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Particulate matter and carbon monoxide multiple regression models using environmental characteristics in a high diesel-use area of Baguio City, Philippines

Brandon E. Cassidy^a, Mary Anne Alabanza-Akers^b, Timothy A. Akers^c, Daniel B. Hall^d, P. Barry Ryan^e, Charlene W. Bayer^f, Luke P. Naeher^{a,*}

^a *The University of Georgia (UGA), College of Public Health, Department of Environmental Health Science, Athens, Georgia, GA 30602-2102, USA*

^b *UGA, College of Environment and Design, Athens, Georgia, USA*

^c *Kennesaw State University, WellStar College of Health and Human Services, Kennesaw, Georgia, USA*

^d *UGA, Franklin College of Arts and Sciences, Department of Statistics, Athens, Georgia, USA*

^e *Emory University, Rollins School of Public Health, Atlanta, Georgia, USA*

^f *Georgia Tech Research Institute, Atlanta, Georgia, USA*

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Abstract

In Baguio City, Philippines, a mountainous city of 252,386 people where 61% of motor vehicles use diesel fuel, ambient particulate matter $<2.5 \mu\text{m}$ ($\text{PM}_{2.5}$) and $<10 \mu\text{m}$ (PM_{10}) in aerodynamic diameter and carbon monoxide (CO) were measured at 30 street-level locations for 15 min apiece during the early morning (4:50–6:30 am), morning rush hour (6:30–9:10 am) and afternoon rush hour (3:40–5:40 pm) in December 2004. Environmental observations (e.g. traffic-related variables, building/roadway designs, wind speed and direction, etc.) at each location were noted during each monitoring event. Multiple regression models were formulated to determine which pollution sources and environmental factors significantly affect ground-level $\text{PM}_{2.5}$, PM_{10} and CO concentrations. The models showed statistically significant relationships between traffic and early morning particulate air pollution [$(\text{PM}_{2.5} p=0.021)$ and $\text{PM}_{10} (p=0.048)$], traffic and morning rush hour CO ($p=0.048$), traffic and afternoon rush hour CO ($p=0.034$) and wind and early morning CO ($p=0.044$). The mean early morning, street-level $\text{PM}_{2.5}$ ($110 \pm 8 \mu\text{g}/\text{m}^3$; mean ± 1 standard error) was not significantly different (p -value > 0.05) from either rush hour $\text{PM}_{2.5}$ concentration (morning = $98 \pm 7 \mu\text{g}/\text{m}^3$; afternoon = $107 \pm 5 \mu\text{g}/\text{m}^3$) due to nocturnal inversions in spite of a 100% increase in automotive density during rush hours. Early morning street-level CO (3.0 ± 1.7 ppm) differed from morning rush hour (4.1 ± 2.3 ppm) ($p=0.039$) and afternoon rush hour (4.5 ± 2.2 ppm) ($p=0.007$). Additionally, $\text{PM}_{2.5}$, PM_{10} , CO, nitrogen dioxide (NO_2) and select volatile organic compounds were continuously measured at a downtown, third-story monitoring station along a busy roadway for 11 days. Twenty-four-hour average ambient concentrations were: $\text{PM}_{2.5} = 72.9 \pm 21 \mu\text{g}/\text{m}^3$; CO = 2.61 ± 0.6 ppm; $\text{NO}_2 = 27.7 \pm 1.6$ ppb; benzene = $8.4 \pm 1.4 \mu\text{g}/\text{m}^3$; ethylbenzene = $4.6 \pm 2.0 \mu\text{g}/\text{m}^3$; p -xylene = $4.4 \pm 1.9 \mu\text{g}/\text{m}^3$; m -xylene = $10.2 \pm 4.4 \mu\text{g}/\text{m}^3$; o -xylene = $7.5 \pm 3.2 \mu\text{g}/\text{m}^3$. The multiple regression models suggest that traffic and wind in Baguio City, Philippines significantly affect street-level pollution concentrations. Ambient $\text{PM}_{2.5}$ levels measured are above USEPA daily ($65 \mu\text{g}/\text{m}^3$) and Filipino/USEPA annual standards ($15 \mu\text{g}/\text{m}^3$) with concentrations of a magnitude rarely seen in most countries except in areas where local topography plays a significant role in air

* Corresponding author. Tel.: +1 706 542 2454; fax: +1 706 542 7472.

E-mail address: LNaeher@uga.edu (L.P. Naeher).

pollution entrapment. The elevated pollution concentrations present and the diesel-rich nature of motor vehicle emissions are important pertaining to human exposure and health information and as such warrant public health concern.

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1. Introduction

Ambient air pollution, which includes but is not limited to particulate matter (PM), carbon monoxide (CO), volatile organic compounds (VOCs) and nitrogen oxides (NO_x), is a major environmental health problem present within a variety of urban and rural settings. Although high air pollution concentrations have been documented within rural areas (Hassan et al., 1995; Naeher et al., 2007; Reinhardt et al., 2001), ambient air pollution is most prevalent within urban areas potentially resulting in large-scale exposures within the residing population. The World Health Organization (WHO) estimates that 1.5 billion urban dwellers live in areas with levels of outdoor air pollution above the maximum recommended limits (WHO, 2005).

Epidemiological studies have shown a positive correlation between exposure to air pollutants and morbidity/mortality including asthma, chronic obstructive pulmonary disease, cardiovascular disease, lower birth weights, cancer, and premature births (ATSDR, 1997; Dockery et al., 1993; HEI, 2001; WHO, 2000). In Asia alone over 500,000 people die each year from diseases related to air pollution (WHO, 2005). Furthermore, studies have shown that particulates generated from combustion processes, especially diesel exhaust particulates, are more toxic and often result in more exacerbated health effects than those from non-combustion processes (Bremner et al., 1999; Brunekreef et al., 1997; Hoek et al., 2000; South Coast, 2000; Van Vliet et al., 1997).

Although there is a steadily growing air pollution study database, personal air pollution exposures have not been adequately studied and documented in many developing countries. For example, the only air pollutant that has been historically monitored within the Philippines is total suspended particulates (TSP), which incorporates all PM less than 50 µm in aerodynamic diameter. However, studies have shown that particles less than 2.5 µm in aerodynamic diameter (PM_{2.5}) are primarily responsible for most of the particle-related health effects (Dockery et al., 1993; HEI, 2001). Even though the 1999 Philippine Clean Air Act set ambient standards for PM₁₀, NO₂, and CO, multiple parts of the country including Baguio City have not fully complied with these new monitoring requirements as of the time of

this study due to limited resources (Republic of the Philippines, 2003).

Data collected in the downtown area of Baguio City, Philippines (Central Business District or CBD) in 2000 and 2001 indicated that Baguio was one of the most polluted cities within the Philippines with respect to PM (World Bank, 2002), much of which was derived from diesel-fueled motor vehicles [(61% of the 22,713 registered vehicles in Baguio use diesel) (Baguio DOTC, 2003)]. Additionally, unleaded gasoline was introduced in the Philippines in February 1994 and leaded gasoline was nationally phased out in 2000. The motor vehicles present that formerly used leaded gasoline were not equipped with catalytic converters and therefore would release a higher level of VOCs and NO_x during the combustion of unleaded gasoline (Hoekman, 1992). Due to the importance of Baguio as a tourism and educational hub within the northern Philippines, it is important to characterize the city's air quality and to identify potential air pollution sources.

Adequate air pollution exposure studies can be costly which may prove to be a limiting factor for many areas, particularly within developing countries. Therefore, a low-cost study design that could sufficiently predict pollutant concentrations primarily using environmental variables may prove to be suitable for areas that could not afford the equipment and personnel needed for a full air pollution study.

The objectives of this study were: 1) to identify the most predictive environmental observation variables in urban, diesel-rich areas of Baguio City, Philippines in relation to PM_{2.5}, PM₁₀ and CO concentrations during periods associated with varying motor vehicle densities and nocturnal inversions and; 2) to monitor ambient concentrations of selected air pollutants [PM_{2.5}, PM₁₀, CO, NO₂ and selected VOCs (BTEX: benzene, toluene, ethylbenzene and xylenes)] in downtown Baguio City in order to determine diurnal pollution patterns.

2. Methods

2.1. Study location

This study was conducted December 13–25, 2004 in Baguio City, Philippines. Baguio City, a city of 252,386

people as of 2000, is located at 16°N and 120°E on the island of Luzon in the Pacific Ocean 125 miles north of Manila approximately 5000 ft above sea level within the Cordillera Mountains. Baguio's elevation and corresponding cooler temperature (mean annual temperature of 68 °F) result in a regular flow of visitors from the lowlands, especially Manila. During the peak of the tourist influx, particularly during Lent (February to April), transients triple the Baguio population (WOW-Philippines, 2005).

Baguio City's CBD is located at the bottom of a mountain basin where airflow is partially impeded by the surrounding mountains resulting in an increase in frequency and intensity of nocturnal inversions, a reversal in the normal temperature lapse rate during the night with the temperature rising with increased elevation instead of falling. The asphalt-paved streets within the CBD are generally lined with buildings of two or three stories with some as high as ten stories.

Approximately half the area of the city has a slope of 25% or more (WOWPhilippines, 2005). The CBD is home to a variety of activities including but not limited to educational establishments (primary, secondary and universities), hospitals, commercial businesses, restaurants and offices/professional activities.

2.2. Street-level monitoring and environmental variables

Thirty sites (Fig. 1) within the CBD covering various levels of pedestrian, automotive and commercial activities were selected based on the general locations used in a previous study examining the impact of urban environmental features and economic status on the health conditions of 187 street vendors working within Baguio City's CBD (Akers et al., 2004). Street-level, real-time PM_{2.5}, PM₁₀ and CO were measured and environmental observational data were collected at each site during three monitoring periods on weekdays between December 13

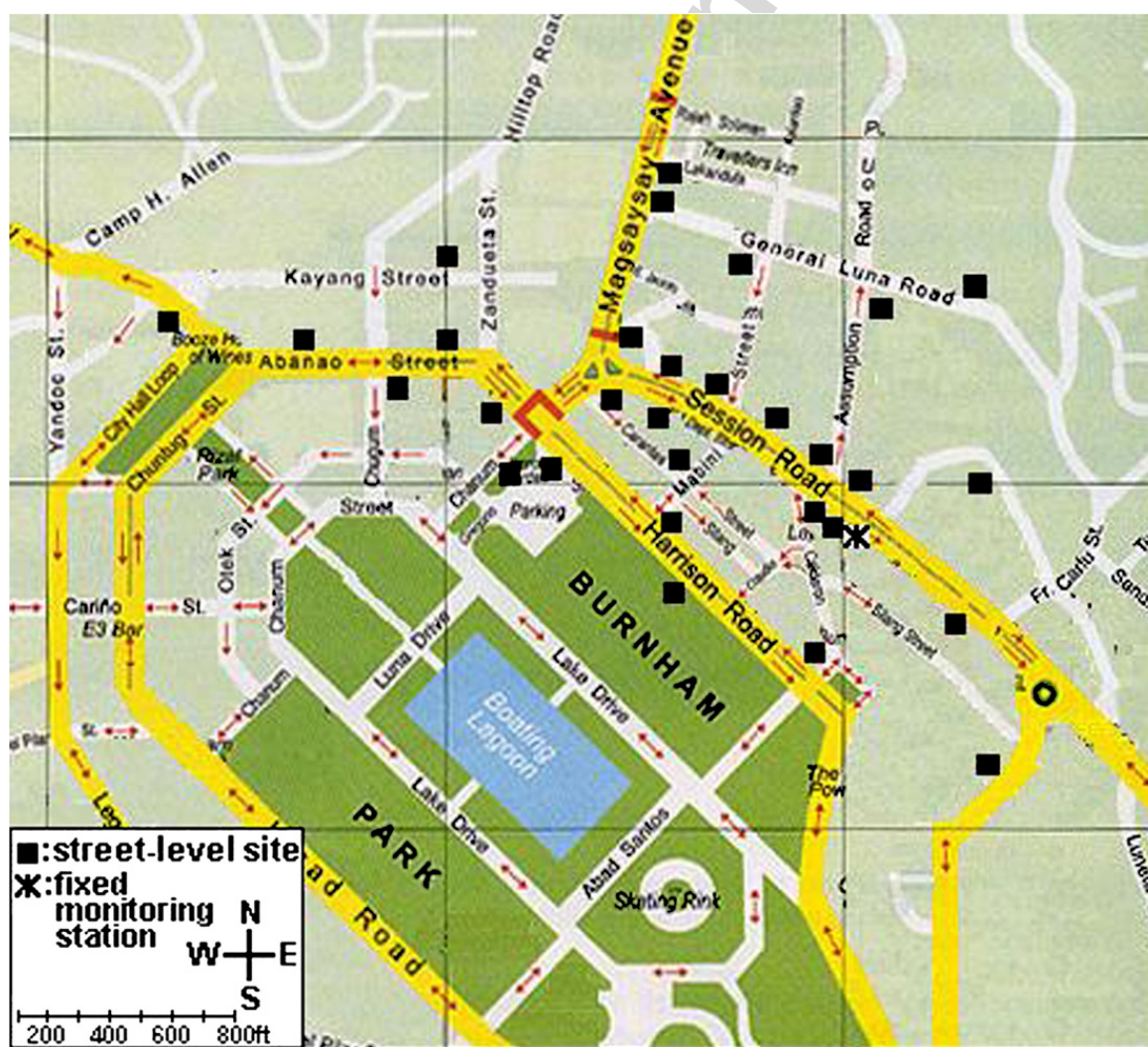


Fig. 1. Location of fixed monitoring site and 30 street sites within downtown Baguio City, Philippines.

and 22, 2004. Preliminary ambient pollution data collected at the fixed-site monitoring station and traffic observations within the CBD were used to select the three monitoring periods. Fifteen minutes of continuous, real-time data were collected once at each site between 4:50 and 6:30 am (a period of low automotive density and limited vertical atmospheric mixing), 6:30–9:10 am (morning rush hour with low to moderate atmospheric mixing including residual air pollutants returning to the ground in visible sheets after the nocturnal inversion breakup) and 3:40–5:40 pm (afternoon rush hour with moderate to high atmospheric mixing). Although the afternoon ambient pollution concentrations measured at the fixed-site monitoring station peaked at approximately 6 pm, street-level sampling ended by 5:40 pm (sunset) to ensure technician safety.

Real-time $PM_{2.5}$ and PM_{10} concentrations at each monitoring site were measured using laser photometer aerosol monitors with dataloggers (DustTrak-TSI Inc., model 8520) while real-time CO concentrations were measured in duplicate using Langan CO monitors (Langan Products Inc., model T15v). All monitors were located in or attached to a backpack with the sensor/air intake located at the chest of the investigator carrying the

equipment (approximately 1.5 m from the ground and 2 m from the closest road lane).

Thirteen environmental characteristics were noted at each of the 30 sites during each sampling period (Table 1). Automobiles and people were counted if they crossed a predetermined line perpendicular to the road in front of the monitoring site. If the site was located at the corner of an intersection of two roads, counts included the quantity from both roads. Upwind, non-motor vehicle pollution sources primarily included street vendors cooking with liquid petroleum gas, kerosene or coal and restaurants/bakeries cooking with natural gas or electricity within 20 m.

2.3. Fixed-site monitoring station

A fixed monitoring station was established to collect ambient $PM_{2.5}$ (real-time and time-integrated), PM_{10} (real-time), CO (real-time), NO_2 and BTEX VOCs (both passive diffusion, time-integrated) concentrations throughout the 11-day sampling period. The monitoring station was located on a third floor windowsill underneath an awning facing Session Road, a major six-lane road within Baguio's CBD that acts as the commercial artery of Baguio.

Table 1
Environmental observation variables used to characterize the 30 street-level sites within Baguio City, Philippines

| Variable description | Scale | Levels for dichotomous and ordinal variable | Cluster title |
|---|-------------|---|------------------------------|
| Gasoline-powered vehicles per minute | Continuous | – | Traffic Principle Component |
| Diesel-powered vehicles per minute | Continuous | – | |
| Total motor vehicles per minute | Continuous | – | |
| People per minute (foot traffic) | Continuous | – | |
| Presence/absence of a stop sign/light, traffic cop, or other means to stop traffic | Dichotomous | 0 = Absent, 1 = present | |
| Traffic flow | Ordinal | 0 = Traffic is moving smoothly, 1 = traffic is moving, but not smoothly, 2 = traffic is backed up | |
| Width of road in meters from sidewalk to sidewalk | Continuous | – | Roadsize Principle Component |
| Number of lanes in the road | Continuous | – | |
| Presence/absence of a median in roadway | Dichotomous | 0 = No median present, 1 = median present | |
| Average number of building stories present in immediate surroundings | Continuous | – | Average Building Story |
| Presence/absence of appreciable wind | Dichotomous | 0 = Wind absent, 1 = wind present | Wind |
| Presence/absence of upwind, non-motor vehicle-related pollution sources within 20 m | Dichotomous | 0 = Absent, 1 = present | Upwind Pollution Source |
| Presence/absence of hilly terrain | Dichotomous | 0 = Absent, 1 = present | Hill |
| Sampling period during which measurements were taken | Nominal | 0 = Early morning, 1 = morning rush, 2 = afternoon rush | – |

Twenty-four-hour time-integrated PM_{2.5} samples were collected in duplicate using 37 mm Teflon filters (Pall, Teflon 2.0 µm pore size), Harvard Impactors (Air Diagnostics & Engineering Inc.) and SKC universal pumps (SKC Inc. model 224-PCXR8). Sampled filters were frozen during all storage and transportation periods to prevent volatilization. Filters were desiccated in climate-controlled conditions (20.6 ± 1.4 °C; 31.0 ± 13.4% relative humidity) for a 48-hour period prior to the weighing of the filters. Each filter was weighed twice before and after sampling following the EPA's Quality Assurance Guidance Document (USEPA, 1998) using a Cahn C-35 microbalance with 0.1 µg sensitivity. Air densities during weighing sessions corrected for temperature and atmospheric pressure, nominal densities of calibration masses, and control filters were used to adjust the balance readings for the buoyancy effect of air (Koistinen et al., 1999).

Real-time PM_{2.5} and PM₁₀ levels were measured with DustTrak aerosol monitors. At the beginning of the study the four DustTraks (two for the Session Road monitoring station and two for the 30 street-level sites) operated in parallel for 20 h (8 and 12 h with PM_{2.5} and PM₁₀ inlets, respectively) in Baguio City in order to determine and control for inter-instrument variation. Additionally, a concentration ratio was established comparing the average daily real-time and gravimetric PM_{2.5} concentrations at the fixed monitoring station throughout the entire sampling period in order to adjust the real-time concentrations to increase comparability between the two sampling methods.

Real-time CO levels were continuously measured using a Langan CO monitor (Langan Products Inc., model T15v). The CO monitors were calibrated at the University of Georgia at the beginning and the end of the study with a zero gas and a 100 ppm CO gas. Both real-time CO and PM monitors operated in parallel and logged their respective mean concentrations at 30-second intervals.

Nitrogen dioxide was measured using Palmes Tubes (Palmer et al., 1976), all of which sampled for 72-hour periods. NO₂ concentrations were determined spectrophotometrically using a UV–VIS spectrophotometer (Milton Roy Company, Spectronic 20D) and a ten-point, cubic-spline fit calibration curve. The analytical limit of detection, determined using the standard deviation of field blank absorption, corresponded to 4 ppb for a 72-hour sampling period.

VOCs were collected using passive diffusion stainless steel tubes (90 mm long, 6.3 mm OD and 5 mm ID, Perkin-Elmer) packed with Tenax™ TA (60/80 mesh, 200 mg) as the absorbing medium. Each VOC tube had a

72-hour sampling period corresponding to the same sampling period of each Palmes Tube. VOC samples were analyzed using an automated thermal desorption system (Markes Unity) coupled to a ThermoElectron TRACE DSQ GC/MS. Sample volumes were calculated from the passive uptake rate of 0.54 mL/min (Brown et al., 1993; Brown and Crump, 1998, 1998; Brown, 2000).

2.4. Statistical analysis

Four environmental variables (nearby upwind non-motor vehicle pollution source, wind, road width, and people per minute) contained at least one missing value among the monitoring sites. Multiple imputation was used to fill in the missing values (Schafer, 1997) using PROCs MI and MIANALYZE in SAS version 9.1, and the results were pooled to account for and reduce the additional error introduced by estimating the missing data. The predictive mean matching method (Schenker and Taylor, 1996) was used for continuous variables (road width and people per minute) and the logistic regression method of imputation (Rubin, 1987) was used for the dichotomous variables (wind and non-motor vehicle pollution source).

Since several of the environmental variables suffered from substantial multicollinearity it was necessary to reduce the dimensionality of the predictor variables. Variable clustering techniques were used in order to avoid invalid statistical inferences often seen with backward, forward, and step-wise selection (e.g. confidence intervals too wide, *p*-values too small, detection of spurious relationships, etc.) (Harrell, 2001). Variable clustering methodology was implemented using PROC VARCLUS in SAS (Harrell, 2001; Khatree and Naik, 2000) where all variables are placed in a single cluster that is split until a stopping criterion is reached. Conceptually, this procedure uses an objective method to split all clusters in which more than one underlying dimension is represented. This is done in several steps where at each step the cluster whose second dimension is largest is chosen for splitting. Cluster splitting terminates when all clusters have second eigenvalues less than 1. After variable clustering each of the main clusters identified is represented in the analyses by the first principal component of the variables belonging to that cluster which explains at least 75% of the variability of the environmental variables within the cluster (Table 1). Several variables were not found to cluster strongly with other variables and were therefore analyzed individually (average building story, presence of hills, presence of wind, and nearby non-vehicle pollution source).

Linear mixed-effect multiple regression models were fitted of the form:

$$y_{ij} = \beta_{0j} + b_i + \beta_{1j}X_{1ij} + \beta_{2j}X_{2ij} + \dots + \beta_{6j}X_{6ij} + e_{ij}; i = 1, \dots, 30; j = 1, 2, 3$$

for the early morning, morning rush hour and afternoon rush hour average concentrations of CO, PM₁₀ and PM_{2.5}. Here, y_{ij} is the response (lnCO, lnPM₁₀, or lnPM_{2.5}) for the i th site during the j th measurement period. X_{1ij}, \dots, X_{6ij} are the environmental observation explanatory variables, and $\beta_{0j}, \beta_{1j}, \dots, \beta_{6j}$ are intercept and parameter estimates specific to the j th period. In addition, b_i is a normally distributed, site-specific random effect with zero mean and constant variance to account for within-site correlations among repeated measures taken at each site over the three measurement periods, and e_{ij} is a mean 0, constant variance, normal error term. Models were fit to each imputed data set using SAS PROC MIXED and then combined with PROC MIANALYZE. Because all three pollutant concentration variables exhibited strong heteroscedasticity, each response variable was modeled on the log scale which was successful in stabilizing the variance in the response.

PM_{2.5}, PM₁₀ and CO concentrations at each of the 30 individual street-level sites and during each monitoring period were compared for a difference in mean pollutant measurements using a least significant difference (LSD) test.

3. Results

3.1. Sampling Period Selection and Corresponding Pollution Concentrations

Traffic and commercial activities as well as preliminary ambient air pollution data within the CBD were used in the selection of both high (6:30–9:10 am,

3:40–5:40 pm) and moderately low PM and CO concentration (4:50–6:30 am) sampling periods. The high pollution sampling periods, both corresponding to rush hour periods, occurred during the day while the majority of the early morning sampling period occurred before sunrise. Although the motor vehicle density during the early morning sampling period was approximately one half of that present during the rush hours, the PM_{2.5} and PM₁₀ mean concentrations among the 30 sites were not significantly different among the three monitoring periods ($p > 0.05$, $\alpha = 0.05$) (Table 2). The corresponding street-level CO concentrations among the 30 sites statistically differed between early morning and morning rush hour ($p = 0.039$) and early morning and afternoon rush hour ($p = 0.007$) (Table 2).

Real-time concentrations measured at the Session Road monitoring station indicated that on average the lowest one-hour average ambient PM_{2.5} concentration at the Session Road station during the day (6:15 am to 5:30 pm) was 24.8 $\mu\text{g}/\text{m}^3$ (9:45–10:45 am) while the lowest average one-hour PM_{2.5} concentration during the night (5:30 pm–6:15 am) was 43.4 $\mu\text{g}/\text{m}^3$ (2:45–3:45 am). The lowest one-hour average ambient PM_{2.5} during the night was 75% higher than the day in spite of more vehicular, residential and commercial activities occurring during the day (Fig. 2).

3.2. Linear mixed-effect multiple regression modeling

The pooled results of the ln(CO), ln(PM_{2.5}) and ln(PM₁₀) multiple regression analyses appear in Table 3. The parameter estimates (β) listed in the table represents the pollutants' multiplicative effects in relation to the environmental variable or cluster listed. For example, a parameter estimate of -0.482 represents a multiplicative effect of $e^{-0.482}$ (38% decrease in pollution concentration). The explanatory variables within the CO multiple regression models containing significant parameter estimates were Wind in the early morning (parameter

Table 2
Mean PM_{2.5}, PM₁₀, CO and automotive counts for all 30 monitoring sites by sampling period

| | | PM _{2.5} ($\mu\text{g}/\text{m}^3$) | PM ₁₀ ($\mu\text{g}/\text{m}^3$) | CO (ppm) | Gasoline autos/min | Diesel autos/min |
|---------------------------------------|------------------------------|--|---|---------------|--------------------|------------------|
| Early morning (4:50–6:30 am) | Average \pm standard error | 110 \pm 14 | 118 \pm 14 | 3.0 \pm 1.7 | 2.5 \pm 1.6 | 10.4 \pm 6.5 |
| | Maximum | 240 | 272 | 5.3 | 5.0 | 23.1 |
| | Minimum | 50 | 54 | 1.9 | 0.0 | 0.1 |
| Morning rush hour (6:30–9:10 am) | Average \pm standard error | 98 \pm 13 | 124 \pm 20 | 4.1 \pm 2.3 | 6.6 \pm 3.9 | 18.7 \pm 9.5 |
| | Maximum | 274 | 55 | 9.8 | 20.9 | 41.9 |
| | Minimum | 42 | 48 | 2.2 | 0.3 | 0.9 |
| Afternoon rush hour (3:40–5:40 pm) | Average \pm standard error | 107 \pm 10 | 117 \pm 11 | 4.5 \pm 2.2 | 6.6 \pm 3.8 | 20.5 \pm 10.6 |
| | Maximum | 287 | 300 | 11.2 | 18.0 | 44.1 |
| | Minimum | 47 | 52 | 2.4 | 0.1 | 1.8 |

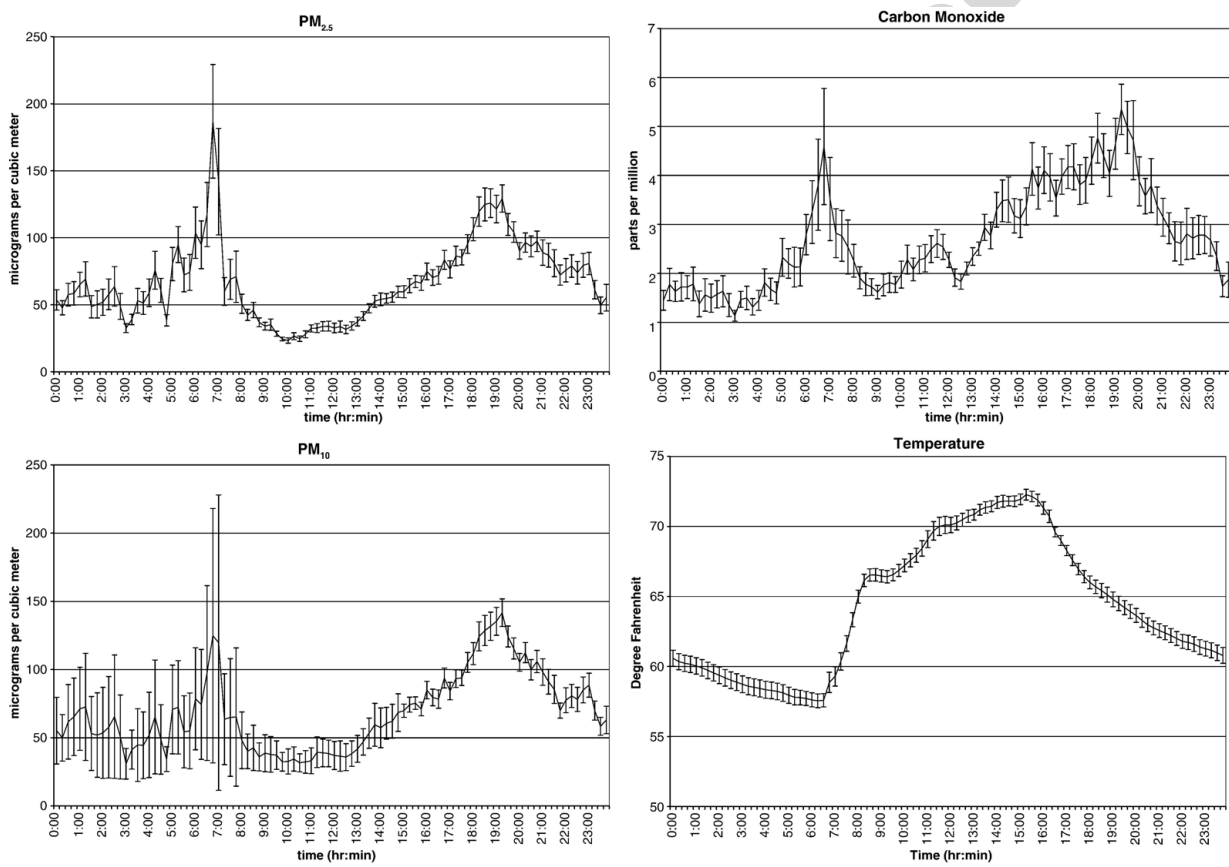


Fig. 2. 15-minute mean ± 1 standard error $PM_{2.5}$, PM_{10} , CO and temperature present at the Session Road monitoring station throughout the entire sampling period ($n=11$ days).

Table 3

Statistically significant predictors of the linear mixed-effect regression models for $\ln(\text{CO})$, $\ln(\text{PM}_{2.5})$ and $\ln(\text{PM}_{10})$

| Pollutant | Statistically significant predictors | Period 1 | | | Period 2 | | | Period 3 | | |
|------------------------|--------------------------------------|--------------------------|----------------|-----------------|--------------------------|----------------|-----------------|--------------------------|----------------|-----------------|
| | | Parameter estimate | Standard error | <i>p</i> -value | Parameter estimate | Standard error | <i>p</i> -value | Parameter estimate | Standard error | <i>p</i> -value |
| $\ln(\text{CO})$ | Traffic PC | No significant variables | | | 0.179 | 0.084 | 0.048 | 0.204 | 0.089 | 0.034 |
| | Any wind | -0.482 | 0.221 | 0.044 | No significant variables | | | No significant variables | | |
| $\ln(\text{PM}_{2.5})$ | Traffic PC | 0.542 | 0.213 | 0.021 | No significant variables | | | No significant variables | | |
| $\ln(\text{PM}_{10})$ | Traffic PC | 0.458 | 0.214 | 0.048 | No significant variables | | | No significant variables | | |

Period 1 = early morning: 4:50–6:30 am.

Period 2 = morning rush hour: 6:30–9:10 am.

Period 3 = afternoon rush hour: 3:40–5:40 pm.

estimate = -0.482; 38% decrease with wind present; $p=0.044$) and Traffic Principal Component (Traffic PC) in both morning rush hour (parameter estimate = 0.179; 20% increase; $p=0.048$) and afternoon rush hour (parameter estimate = 0.204; 23% increase; $p=0.034$). Traffic PC was the only significant explanatory variable produced in the $\text{PM}_{2.5}$ (parameter estimate = 0.542; 72% increase; $p=0.021$) and PM_{10} (parameter estimate = 0.458; 58% increase; $p=0.048$) multiple regression models, and both occurred during the early morning monitoring period.

3.3. Average ambient concentrations at Session Road station

Table 4 shows the mean \pm standard deviation, maximum and minimum 24-hour average of the pollutants measured at the Session Road station over the 11 days of

Table 4

24-hour pollutant average at Session Road monitoring station over the entire sampling period

| Pollutant | # of days | Unit | Average \pm standard deviation | Max | Min |
|---|-----------|--------------------------|----------------------------------|-------|------|
| $\text{PM}_{2.5}$ (Harvard Impactor) | 11 | $\mu\text{g}/\text{m}^3$ | 72.9 \pm 21.2 | 124.4 | 46.7 |
| $\text{PM}_{2.5}$ (Harvard Impactor) | 8 | $\mu\text{g}/\text{m}^3$ | 67.0 \pm 17.5 | 105.0 | 46.7 |
| $\text{PM}_{2.5}$ (DustTrak) ^a | 8 | $\mu\text{g}/\text{m}^3$ | 67.0 \pm 28.2 | 117.5 | 43.0 |
| PM_{10} (DustTrak) ^a | 8 | $\mu\text{g}/\text{m}^3$ | 80.1 \pm 28.0 | 127.9 | 56.8 |
| CO | 11 | ppm | 2.64 \pm 0.6 | 3.6 | 1.4 |
| NO_2 ^b | 11 | ppb | 27.7 \pm 1.6 | 26.1 | 29.7 |
| Benzene ^b | 11 | $\mu\text{g}/\text{m}^3$ | 8.4 \pm 1.4 | 9.9 | 6.9 |
| Ethylbenzene ^b | 11 | $\mu\text{g}/\text{m}^3$ | 4.6 \pm 2.0 | 6.6 | 1.9 |
| <i>p</i> -xylene ^b | 11 | $\mu\text{g}/\text{m}^3$ | 4.4 \pm 1.9 | 6.3 | 1.8 |
| <i>m</i> -xylene ^b | 11 | $\mu\text{g}/\text{m}^3$ | 10.2 \pm 4.4 | 14.8 | 4.7 |
| <i>o</i> -xylene ^b | 11 | $\mu\text{g}/\text{m}^3$ | 7.5 \pm 3.2 | 10.8 | 3.4 |

^a Complete 24-hour real-time data were collected for only 8 out of 11 days due to equipment problems; data from the 3 incomplete days are omitted.

^b Samples ran for a 72-hour period.

sampling. Complete 24-hour DustTrak $\text{PM}_{2.5}$ and PM_{10} data were only collected on 8 of the total 11 sampling days due to equipment problems with the three days of incomplete data occurring within the first half of sampling. The average $\text{PM}_{2.5}$ and PM_{10} concentrations measured by the DustTraks during the eight days of uninterrupted sampling were 67.0 ± 28.2 and 80.1 ± 28.0 , respectively. The 24-hour average gravimetric $\text{PM}_{2.5}$ during the 8 days corresponding to the DustTrak data was $67.0 \pm 17.5 \mu\text{g}/\text{m}^3$ and was $72.9 \pm 21.2 \mu\text{g}/\text{m}^3$ (max = $124.4 \mu\text{g}/\text{m}^3$; min = $46.7 \mu\text{g}/\text{m}^3$) during the total 11 days sampling period. CO and NO_2 concentrations throughout the entire sampling period were 2.64 ± 0.6 ppm and 27.7 ± 1.6 ppb, respectively. The 24-hour (PM and CO) and 72-hour (NO_2 and VOCs) mean concentrations of each pollutant except BTEX VOCs decreased as December 25 (last day of sampling) approached with the highest sample concentration (either 24 h or 72 h depending on the pollutant) of each pollutant occurred within the first half of the study. Toluene values are not reported due to high-variability in field blank concentrations.

4. Discussion

4.1. Multiple regression models and nocturnal inversions

In spite of more motor vehicle, residential and commercial activities occurring within Baguio's CBD during the day opposed to the night, the lowest one-hour average ambient $\text{PM}_{2.5}$ concentration measured at the Session Road station during the night was 75% higher than that during the day (Fig. 2). This difference in ambient concentrations is most likely due to the presence of nocturnal inversions often present within Baguio due to its location within a mountain basin. Inversions prevent the vertical mixing of air during the night therefore increasing air stagnation resulting in the production of a "blanket" of air pollution in the lower

atmosphere. Morning PM was shown to greatly increase just after sunrise when the pollution blanket was broken up by the sun and returned to ground-level as indicated in the increase of temperature and PM concentrations starting at 6:30 am in Fig. 2.

Due to nocturnal inversions and varying pollution sources throughout the day making each sampling period unique, individual models were formulated for each sampling period opposed to one model containing all the data merged from the three sampling periods. Within the PM_{2.5} and PM₁₀ multiple regression models traffic intensity was the only significant explanatory variable and was only significant in the early morning sampling period. During this time period the limited vertical mixing of the lower atmosphere due to the nocturnal inversion created a scenario in which air pollution dispersed poorly allowing the PM to remain present for longer periods of time. The scarcity of commercial pollution emissions within the CBD during the 4:30–6:30 am monitoring period created a scenario in which motor vehicle emissions could comprise a larger percentage of street-level PM_{2.5} and PM₁₀. Secondly, the presence of wind had a significantly negative association with early morning CO concentrations because increased wind speeds would result in increased horizontal CO dispersion rates.

Although motor vehicle densities were highest during the rush hour periods, other pollution sources were present (e.g. street vendors and restaurants/bakeries) contributing to the overall pollution. During the morning rush hour period (6:30–9:10 am) Baguio's CBD was heavily influenced by the remnants of the inversion's "pollution blanket" as it returned to the ground in heavy, visible sheets as well as few commercial and residential point sources. The afternoon rush hour period (3:40–5:40 pm) was similar to the morning rush hour except all commercial businesses were open and the vertical

mixing of the lower atmosphere was expected to be at its highest rate. Non-automotive pollution sources were not found to be significant during the rush hours potentially due to the inability to adequately quantify pollution sources such as the inversion blanket and those originating from within buildings.

4.2. Ambient pollution concentrations

The results of this study indicate that air pollution levels, particularly PM, in Baguio City are potentially elevated and therefore may merit public health concern. Since there are no Filipino PM_{2.5} ambient standards, the US National Ambient Air Quality Standards (NAAQS) will be used for comparison. The mean 24-hour PM_{2.5} concentration measured at the Session Road fixed monitoring site (72.9 $\mu\text{g}/\text{m}^3$; $n=11$ 24-hour samples) was higher than the NAAQS annual (15 $\mu\text{g}/\text{m}^3$) and 24-hour (65 $\mu\text{g}/\text{m}^3$) standards present in the US (US CFR, 1997). Although the sampling period was not long enough to declare the area out of compliance, the concentrations present, if sustained for a long enough period of time, would result in a violation of these standards. With all five of the eleven sampling days over the 24-hour limit (65 $\mu\text{g}/\text{m}^3$) occurring within the first half of the study (Dec. 14–19), the negative trend indicated that pollution concentrations were decreasing as the religious and political holiday season (Christmas) approached. This decrease is believed to be due to less automotive traffic within the CBD because of increased leave from work and the closings of the schools and colleges within the CBD for the holiday season. The mean 24-hour CO (2.64 ppm) and NO₂ (27.7 ppb) concentrations measured at the Session Road fixed monitoring site were below established Philippine (24-hour NO₂=0.08 ppm; 8-hour CO=9 ppm; 1-hour CO=31 ppm) and US (annual NO₂=0.053 ppm; 8-hour

Table 5
Mean PM_{2.5} concentrations measured in various urban, ambient air pollution studies throughout the world

| Citation | Sampling period | Sampling location | PM _{2.5} ±1 standard deviation ($\mu\text{g}/\text{m}^3$) |
|----------------------------|----------------------------|-----------------------------------|--|
| Yang et al. (2005) | July 1999–June 2000 | Beijing, China | 116.0 |
| Chan et al. (2005) | August 2003 | Beijing, China | 93.6 |
| This study | December 2004 | Baguio City, Philippines | 72.9±21.2 |
| Kang et al. (2004) | April 2001–February 2002 | Seoul, South Korea | 48.5 |
| Götschi et al. (2005) | June 2000–December 2001 | Turin, Italy | 44.9±22.5 |
| Shendell and Naeher (2002) | May–June 1997 | Guatemala City, Guatemala | 37.9±21.5 |
| Cassidy et al. (in review) | July–August 2003 | Trujillo, Peru | 36.1±9.2 |
| Chow et al. (2002) | February–March 1997 | Mexico City, Mexico | 38.7 |
| USEPA (2005) | January 2002–December 2004 | Los Angeles-South Coast Air Basin | 24.8 |
| Götschi et al. (2005) | June 2000–December 2001 | Barcelona, Spain | 22.2±7.6 |
| Götschi et al. (2005) | June 2000–December 2001 | Paris, France | 17.8±6.9 |
| Götschi et al. (2005) | June 2000–December 2001 | Reykjavik, Iceland | 3.7±1.7 |

CO=9 ppm; 1-hour CO=35 ppm) air pollution standards indicating that these levels are unlikely to lead to adverse health outcomes within the general population.

Table 5 compares the ambient concentrations measured in this study to urban, ambient PM_{2.5} concentrations seen in other studies from around the world. Excluding the studies in Beijing, China no study observed an average ambient PM_{2.5} concentration as high as the levels present in Baguio City. Even the Los Angeles-South Coast Air Basin, which had the highest 2002–2004 average ambient PM_{2.5} of all areas within the United States, had a mean PM_{2.5} concentration 1/3 of that measured in Baguio City. Continuous ambient concentrations of the magnitude seen in Baguio are rarely seen in developed countries and sporadically seen within developing countries except in areas prone to elevated pollution concentrations partially due to local topography. The combination of pollution sources and the local topography make Baguio City's ambient air quality worse than that seen in most locations throughout the world.

In 2003 there were a total of 22,713 vehicles registered in Baguio City (Department of Transportation and Communication, 2003). Of these cars 61% run on diesel fuel, and the majority of the motor vehicles present within the CBD, primarily taxis and jitneys, use diesel. In addition to the fact that the ambient and street-level concentrations potentially exceed pollution standards, the fact that diesel fuel emissions comprise a large percentage of the ambient pollution in Baguio's CBD makes the scenario more threatening. Studies have shown that diesel exhaust particles are often more toxic than those from other combustion processes resulting in increased exacerbation of negative health effects (Bremner et al., 1999; Brunekreef et al., 1997; Hoek et al., 2000; Van Vliet et al., 1997).

With three elementary/high schools, two technical schools and four colleges within Baguio's CBD there is a regular presence of children, teenagers and young adults within the area. The average pedestrian count during the monitoring periods of the 30 street sites was 29.0 people per sidewalk per minute (max of 146 people per minute), several of which were young children. Van Vliet et al. (1997) studied whether motor vehicle exhaust had an effect on respiratory health of children who attended schools within 1000 m of a major roadway and found that traffic density of the closest roadway and the amount of time the school was downwind of the roadway were significant predictors of black smoke concentrations, an indicator for diesel emissions, in the schools. The study derived that long-term exposures to traffic-related air pollution, in particular diesel exhaust particles, may increase multiple chronic respiratory symptoms especially in girls. A separate study performed by the University

of the Philippines measured the impact of vehicular emissions on vulnerable populations in Metro Manila in 1990–1991 and 1994 found that the prevalence of respiratory symptoms among school children and children who work as street vendors ranged from 4.8 to 27.5% and 15.8 to 40.6%, respectively (Subida and Torres, 1994).

4.3. Limitations

The limitations of this study primarily stem from the short sampling time. Since ambient sampling took place over 11 days, this study could not address seasonal effects making it difficult to determine if the ambient concentrations measured were representative of the annual average. With historic air pollution data outside of TSP lacking, it is hard to determine how pollution concentrations fluctuate throughout the year. However, the study took place during the city's dry season (October to May) when rain, which removes PM from the atmosphere, is scarce. Since the study occurred during the dry season and in winter when temperature inversions are likely to be stronger, the pollution concentrations measured may be greater than those during the warmer, wetter season. However, air pollution concentrations were declining during the second half of sampling period potentially due to a holiday effect which would lower the average concentrations measured in comparison to a time that saw no such effect.

Secondly, the use of DustTraks in a variety of settings created a limiting factor. All of the DustTraks were adjusted according to a concentration ratio created using the data produced by a DustTrak and two gravimetric PM_{2.5} monitors collocated at the Session Road station over the 11 days of sampling. The PM measured three stories above street-level at the monitoring station may not be representative of the PM measured at various locations within the CBD therefore potentially changing the concentration ratio. Since gravimetric measurements could be not taken at the 30 street-level monitoring sites, the concentration ratio produced at the fixed monitoring station was used for all locations in the study.

Thirdly, the air currents present at the third story location of the fixed monitoring site may have been affected by the structural design of the windowsill, awning and surrounding buildings. These microair current variations may have been different at ground-level potentially affecting pollution dispersion patterns. Ideally, an additional fixed monitoring station would have been established at ground-level directly below the third-story monitors in order to correlate the ground-level and third-story diurnal pollution fluctuations, determine the vertical pollutant distribution, and investigate whether or

not potential air current variations significantly altered pollutant concentration variations at the third-story level. A lack of additional monitoring equipment and equipment security issues prevented a ground-level monitoring station from being present within the CBD.

Finally, only 45 min of sampling per site was collected, most of which were during times of high pollution concentrations. Therefore, the ability to extrapolate these short samples to human exposures over long periods of time is limited. However, many health conditions associated with short-term PM exposures such as reduced breathing capacity can be seen within minutes thus making these “worst case” samples important in relation to acute exposures.

5. Conclusions

The data suggest that ambient PM_{2.5} levels in Baguio City, Philippines are potentially above the US EPA daily (65 µg/m³) and annual ambient standards (15 µg/m³) and as such warrant public health concern. Further, the data suggests that nocturnal inversions play a large role in the night and early morning's PM concentrations within the CBD by limiting the vertical mixing of the lower atmosphere and preventing the dilution of PM and CO. The use of environmental observational variables in predicting PM and CO concentrations indicated that traffic-related variables and the presence of wind were the most representative environmental observational variables.

Future research in Baguio City, Philippines is necessary to determine seasonal variation of ambient pollution as well as measuring personal exposures of air pollution to tourists and citizens. With over one-half million people visiting Baguio annually and multiple schools located in Baguio's CBD, pollution concentrations of the magnitude seen in this study should be further investigated. Additionally, the presence of air pollution within Baguio City may pose potential economic implications for the city where tourist-related income plays an important role in the local economy.

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