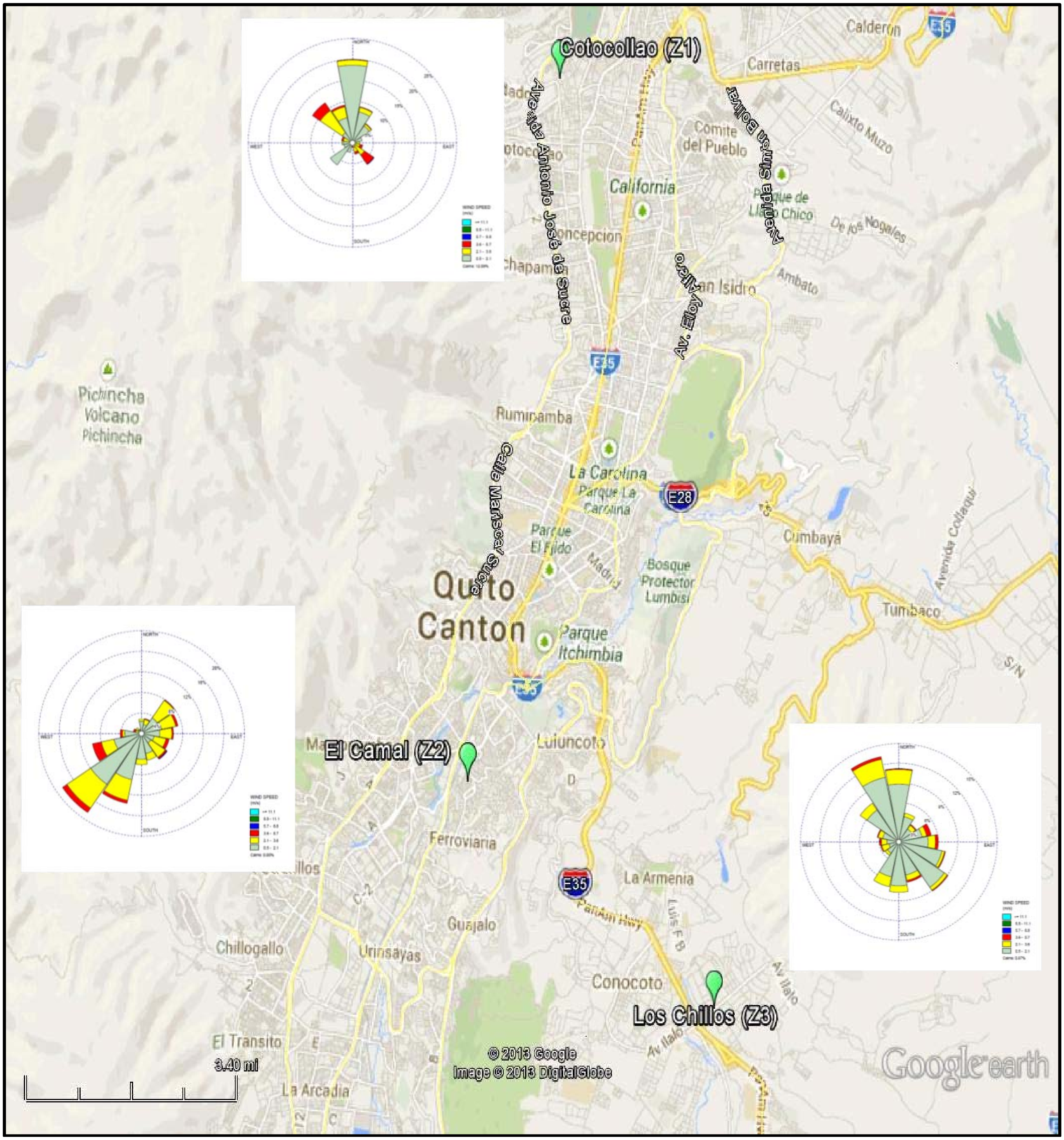

Figure A.9: Wind Roses September 2010

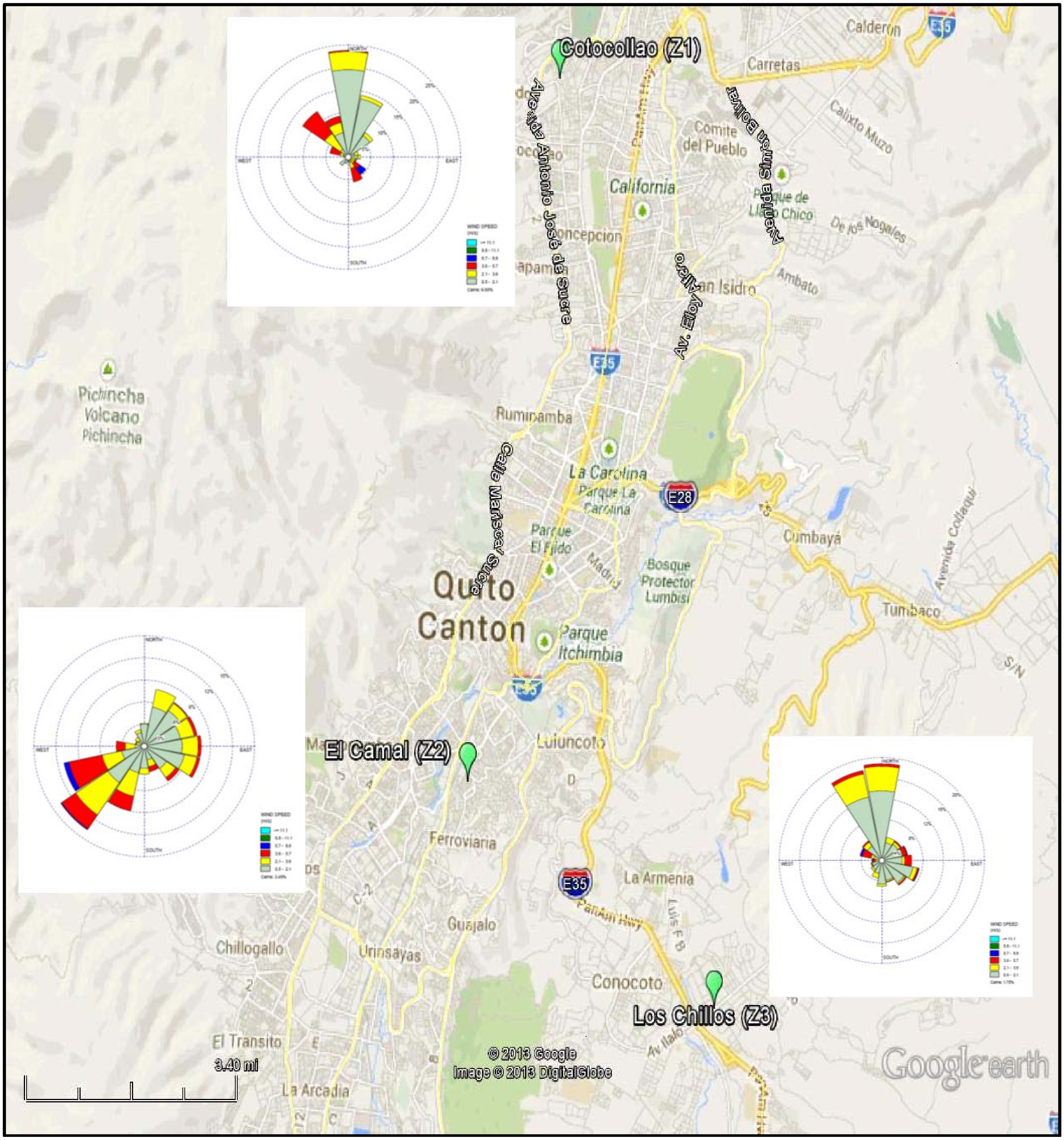

Figure A.10: Wind Roses October 2010

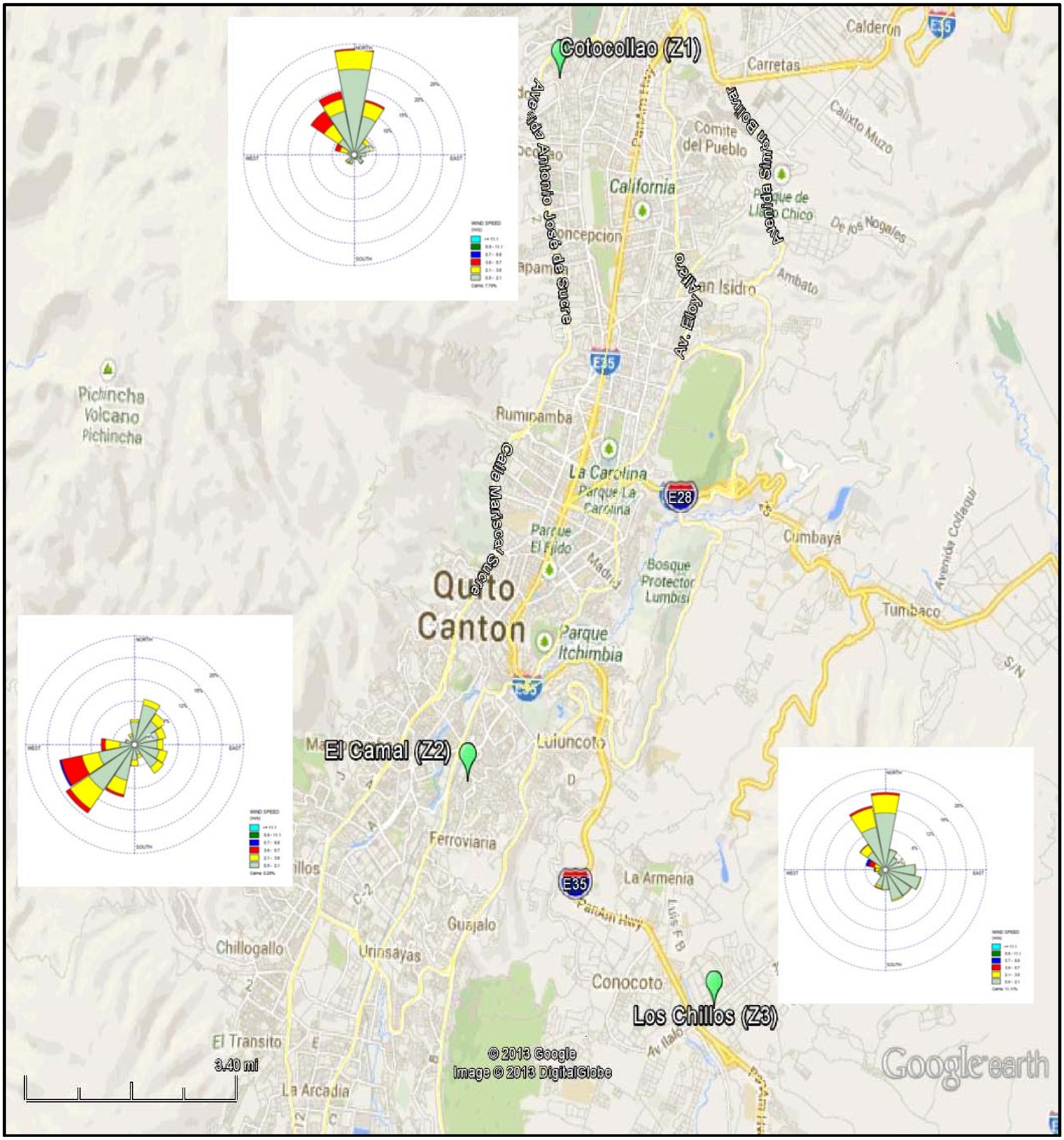

Figure A.11: Wind Roses November 2010

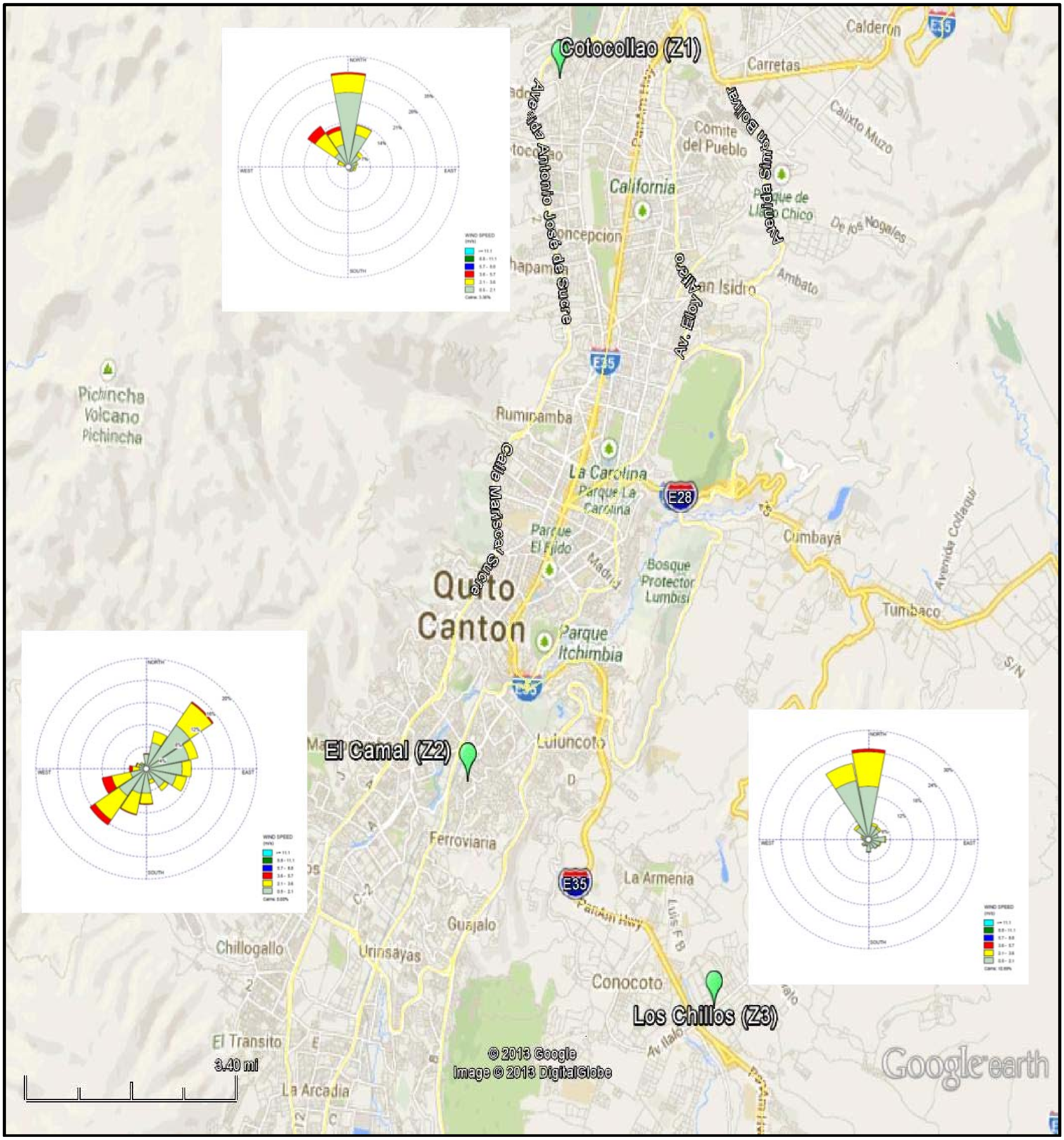

Figure A.12: Wind Roses December 2010

Appendix B: List of Residences

Table B.1: Residential sites

Residence ID	Zone	Latitude	Longitude	Elevation (m)	Month	Indoor			Outdoor		
						$PM_{2.5}$	$PM_{10-2.5}$	PM_{10}	$PM_{2.5}$	$PM_{10-2.5}$	PM_{10}
353-058	1	0°05'25"S	78°31'30"O	3055	Sep	9.2	1.7	10.9	NA	NA	NA
178-020	1	0°05'52"S	78°31'07"O	3004	Sep	18.2	5.2	23.3	NA	NA	NA
333-054	1	0°05'23"S	78°31'12'O	3002	Jan	19.8	34.5	54.3	12.8	39.9	52.7
333-054	1	0°05'23"S	78°31'12'O	3002	Feb	NA	NA	NA	34.2	11.1	45.3
205-025	1	0°06'10"S	78°30'43"O	2862	Sep	12.9	6.7	19.6	NA	NA	NA
458-080	1	0°05'04"S	78°30'37"O	2861	Jun	18.0	18.7	36.7	NA	NA	NA
428-073	1	0°05'04"S	78°30'37"O	2861	Aug	41.0	23.3	64.3	NA	NA	NA
168-018	1	0°05'04"S	78°30'37"O	2861	Aug	14.6	12.1	26.7	NA	NA	NA
138-013	1	0°04'59"S	78°30'19"O	2840	Jun	16.0	23.4	39.3	NA	NA	NA
343-055	1	0°05'00"S	78°30'10"O	2818	Jun	18.3	24.4	42.6	NA	NA	NA
258-039	1	0°05'04"S	78°30'19"O	2835	Jul	24.5	17.6	42.1	NA	NA	NA
398-067	1	0°06'20"S	78°29'60"O	2754	Feb	14.6	17.2	31.7	NA	NA	NA
208-026	1	0°06'37"S	78°29'47"O	2771	Apr	4.4	3.7	8.1	NA	NA	NA
308-049	1	0°06'49"S	78°29'51"O	2792	Feb	15.5	13.0	28.4	NA	NA	NA
451-071	1	0°06'45"S	78°29'39"O	2769	Mar	25.1	6.3	31.4	NA	NA	NA
385-075	1	0°06'46"S	78°29'42"O	2774	Feb	12.2	7.1	19.2	NA	NA	NA
125-101	1	0°06'13"S	78°29'13"o	2720	Feb	35.9	28.6	64.5	NA	NA	NA
255-038	1	0°06'05"S	78°29'03"O	2770	Jul	115.4	24.5	139.9	NA	NA	NA
533-094	1	0°06'16"S	78°29'11"O	2732	Apr	48.7	29.7	78.4	NA	NA	NA
218-029	1	0°06'13"S	78°29'10"O	2720	Mar	35.8	0.6	36.4	NA	NA	NA
438-075	1	0°07'10"S	78°29'06"O	2831	May	22.1	17.7	39.8	NA	NA	NA
348-057	1	0°07'08"S	78°29'32"O	2782	Jan	15.6	10.0	25.6	NA	NA	NA
348-057	1	0°07'08"S	78°29'32"O	2782	Feb	NA	NA	NA	13.0	9.7	22.7
348-057	1	0°07'08"S	78°29'32"O	2782	Apr	NA	NA	NA	19.3	7.1	26.4
348-057	1	0°07'08"S	78°29'32"O	2782	May	NA	NA	NA	15.5	11.5	27.0
348-057	1	0°07'08"S	78°29'32"O	2782	Jun	NA	NA	NA	9.9	10.9	20.8
348-057	1	0°07'08"S	78°29'32"O	2782	Jul	NA	NA	NA	14.6	10.0	24.6
348-057	1	0°07'08"S	78°29'32"O	2782	Aug	NA	NA	NA	10.9	10.7	21.6
348-057	1	0°07'08"S	78°29'32"O	2782	Sep	NA	NA	NA	14.1	10.1	24.2
348-057	1	0°07'08"S	78°29'32"O	2782	Oct	NA	NA	NA	12.4	7.9	20.3
348-057	1	0°07'08"S	78°29'32"O	2782	Nov	NA	NA	NA	15.5	8.9	24.4
348-057	1	0°07'08"S	78°29'32"O	2782	Dec	NA	NA	NA	13.9	10.5	24.3
368-061	1	0°07'25"S	78°29'41"O	2804	Jan	NA	NA	NA	12.4	18.2	30.6
368-061	1	0°07'25"S	78°29'41"O	2804	Jul	NA	NA	NA	12.4	10.5	22.8
368-061	1	0°07'25"S	78°29'41"O	2804	Aug	NA	NA	NA	16.5	10.2	26.7
368-061	1	0°07'25"S	78°29'41"O	2804	Sep	NA	NA	NA	8.0	7.1	15.1

Table B.1 (cont'd): Residential sites

Residence ID	Zone	Latitude	Longitude	Elevation (m)	Month	Indoor			Outdoor		
						$PM_{2.5}$	$PM_{10-2.5}$	PM_{10}	$PM_{2.5}$	$PM_{10-2.5}$	PM_{10}
368-061	1	0°07'25"S	78°29'41"O	2804	Oct	NA	NA	NA	12.1	11.4	23.4
368-061	1	0°07'25"S	78°29'41"O	2804	Nov	NA	NA	NA	12.5	8.8	21.3
368-061	1	0°07'25"S	78°29'41"O	2804	Dec	NA	NA	NA	13.7	11.0	24.6
473-083	1	0°07'44"S	78°29'55"O	2835	Apr	149.8	18.5	168.3	NA	NA	NA
215-028	1	0°07'07"S	78°29'52"O	2812	Mar	10.4	11.3	21.7	5.3	10.5	15.8
215-028	1	0°07'07"S	78°29'52"O	2812	Apr	NA	NA	NA	11.4	8.4	19.8
215-028	1	0°07'07"S	78°29'52"O	2812	May	NA	NA	NA	9.3	11.0	20.3
215-028	1	0°07'07"S	78°29'52"O	2812	Jun	NA	NA	NA	10.9	12.9	23.8
215-028	1	0°07'07"S	78°29'52"O	2812	Jul	NA	NA	NA	11.7	11.1	22.8
215-028	1	0°07'07"S	78°29'52"O	2812	Aug	NA	NA	NA	9.4	10.1	19.5
215-028	1	0°07'07"S	78°29'52"O	2812	Sep	NA	NA	NA	12.4	13.1	25.5
215-028	1	0°07'07"S	78°29'52"O	2812	Oct	NA	NA	NA	13.2	13.3	26.5
215-028	1	0°07'07"S	78°29'52"O	2812	Nov	NA	NA	NA	13.0	11.1	24.1
215-028	1	0°07'07"S	78°29'52"O	2812	Dec	NA	NA	NA	13.2	13.7	27.0
413-070	1	0°07'03"S	78°30'18"O	2867	Jul	21.3	30.0	51.3	NA	NA	NA
135-012	1	0°07'03"S	78°30'18"O	2867	Jul	70.8	41.6	112.5	NA	NA	NA
283-044	1	0°07'03"S	78°30'18"O	2867	Aug	58.9	38.4	97.3	NA	NA	NA
403-068	1	0°06'47"S	78°29'51"O	2790	Apr	NA	15.6	NA	NA	NA	NA
198-024	1	0°07'16"S	78°30'40"O	2952	Sep	15.5	8.3	23.8	NA	NA	NA
528-093	1	0°07'34"S	78°30'42"O	3060	Jun	18.3	20.4	38.7	NA	NA	NA
253-030	1	0°09'59"S	78°29'12"O	2790	May	14.6	28.4	43.0	NA	NA	NA
245-035	1	0°05'23"S	78°31'12'O	3002	Jan	16.3	28.4	44.7	2.1	3.5	5.6
245-035	2	0°05'23"S	78°31'12'O	3003	Feb	NA	NA	NA	14.0	16.5	30.4
368-070	1	0°07'25"S	78°29'41"O	2804	Jan	10.1	10.3	20.4	NA	NA	NA
368-070	1	0°07'25"S	78°29'41"O	2804	Feb	NA	NA	NA	9.1	11.7	20.9
368-070	1	0°07'25"S	78°29'41"O	2804	Apr	NA	NA	NA	12.3	8.4	20.7
368-070	1	0°07'25"S	78°29'41"O	2804	May	NA	NA	NA	8.6	11.1	19.7
108-006	1	0°07'01"S	78°19'50"O	2453	Mar	12.8	17.2	29.9	10.5	12.4	22.8
108-006	1	0°07'01"S	78°19'50"O	2453	Apr	NA	NA	NA	NA	0.1	NA
108-006	1	0°07'01"S	78°19'50"O	2453	May	NA	NA	NA	NA	12.1	NA
108-006	1	0°07'01"S	78°19'50"O	2454	Jun	NA	NA	NA	7.2	15.1	22.3
108-006	1	0°07'01"S	78°19'50"O	2454	Jul	NA	NA	NA	12.0	12.9	24.8
108-006	1	0°07'01"S	78°19'50"O	2454	Aug	NA	NA	NA	11.1	13.4	24.4
108-006	1	0°07'01"S	78°19'50"O	2455	Sep	NA	NA	NA	12.2	14.2	26.3
108-006	1	0°07'01"S	78°19'50"O	2455	Oct	NA	NA	NA	13.6	15.5	29.1
108-006	1	0°07'01"S	78°19'50"O	2455	Nov	NA	NA	NA	13.0	11.0	24.0
108-006	1	0°07'01"S	78°19'50"O	2455	Dec	NA	NA	NA	15.2	20.6	35.8

Table B.1 (cont'd): Residential sites

Residence ID	Zone	Latitude	Longitude	Elevation (m)	Month	Indoor			Outdoor		
						$PM_{2.5}$	$PM_{10-2.5}$	PM_{10}	$PM_{2.5}$	$PM_{10-2.5}$	PM_{10}
348-077	1	0°07'08"S	78°29'32"O	2782	Apr	NA	NA	NA	19.3	7.1	26.4
348-077	1	0°07'08"S	78°29'32"O	2782	May	NA	NA	NA	15.5	11.5	27.0
348-077	1	0°07'08"S	78°29'32"O	2782	Jun	NA	NA	NA	9.9	10.9	20.8
348-077	1	0°07'08"S	78°29'32"O	2782	Jul	NA	NA	NA	14.6	10.0	24.6
83-002	1	NA	NA	NA	Oct	117.0	6.6	123.6	NA	NA	NA
535-095	1	NA	NA	NA	Oct	21.0	16.5	37.5	NA	NA	NA
233-032	1	NA	NA	NA	Oct	30.9	11.2	42.1	NA	NA	NA
453-078	1	NA	NA	NA	Oct	11.6	5.2	16.8	NA	NA	NA
423-072	1	NA	NA	NA	Nov	21.4	14.3	35.6	NA	NA	NA
408-069	1	NA	NA	NA	Nov	34.7	24.6	59.4	NA	NA	NA
483-085	1	NA	NA	NA	Nov	12.9	20.6	33.5	NA	NA	NA
248-036	1	NA	NA	NA	Nov	43.3	20.3	63.6	NA	NA	NA
273-042	1	NA	NA	NA	Dec	11.5	5.7	17.2	NA	NA	NA
538-096	1	NA	NA	NA	Dec	11.3	7.0	18.3	NA	NA	NA
448-077	1	NA	NA	NA	Dec	11.9	6.3	18.1	NA	NA	NA
513-099	1	NA	NA	NA	Dec	10.2	4.4	14.6	NA	NA	NA
249-139	2	0°15'08"S	78°31'01"O	2848	Mar	29.6	15.1	44.6	NA	NA	NA
11-103	2	0°15'13"S	78°30'47"O	2886	Jun	39.3	13.8	53.1	NA	NA	NA
165-125	2	0°15'14"S	78°30'48"O	2883	Jan	8.8	3.7	12.5	13.2	9.6	22.8
165-125	2	0°15'14"S	78°30'48"O	2883	Feb	NA	NA	NA	11.5	8.7	20.1
165-125	2	0°15'14"S	78°30'48"O	2883	Mar	NA	NA	NA	12.8	11.3	24.2
165-125	2	0°15'14"S	78°30'48"O	2883	Apr	NA	NA	NA	17.3	7.4	24.7
165-125	2	0°15'14"S	78°30'48"O	2883	May	NA	NA	NA	11.5	7.4	19.0
165-125	2	0°15'14"S	78°30'48"O	2883	Jun	NA	NA	NA	8.3	6.3	14.6
165-125	2	0°15'14"S	78°30'48"O	2883	Jul	NA	NA	NA	NA	4.8	NA
165-125	2	0°15'14"S	78°30'48"O	2883	Aug	NA	NA	NA	14.3	10.1	24.4
165-125	2	0°15'14"S	78°30'48"O	2883	Sep	NA	NA	NA	10.4	7.4	17.8
165-125	2	0°15'14"S	78°30'48"O	2883	Oct	NA	NA	NA	11.7	5.6	17.3
165-125	2	0°15'14"S	78°30'48"O	2883	Nov	NA	NA	NA	16.6	4.6	21.2
165-125	2	0°15'14"S	78°30'48"O	2883	Dec	NA	NA	NA	76.1	NA	NA
627-199	2	0°15'15"S	78°30'39"O	2918	Apr	10.0	4.4	14.4	NA	NA	NA
72-110	2	0°15'18"S	78°30'44"O	2905	Feb	4.7	5.3	10.0	NA	NA	NA
548-187	2	0°15'18"S	78°30'45"O	2903	Apr	20.8	16.7	37.5	NA	NA	NA
603-196	2	0°15'18"S	78°30'45"O	2903	Sep	20.5	13.7	34.2	NA	NA	NA
312-151	2	0°15'21"S	78°30'51"O	2892	Jan	25.5	15.8	41.3	14.0	10.4	24.4
312-151	2	0°15'21"S	78°30'51"O	2892	Mar	NA	NA	NA	9.9	11.6	21.5
312-151	2	0°15'21"S	78°30'51"O	2892	Apr	NA	NA	NA	10.0	8.4	18.3

Table B.1 (cont'd): Residential sites

Residence ID	Zone	Latitude	Longitude	Elevation (m)	Month	Indoor			Outdoor		
						$PM_{2.5}$	$PM_{10-2.5}$	PM_{10}	$PM_{2.5}$	$PM_{10-2.5}$	PM_{10}
312-151	2	0°15'21"S	78°30'51"O	2892	May	NA	NA	NA	12.8	8.9	21.7
312-151	2	0°15'21"S	78°30'51"O	2892	Jun	NA	NA	NA	14.4	8.2	22.6
312-151	2	0°15'21"S	78°30'51"O	2892	Jul	NA	NA	NA	8.6	5.7	14.3
312-151	2	0°15'21"S	78°30'51"O	2892	Aug	NA	NA	NA	14.1	11.0	25.1
312-151	2	0°15'21"S	78°30'51"O	2892	Sep	NA	NA	NA	24.7	11.6	36.3
312-151	2	0°15'21"S	78°30'51"O	2892	Oct	NA	NA	NA	13.3	5.6	18.9
312-151	2	0°15'21"S	78°30'51"O	2892	Nov	NA	NA	NA	9.0	3.4	12.4
312-151	2	0°15'21"S	78°30'51"O	2892	Dec	NA	NA	NA	NA	10.8	NA
256-140	2	0°15'20"S	78°30'53"O	2879	Dec	38.8	13.4	52.2	NA	NA	NA
410-167	2	0°15'18"S	78°30'55"O	2868	Mar	23.7	8.6	32.3	NA	NA	NA
459-175	2	0°15'18"S	78°30'55"O	2868	Mar	14.6	12.6	27.2	NA	NA	NA
284-146	2	0°15'29"S	78°30'52"O	2929	May	30.7	24.0	54.7	NA	NA	NA
277-145	2	0°15'29"S	78°30'50"O	2943	May	9.9	9.0	18.8	NA	NA	NA
67-109	2	0°15'26"S	78°31'00"O	2882	Feb	10.4	23.2	33.6	NA	NA	NA
543-186	2	0°15'23"S	78°30'60"O	2872	Jan	13.1	12.2	25.3	14.3	12.4	26.8
543-186	2	0°15'23"S	78°30'60"O	2872	Feb	NA	NA	NA	10.4	10.0	20.4
543-186	2	0°15'23"S	78°30'60"O	2872	Apr	NA	NA	NA	9.0	8.3	17.3
543-186	2	0°15'23"S	78°30'60"O	2872	May	NA	NA	NA	11.5	8.3	19.7
543-186	2	0°15'23"S	78°30'60"O	2872	Jun	NA	NA	NA	14.2	8.8	23.0
543-186	2	0°15'23"S	78°30'60"O	2872	Jul	NA	NA	NA	9.2	4.6	13.8
543-186	2	0°15'23"S	78°30'60"O	2872	Aug	NA	NA	NA	14.3	9.7	24.0
543-186	2	0°15'23"S	78°30'60"O	2872	Sep	NA	NA	NA	12.3	8.9	21.2
543-186	2	0°15'23"S	78°30'60"O	2872	Oct	NA	NA	NA	12.5	6.7	19.2
543-186	2	0°15'23"S	78°30'60"O	2872	Nov	NA	NA	NA	17.1	5.3	22.4
543-186	2	0°15'23"S	78°30'60"O	2872	Dec	NA	NA	NA	17.2	7.0	24.3
291-147	2	0°15'23"S	78°31'02"O	2870	Mar	11.5	12.8	24.3	NA	NA	NA
88-113	2	0°15'18"S	78°31'03"O	2857	Dec	40.1	6.6	46.8	NA	NA	NA
400-165	2	0°15'19"S	78°31'04"O	2858	Feb	29.4	8.3	37.7	NA	NA	NA
263-141	2	0°15'17"S	78°31'05"O	2855	Feb	11.5	9.2	20.7	NA	NA	NA
546-190	2	0°15'22"S	78°31'14"O	2857	Jun	16.5	8.2	24.7	NA	NA	NA
592-194	2	0°15'40"S	78°31'08"O	2911	Jul	35.2	14.7	50.0	NA	NA	NA
161-124	2	0°15'37"S	78°31'10"O	2882	Jan	25.8	21.4	47.2	14.2	10.8	25.0
161-124	2	0°15'37"S	78°31'10"O	2882	Feb	NA	NA	NA	10.3	10.0	20.2
161-124	2	0°15'37"S	78°31'10"O	2882	Mar	NA	NA	NA	11.5	9.9	21.4
161-124	2	0°15'37"S	78°31'10"O	2882	Apr	NA	NA	NA	10.4	10.6	21.0
161-124	2	0°15'37"S	78°31'10"O	2882	May	NA	NA	NA	11.5	8.1	19.5
161-124	2	0°15'37"S	78°31'10"O	2882	Jun	NA	NA	NA	14.2	10.9	25.0

Table B.1 (cont'd): Residential sites

Residence ID	Zone	Latitude	Longitude	Elevation (m)	Month	Indoor			Outdoor		
						$PM_{2.5}$	$PM_{10-2.5}$	PM_{10}	$PM_{2.5}$	$PM_{10-2.5}$	PM_{10}
161-124	2	0°15'37"S	78°31'10"O	2882	Jul	NA	NA	NA	8.0	5.2	13.2
578-150	2	0°15'39"S	78°30'52"O	2982	May	14.4	11.1	25.5	NA	NA	NA
102-115	2	0°15'26"S	78°30'36"O	2975	Jun	20.9	11.3	32.2	NA	NA	NA
018-104	2	0°15'18"S	78°30'34"O	2954	Apr	12.1	9.4	21.4	NA	NA	NA
359-157	2	0°15'19"S	78°30'35"O	2953	Jul	24.1	11.1	35.2	NA	NA	NA
158-123	2	0°15'19"S	78°30'35"O	2953	Jul	17.0	18.5	35.5	NA	NA	NA
599-195	2	0°15'41"S	78°30'49"O	2995	Sep	17.0	15.0	31.9	NA	NA	NA
494-179	2	0°15'47"S	78°30'28"O	3150	Jun	12.3	11.0	23.3	NA	NA	NA
186-129	2	0°15'32"S	78°30'34"O	3008	Aug	14.7	27.6	42.3	NA	NA	NA
445-173	2	0°15'19"S	78°30'29"O	2992	Apr	20.0	18.4	38.5	NA	NA	NA
361-159	2	0°15'11"S	78°30'21"O	3028	Aug	14.5	7.5	22.0	NA	NA	NA
39-106	2	0°15'37"S	78°31'10"O	2882	Jul	10.5	12.1	22.6	NA	NA	NA
39-106	2	0°15'37"S	78°31'10"O	2882	Aug	NA	NA	NA	16.4	10.8	27.2
39-106	2	0°15'37"S	78°31'10"O	2882	Sep	NA	NA	NA	16.9	8.3	25.2
39-106	2	0°15'37"S	78°31'10"O	2882	Oct	NA	NA	NA	12.0	5.7	17.6
39-106	2	0°15'37"S	78°31'10"O	2882	Nov	NA	NA	NA	17.7	6.1	23.8
39-106	2	0°15'37"S	78°31'10"O	2882	Dec	NA	NA	NA	11.7	4.0	15.8
319-152	2	0°15'21"S	78°30'51"O	2892	Sep	37.3	45.7	83.0	NA	NA	NA
237-137	2	NA	NA	NA	Oct	14.1	1.8	15.9	NA	NA	NA
242-138	2	NA	NA	NA	Oct	14.5	5.1	19.7	NA	NA	NA
264-142	2	NA	NA	NA	Oct	9.2	2.4	11.7	NA	NA	NA
487-178	2	NA	NA	NA	Oct	39.1	9.2	48.3	NA	NA	NA
403-166	2	NA	NA	NA	Nov	17.9	15.1	33.1	NA	NA	NA
557-189	2	NA	NA	NA	Nov	25.9	6.5	32.3	NA	NA	NA
417-168	2	NA	NA	NA	Nov	18.1	17.1	35.2	NA	NA	NA
004-102	2	NA	NA	NA	Nov	45.1	9.2	54.2	NA	NA	NA
74-111	2	NA	NA	NA	Dec	31.2	2.9	34.1	NA	NA	NA
235-136	2	NA	NA	NA	Dec	13.2	3.1	16.4	NA	NA	NA
367-269	3	0°17'26"S	78°27'59"O	2463	Jul	7.7	4.5	12.2	NA	NA	NA
437-283	3	0°17'30"S	78°27'27"O	2455	Jun	15.0	13.4	28.4	NA	NA	NA
2-203	3	0°17'28"S	78°28'37"O	2535	Jul	14.3	13.4	27.7	NA	NA	NA
260-250	3	0°17'33"S	78°28'35"O	2539	Jun	15.9	14.8	30.8	NA	NA	NA
340-265	3	0°17'450"S	78°26'49"O	2465	Aug	11.0	9.4	20.4	NA	NA	NA
474-289	3	0°17'49"S	78°26'52"O	2470	Aug	19.2	8.4	27.6	NA	NA	NA
487-293	3	0°17'54"S	78°26'49"O	2472	Aug	11.0	6.2	17.2	NA	NA	NA
462-288	3	0°17'51"S	78°26'58"O	2469	Aug	16.2	6.7	22.8	NA	NA	NA
171-232	3	0°18'00"S	78°27'26"O	2462	Jul	13.5	24.4	37.9	NA	NA	NA

Table B.1 (cont'd): Residential sites

Residence ID	Zone	Latitude	Longitude	Elevation (m)	Month	Indoor			Outdoor		
						$PM_{2.5}$	$PM_{10-2.5}$	PM_{10}	$PM_{2.5}$	$PM_{10-2.5}$	PM_{10}
502-296	3	0°18'07"S	78°27'33"O	2464	May	56.6	55.5	112.1	NA	NA	NA
174-234	3	0°18'07"S	78°27'29"O	2467	Jan	61.0	21.9	82.9	NA	14.9	NA
174-234	3	0°18'07"S	78°27'29"O	2467	Mar	NA	NA	NA	20.9	23.1	44.0
174-234	3	0°18'07"S	78°27'29"O	2467	Apr	NA	NA	NA	24.9	14.0	38.9
174-234	3	0°18'07"S	78°27'29"O	2467	May	NA	NA	NA	28.4	21.1	49.5
174-234	3	0°18'07"S	78°27'29"O	2467	Jun	NA	NA	NA	9.7	11.1	20.8
174-234	3	0°18'07"S	78°27'29"O	2467	Jul	NA	NA	NA	21.4	29.3	50.7
174-234	3	0°18'07"S	78°27'29"O	2467	Aug	NA	NA	NA	25.7	34.5	60.3
174-234	3	0°18'07"S	78°27'29"O	2467	Sep	NA	NA	NA	26.6	18.2	44.8
174-234	3	0°18'07"S	78°27'29"O	2467	Oct	NA	NA	NA	21.8	15.8	37.6
174-234	3	0°18'07"S	78°27'29"O	2467	Nov	NA	NA	NA	27.1	19.2	46.3
174-234	3	0°18'07"S	78°27'29"O	2467	Dec	NA	NA	NA	8.9	4.6	13.5
432-282	3	0°18'21"S	78°28'17"O	2486	Mar	7.6	4.3	11.9	NA	NA	NA
352-267	3	0°18'25"S	78°27'40"O	2464	Sep	30.9	60.7	91.7	NA	NA	NA
527-299	3	0°18'22"S	78°27'22"O	2473	Jan	NA	9.7	NA	NA	12.1	NA
527-299	3	0°18'22"S	78°27'22"O	2473	Apr	NA	NA	NA	6.4	4.8	11.2
527-299	3	0°18'22"S	78°27'22"O	2473	May	NA	NA	NA	13.0	10.2	23.2
527-299	3	0°18'22"S	78°27'22"O	2473	Jun	NA	NA	NA	6.1	8.1	14.2
527-299	3	0°18'22"S	78°27'22"O	2473	Jul	NA	NA	NA	8.9	10.3	19.2
527-299	3	0°18'22"S	78°27'22"O	2473	Aug	NA	NA	NA	8.0	9.8	17.8
527-299	3	0°18'22"S	78°27'22"O	2473	Sep	NA	NA	NA	13.5	9.5	23.0
527-299	3	0°18'22"S	78°27'22"O	2473	Oct	NA	NA	NA	14.0	11.2	25.2
527-299	3	0°18'22"S	78°27'22"O	2473	Nov	NA	NA	NA	11.6	2.5	14.2
527-299	3	0°18'22"S	78°27'22"O	2473	Dec	NA	NA	NA	10.0	6.0	16.0
227-245	3	0°18'34"S	78°27'07"O	2477	Jan	30.1	8.3	38.4	NA	9.1	NA
227-245	3	0°18'34"S	78°27'07"O	2477	Mar	NA	NA	NA	6.7	8.2	14.9
227-245	3	0°18'34"S	78°27'07"O	2477	Apr	NA	NA	NA	5.9	3.7	9.6
227-245	3	0°18'34"S	78°27'07"O	2477	May	NA	NA	NA	13.3	11.3	24.6
227-245	3	0°18'34"S	78°27'07"O	2477	Jun	NA	NA	NA	24.3	10.1	34.4
227-245	3	0°18'34"S	78°27'07"O	2477	Jul	NA	NA	NA	9.4	13.5	23.0
227-245	3	0°18'34"S	78°27'07"O	2477	Aug	NA	NA	NA	12.1	15.2	27.3
227-245	3	0°18'34"S	78°27'07"O	2477	Sep	NA	NA	NA	26.1	19.0	45.1
227-245	3	0°18'34"S	78°27'07"O	2477	Oct	NA	NA	NA	14.7	12.7	27.3
227-245	3	0°18'34"S	78°27'07"O	2477	Nov	NA	NA	NA	11.0	6.8	17.8
227-245	3	0°18'34"S	78°27'07"O	2477	Dec	NA	NA	NA	4.1	3.5	7.6
402-277	3	0°18'22"S	78°26'43"O	2473	May	20.9	22.4	43.3	NA	NA	NA
281-253	3	0°18'25"S	78°26'18"O	2512	May	30.4	26.6	57.0	NA	NA	NA

Table B.1 (cont'd): Residential sites

Residence ID	Zone	Latitude	Longitude	Elevation (m)	Month	Indoor			Outdoor		
						$PM_{2.5}$	$PM_{10-2.5}$	PM_{10}	$PM_{2.5}$	$PM_{10-2.5}$	PM_{10}
102-221	3	0°18'25"S	78°26'18"O	2512	Sep	22.3	29.3	51.6	NA	NA	NA
325-263	3	0°18'17"S	78°27'02"O	2473	Jan	64.0	117.5	181.5	9.7	11.4	21.1
325-263	3	0°18'17"S	78°27'02"O	2473	Mar	NA	NA	NA	7.7	5.6	13.3
325-263	3	0°18'17"S	78°27'02"O	2473	Apr	NA	NA	NA	6.1	5.0	11.0
325-263	3	0°18'17"S	78°27'02"O	2473	May	NA	NA	NA	10.1	9.5	19.6
325-263	3	0°18'17"S	78°27'02"O	2473	Jun	NA	NA	NA	8.1	8.9	17.0
325-263	3	0°18'17"S	78°27'02"O	2473	Jul	NA	NA	NA	3.2	10.7	13.9
325-263	3	0°18'17"S	78°27'02"O	2473	Aug	NA	NA	NA	14.9	16.7	31.6
325-263	3	0°18'17"S	78°27'02"O	2473	Sep	NA	NA	NA	15.8	11.3	27.1
325-263	3	0°18'17"S	78°27'02"O	2473	Oct	NA	NA	NA	14.8	10.8	25.6
325-263	3	0°18'17"S	78°27'02"O	2473	Nov	NA	NA	NA	11.7	7.0	18.7
325-263	3	0°18'17"S	78°27'02"O	2473	Dec	NA	NA	NA	8.9	6.0	14.9
557-302	3	0°18'38"S	78°28'22"O	2498	Apr	3.1	2.5	5.6	NA	NA	NA
7-204	3	0°19'11"S	78°27'39"O	2486	Apr	5.5	6.2	11.7	NA	NA	NA
152-229	3	0°19'15"S	78°27'50"O	2489	Sep	11.2	7.0	18.2	NA	NA	NA
509-297	3	0°18'22"S	78°27'22"O	2473	Mar	13.5	15.9	29.4	NA	NA	NA
47-210	3	0°19'25"S	78°27'47"O	2498	Sep	25.8	23.0	48.8	NA	NA	NA
37-208	3	0°19'31"S	78°26'55"O	2497	May	9.9	6.2	16.1	NA	NA	NA
292-255	3	0°19'36"S	78°26'59"O	2501	Apr	9.7	2.7	12.4	NA	NA	NA
337-264	3	0°21'57"S	78°28'37"O	2535	Jul	31.5	21.8	53.4	NA	NA	NA
387-275	3	NA	NA	NA	Jun	25.8	17.3	43.1	NA	NA	NA
480-290	3	NA	NA	NA	Jun	25.2	22.2	47.5	NA	NA	NA
62-213	3	NA	NA	NA	Oct	34.3	44.0	78.3	NA	NA	NA
241-207	3	NA	NA	NA	Oct	23.8	17.0	40.8	NA	NA	NA
172-233	3	NA	NA	NA	Oct	3.9	2.0	5.8	NA	NA	NA
307-258	3	NA	NA	NA	Oct	14.3	9.2	23.5	NA	NA	NA
235-248	3	NA	NA	NA	Nov	13.3	11.9	25.2	NA	NA	NA
212-242	3	NA	NA	NA	Nov	10.4	4.0	14.4	NA	NA	NA
132-227	3	NA	NA	NA	Nov	9.9	5.3	15.2	NA	NA	NA
87-219	3	NA	NA	NA	Nov	10.1	5.4	15.5	NA	NA	NA
302-257	3	NA	NA	NA	Dec	5.9	3.0	8.9	NA	NA	NA
447-284	3	NA	NA	NA	Dec	8.8	3.5	12.3	NA	NA	NA
422-280	3	NA	NA	NA	Dec	24.6	2.8	27.4	NA	NA	NA
537-300	3	NA	NA	NA	Dec	4.5	2.9	7.4	NA	NA	NA

Appendix C: Characteristics of Study Cohort

A total of 302 children participated in the study from which 3 subjects did not complete the interview questionnaire, so they were excluded from the analysis, leaving with a total of 299 valid responses. Subjects ages ranged from 6-12 year old, with most (22%) of the subjects age 9. Subjects came from all of the three schools and residences that were monitored, including 102 subjects from the Zone 1, 100 subjects from Zone 2 and 97 from Zone 3. The majority of the subjects were of mixed race (*mestizo),* with very few native and black, and a few who did not provide an answer. Table C.1 below presents basic information on the subjects by zone. Subjects' health issues by Zone are presented in Table C.2. The most common health problem reported are headaches followed by eye problems and some form of respiratory problem (asthma, cough, wheezing, sinusitis).

Table C.1: Subject's basic demographics

Characteristic	All Subjects	Schools		
		Z1	Z2	Z3
Total Subjects	299	102	100	97
Gender (Male, Female)	166, 133	59, 43	55, 45	52, 45
Age: Mean(Range)	8 (6-12)	8 (6-12)	8 (7-12)	8 (6-12)
Ethnicity:				
Mixed Race (*Mestizo*)	288	96	96	96
Black	5	2	2	1
Native	3	2	1	0
Grade:				
3	58	19	19	20
4	72	26	23	23
5	58	18	21	19
6	63	23	19	21
7	48	16	18	14

Table C.2: Health issues by zone

Characteristic	All Subjects	Zone		
		Z1	**Z2**	**Z3**
Total Subjects	299	102	100	97
Gender (Male, Female)	166, 133	59, 43	55, 45	52, 45
Age: Mean(Range)	8 (6-12)	8 (6-12)	8 (7-12)	8 (6-12)
Asthma	6	2	2	2
Chronic Cough	38	13	13	12
Sinusitis	9	3	5	1
Wheezing	9	6	2	1
Allergies	8	1	2	5
Heart Problems	14	3	8	3
Seizures	11	6	4	1
Headaches	73	23	28	22
Eye Problems	56	18	23	15
Hearing Problems	12	5	3	4
Urinary Problems	36	15	10	11
Malnutrition	29	14	5	10

In addition to basic demographics and health issues, the interviews also asked for date and reason of the last doctor's appointment. The interviews were conducted twice during the study (6 months apart) and this question was asked each time. Specifically the interview asked how long ago (in days) was the last visit to the doctor and reason for going (diagnosis). The different diagnosis were categorized into three fields as either an infection (e.g. fever, flu, stomach infections), others (e.g. headaches, low weight, accidents), or simply, the subject did not go to the doctor (see Tables C.3 and C.4). In the first interview, almost half (42%) of the subjects reported going to the doctor and being diagnosed with an infection, as compared to 6 months later (second interview), when the majority of the subjects did not visit the doctor, and only 18% of all the subjects who had gone were diagnosed with an infection.

Table C.3: Doctor's diagnosis from first interview

First Interview (January 2010)	All Subjects	Schools		
		Z1	Z2	Z3
Infection	125 (42%)	46 (45%)	35 (35%)	44 (45%)
Other	43 (14%)	17 (17%)	11 (11%)	15 (15%)
Didn't go to doctor	131 (44%)	39 (38%)	54 (54%)	38 (39%)
Total	299	102	100	97

Table C.4: Doctor's diagnosis from second interview

Second Interview (May/June 2010)	All Subjects	Schools		
		Z1	Z2	Z3
Infection	54 (18%)	18 (18%)	18 (18%)	18 (19%)
Other	11 (4%)	3 (3%)	5 (5%)	3 (3%)
Didn't go to doctor	234 (78%)	81 (79%)	77 (77%)	76 (78%)
Total	299	102	100	97

Vita

Teresa Montoya earned her Bachelor of Science degree in Civil Engineering from The University of Texas at El Paso in 2006. She pursued and earned her Master of Science degree in Environmental Engineering in 2010 from The University of Texas at El Paso while working full time at Gray Jansing & Associates, Inc. In 2010, she joined the Environmental Science and Engineering doctoral program at The University of Texas at El Paso.

While pursuing her doctoral degree, she received the Bridge to the Doctorate Fellowship and the Milton Feldstein Memorial Scholarship from The Air & Waste Management Association. She also worked as a research associate and teaching assistant for the department of Civil Engineering and participated in the Summer 2012 EPA/UTEP Air Quality Internship Program.

Permanent address: 6268 Jerry Turner

El Paso, TX, 79932

This thesis/dissertation was typed by: Teresa Montoya