BLACK CARBON AEROSOL CONCENTRATION IN FIVE CITIES AND ITS SCALING WITH CITY POPULATION

BY G. PAREDES-MIRANDA, W. P. ARNOTT, H. MOOSMÜLLER, M. C. GREEN, AND M. GYAWALI

Analysis of aerosol light scattering and absorption measurements in five cities suggests that common air pollutant concentrations scale approximately as the square root of the urban population—consistent with a simple 2D box model.

Pollution accumulation during persistent inversions has been associated with notoriously high death rates during events such as the London smog and five days in Donora (Ahrens 2009). Yet the current increase of city sizes leads to less obvious but persistent increases in air pollution concentrations and related health impacts.

Paul Ehrlich said "Too many cars, too many factories, too much detergent, too much pesticide, multiplying contrails, inadequate sewage treatment plants, too little water, too much carbon dioxide—all can be traced easily to too many people" (Erlich 1971, p. 44). The trend toward urbanization in most countries is aggravating pollution problems (Hodges 1973), suggesting scrutiny of the relation between average local air pollution and city population.

While in recent decades, the rate of world population growth has declined, leading to a prediction of population stabilization in 2050 at about 9 billion people (United Nations 2004), three other factors must be taken into account that affect air pollution: 1) because of the constant technological and economic growth, the global air pollution problem has been increasing for decades (see, e.g., Friedlingstein et al. 2010), linked to the fast growth of energy consumption, industrial production, electric power production, motor vehicle use, etc.; 2) in many parts of the world, the pollution control techniques have not developed at the same pace [although, for example, in the United States air emissions decreased in recent years (Environmental Protection Agency 2012)]; and 3) the fraction of global population that lives in large cities has been rising continually in the last decades, further aggravating the air pollution problem in urban areas.

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Because of their short residence time, and proximity to sources, anthropogenic aerosols tend to have their highest concentrations in urban areas. Graphitic-like carbon (soot), a by-product of the burning of fossil fuels, is a major and ubiquitous absorber of light (Rosen and Novakov 1984). Soot, also known as black carbon aerosol (BC), is an aerosol component with strong human but relatively few natural sources (only naturally ignited fires). Furthermore, BC is generally responsible for most of the absorption of incoming solar radiation by aerosol. In addition, organic carbon (OC) and mineral dust can also absorb a lesser amount of solar radiation; however, currently this amount cannot routinely be quantified (Moosmüller et al. 2009).

Aerosol light scattering and absorption measurements were carried out in Mexico City, Mexico, during the Megacities Initiative: Local and Global Research Observations (MILAGRO) campaign in March 2006 (Paredes-Miranda et al. 2009). We additionally analyzed light absorption and scattering in situ measurements carried out in Las Vegas, Nevada, in January–February 2003; Reno, Nevada, from December 2008 through March 2009; Beijing, China, in a period of 2005/06 (He et al. 2009); and Delhi, India, from April 2008 through March 2009 (Soni et al. 2010). Light absorption and scattering measurements are used to obtain BC and particles with aerodynamic diameter smaller than 2.5 μm, (i.e., $PM_{2.5}$, where PM stands for particulate matter) mass concentration estimates.

A simple model for the city-size dependence of urban atmospheric pollution is proposed that suggests aerosol pollution concentration (and thus, both the absorption and scattering coefficients) should scale approximately with the square root of the city population. This scaling may be considered as a useful metric that arises from the assumption that specific city conditions (such as latitude, altitude, local meteorological conditions, degree of industrialization, population density, city shape, etc.) vary randomly independent of city size. The data from the in situ measurements are used to carry out an intercity comparison and to test the approximate validity of the simple model considered. The point of view of this paper certainly is not to suggest a replacement for detailed air pollution modeling efforts; rather, it is to provide a physically intuitive understanding and interpretation for air pollution levels observed in different cities.

The paper is organized as follows: The "A model for the city-size dependence of urban atmospheric pollution" section describes a simple model for the relation between city size and urban atmospheric pollution, and proposes formulas to estimate the emission per person per day in a city. The "Mexico City, Mexico," "Las Vegas, Nevada," and "Reno, Nevada" sections describe the sites where the in situ measurements were carried out. The "Measurement methods" section describes the measurement methods and instruments used. In the "Results and discussion" section we carry out a review of the meteorological conditions at the sites during the measurement campaigns. The intercity comparison is carried out in the "Average diurnal aerosol light scattering and absorption" section and includes a comparison of our experimental results with the simple theoretical model described in the "A model for the city-size dependence of urban atmospheric pollution" section, an estimation of emission per person per day, as well as a discussion of our results. Comparison between measurements and model are discussed in the "Comparison between measurements and model" section. In the "Conclusions" section we present our conclusions.

A MODEL FOR THE CITY-SIZE DEPENDENCE OF URBAN ATMOSPHERIC POLLUTION.

A simple model has been proposed (Mahmoud et al. 2008) that may be used to estimate the urban PM mass concentration in terms of city population and emission and meteorological parameters, such as averaged wind velocity, planetary boundary layer (PBL) height, and surface net PM mass flux. This model includes a series of simplifications, such as 1) day-to-day variation of PBL height is not included in the model (in general, "steady-state" conditions are considered); 2) an average wind velocity is used for PBL; 3) PM mass concentration at the surface level is assumed representative of the concentration averaged over the height of the PBL; and 4) wind velocity, v, PBL height, h, and surface net PM mass flux, ε (including the effects of emission and deposition), are considered to be statistically independent of city population. The model captures the essential relation between PM mass concentration and city size.

PM mass concentration, $C(x,t)$, is a function of time, t, and the spatial coordinate, x, is parallel to the wind direction. Consider a box where the horizontal area, WL (width times length), represents a fraction of the city surface, and the vertical height, h, represents PBL height (Fig. 1). The PM mass transported by the wind into the box in a period of time dt may be estimated as $C(x,t)Whvdt$. The PM mass leaving the box transported by the wind is $C(x + L, t)Whvdt$. The PM mass that enters into the box because of the emission by sources located in the area WL is equal to $\varepsilon WLdt$. Conservation of PM mass leads to

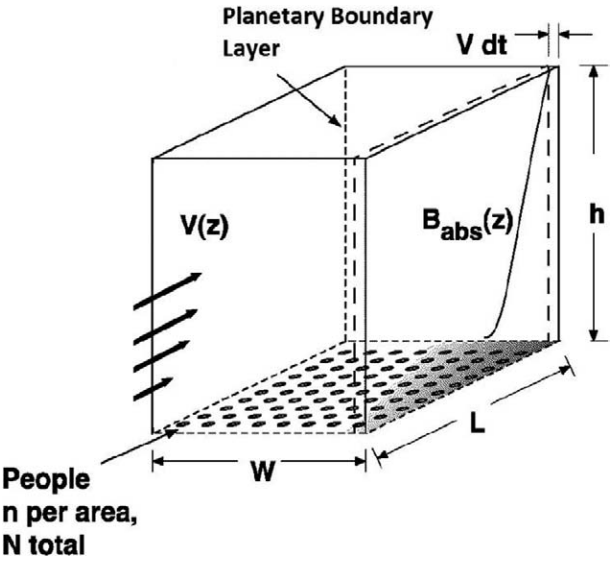

Fig. 1. Sketch of a control box to investigate the local transport of pollutants and the spatial variation of the pollutant concentration in an urban region. Here *V*(z) is the wind profile as a function of height. If the wind velocity is averaged over all the PBL, a value of *V* is obtained. The horizontal linear dimensions of the box in the parallel and perpendicular directions to the wind are, respectively, *W* and *L*; *h* is the PBL height; and B_{abs}(z) is the vertical profile for the absorption coefficient.

$$[C(x + L, t) - C(x,t)]\ Whvdt = \varepsilon WLdt.$$

If we consider an infinitesimal length $L = dx$, this equation can be transformed into a differential equation:

$$\frac{\partial C(x,t)}{\partial x} = \frac{\varepsilon}{vh}. \qquad (1)$$

The quantity vh is time dependent because of the diurnal variation of the PBL height that is driven by the incoming solar radiation absorbed by the ground, and is due to variations in the wind velocity. Integrating Eq. (1) from the upwind limit ($x = 0$) down to the location of the measurement site ($x = x_m$) leads to

$$C(x_m,t) = \left(\frac{1}{vh}\right)\int_0^{x_m} \varepsilon dx + C(0,t), \qquad (2)$$

where $C(0, t)$ is the pollution concentration at the upwind limit of the city. We assume that for relatively big cities, the term $C(0, t)$ in Eq. (2) is independent of city size and is small relative to the term containing the integral. We will ignore it in the following.

If ε is assumed to be constant along the city, the integration of Eq. (2) leads to $C = (\varepsilon x_m)/(vh)$. Considering a location in the geometrical center of the city as representative, we have $x_m \sim A^{1/2}/2$ and, therefore,

$$C \sim (\varepsilon A^{1/2})/(2vh) = (\varepsilon\sigma^{1/2})(2vh)^{-1}N^{1/2} \sim N^{1/2}, \qquad (3)$$

where σ denotes the population density (assumed constant). We now review the assumptions used to obtain Eq. (3). First, it was assumed that, in Eq. (2), none of the meteorological parameters v, h, or ε has a crucial statistical correlation with the city total population. Obviously, this is only an approximation neglecting second-order effects of, for example, modified surface roughness and permeability and temperature (i.e., urban heat island) that can be a spatially varying function of city population. On the other hand, the length interval of integration in Eq. (2) should be proportional to the linear dimension of the city toward wind direction, and thus scales like the square root of the city area, or equivalently, like the square root of the city population, N (see Fig. 2). Consequently, the urban aerosol concentration C should also approximately scale like $N^{1/2}$ [as expressed in Eq. (3)]. Concerning its use for intercity comparisons, the previous argument has many caveats, since 1) v and h depend strongly on latitude, altitude, and in general on local meteorological conditions, as well as on the particular season when the measurements are carried out; and 2) even if ε is essentially population independent, it does depend on specific characteristics of the city lifestyle, such as the degree of industrialization, the number of cars per capita, the population density, emission controls or air pollution regulations, the city shape, and so on. We will assume that all these properties vary randomly with city population N. However, we consider a proportional relationship between C and $N^{1/2}$ as a very useful metric for the intercity comparison, as will be shown in the following analysis. Eq. (3) is taken to apply equally for all common pollutants, including BC.

Urban atmospheric light absorption is dominated by BC absorption (Seinfeld and Pandis 2006; He et al. 2009). The light absorption coefficient, B_{abs}, is given by Eq. (4a) as the product of the mass absorption efficiency, MAE, and the black carbon concentration, C_{BC} (Seinfeld and Pandis 2006). Therefore, from Eq. (3),

$$B_{abs} \sim MAE(\varepsilon_{BC}A^{1/2})/(2vh), \qquad (4a)$$

where ε_{BC} is the net BC surface flux.

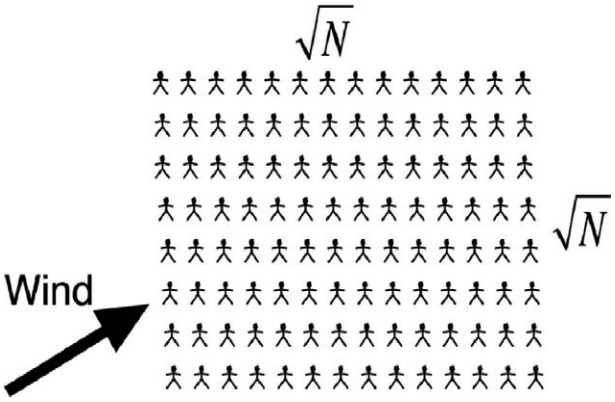

Fig. 2. Air pollution concentration scales approximately as the square root of population.

Light scattering in the urban atmosphere is dominated by $PM_{2.5}$ (Moya et al. 2011). For scattering by fine particles ($PM_{2.5}$),

$$B_{sca} \sim \mathrm{MSE}(\varepsilon_{PM2.5} A^{1/2}) / (2vh), \quad (4b)$$

where $\varepsilon_{PM2.5}$ is the $PM_{2.5}$ surface mass emission flux and MSE is the mass scattering efficiency.

All desirable measurements are made below a relative humidity (RH) of 65% so the hygroscopic growth does not affect the results (this refers to the RH inside the photoacoustic instrument used to measure the B_{sca} and B_{abs} coefficients).

GEOGRAPHICAL SETTING AND INSTRUMENTATION. Three cities were chosen to carry out in situ measurements of light absorption and scattering: Mexico City, Mexico, and Las Vegas and Reno, Nevada. Data from these studies as well as data reported by other authors on studies in Beijing, China (He et al. 2009), and Delhi, India (Soni et al. 2010), are used in the "Results and discussion" section to study how pollutant concentrations scale with city population. Detailed characteristics for each of the first three cities are given next.

Mexico City, Mexico. Mexico City is one of the 20 largest urban regions of the world (Bravo and Torres 2000). The Federal District (D.F.) and 17 counties of the State of Mexico form the Mexico City metropolitan area (MCMA), which has a population of ~23 million people with an area of ~7,815 km^2. It is located at latitude 19.42°N and longitude 99.13°W at an altitude of ~2,240 m. The altitude and latitude of Mexico City play an important role not only in the photochemistry of pollutants but also for the radiation regime; nocturnal radiation cooling occurs, in particular, during the dry season when cloudless nights are very frequent. This condition, associated with a relatively large temperature drop after sunset, reduces the height of the PBL (Galindo 1984). Most of the air pollution is a result of the combustion of fossil fuels (gasoline and diesel). Biomass burning (BB) can also be a relevant pollution source during the dry season, especially for PM (Molina et al. 2007; Yokelson et al. 2007; DeCarlo et al. 2008; Paredes-Miranda et al. 2009).

The site of our measurements was located at the Instituto Mexicano del Petroleo (IMP) northeast of D.F. (latitude 19.49°N, longitude 99.15°W), which was assigned the name of "T0 site" for the MILAGRO campaign that was carried out during 9–28 March 2006 (Paredes-Miranda et al. 2009; Molina et al. 2010).

Las Vegas, Nevada. The Las Vegas, Nevada, metropolitan area (LVMA) has a population of ~2 million within an area of ~1,600 km^2. It is located at latitude 36.10°N and longitude 115.18°W at an altitude of ~610 m. Prevailing winds from October through March are mainly westerly. In April and May, winds tend to be southwesterly and from June through September winds are mostly southerly. Las Vegas was one of the fastest growing metropolitan areas in the United States. According to a study by Watson et al. (2007), LVMA pollution sources are dominated by contributions from paved road dust and on-road mixed fleet gasoline vehicles. Our measurements in LVMA were taken at the East Charleston Street site (latitude 36.16°N, longitude 115.08°W) during the period of 8 January–9 February 2003.

Reno, Nevada. Reno, Nevada, metropolitan area (RNMA) is located at latitude 39.52°N and longitude 119.80°W at an altitude of ~1,373 m and is the largest metropolitan area in northern Nevada (this study includes Sparks, Nevada, as part of the metropolitan area). Southerly prevailing winds from October through February and westerly winds from March through September were reported in a compilation data from 1992 to 2002 at www.wrcc.dri.edu. RNMA has an area of ~242 km^2 and an overall population of ~310,047. Different sources of particulate matter in the RNMA include, for example, motor vehicle exhaust, residential wood combustion, secondary species such as ammonium nitrate and ammonium sulfate (Gillies et al. 2008), and wildfire activity. The site where the measurements were carried out was the physics building of the University of Nevada, Reno (UNR) (latitude 39.54°N, longitude 119.81°W), from 10 December 2008 to 31 March 2009.

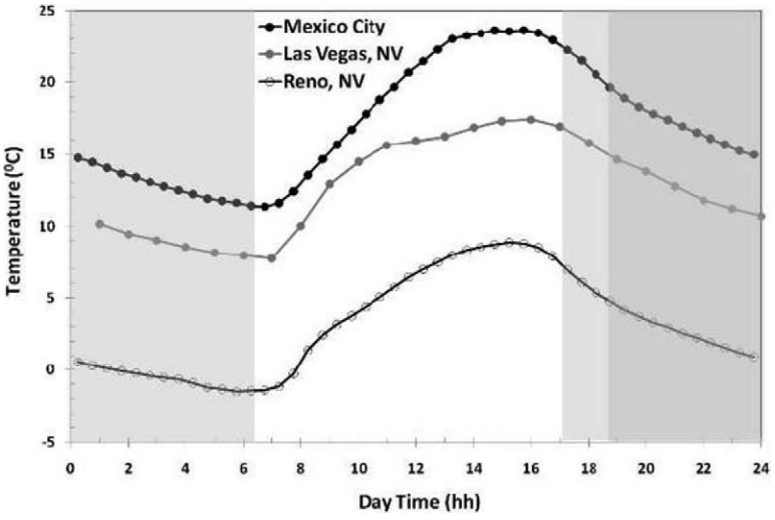

Fig. 3. Temperature as a function of the time of day for three different cities. For MCMA on 9–28 Mar 2006 (CST), for LVMA on 6 Jan–15 Feb 2003 (PST), and for RNMA on 1 Dec 2008–31 Mar 2009.

Measurement methods. Aerosol light absorption at all three sites was measured with the photoacoustic spectrometer (PAS) method at a wavelength of 532 nm (Arnott et al. 2005; Paredes-Miranda et al. 2009). Simultaneous light scattering measurements are accomplished within the PAS by use of an optical sensor configured to operate as a reciprocal nephelometer. At the T0 site in Mexico City, meteorological data were obtained from a Vaisala weather station (Marley et al. 2009). For the LVMA the wind speed was measured at the East Charleston site, while Reno surface meteorology was characterized at an open field about 2 km east of our aerosol optics site on the UNR campus.

RESULTS AND DISCUSSION.

Meteorological discussion. Temperature. Figure 3 shows an intercity comparison of the diurnal variation of air temperature, averaged over the whole studied period—from 9 to 28 March 2006 for Mexico City, local time [i.e., central standard time (CST)]; from 6 January to 15 February 2003 for LVMA, local time [i.e., Pacific Standard Time (PST)]; and from 1 December 2008 to 31 March 2009 for RNMA, local time (i.e., PST). The higher latitude and intermediate altitude of Reno accounts for its lower temperature in winter compared to Mexico City and Las Vegas. In these cities the low night temperature starts to rise at about 0630 (sunrise). The maximum temperature is observed at about 1500 for these cities and starts to drop soon after that.

Wind. Figure 4 shows the corresponding intercity comparison for wind velocity. MCMA and RNMA turn out to be windier than LVMA in the studied period. In the case of Reno and Las Vegas, wind speed starts to increase slowly from about 0800, reaching a maximum at about 1500 when the decline starts. MCMA shows stronger variations of wind velocity, including a sharp increase during the day, peaking at about 1800. When the day is over, winds tend to ventilate Mexico City. MCMA likely gets a break on its air pollution levels due to high wind speeds.

PBL. The development of the PBL in an urban area plays a key role in the distribution of atmospheric constituents. The driving forces to evolve the PBL are wind, heat and moisture surface fluxes, and entrainment flux (i.e., warmer and dryer air that enters the PBL from the free troposphere). These forcing mechanisms critically depend on mesoscale

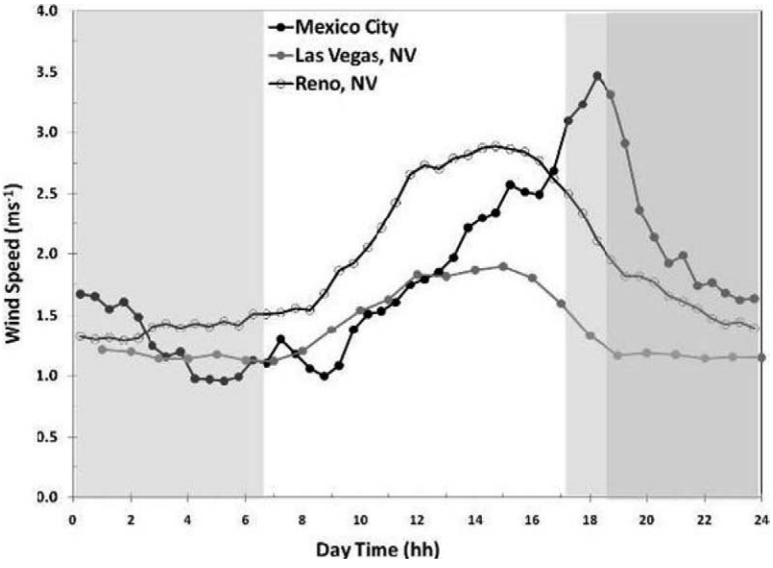

Fig. 4. Wind speeds as a function of the time of the day, for Mexico City, Mexico; Las Vegas, Nevada; and Reno, Nevada. For MCMA on 9–28 Mar 2006 (CST), for LVMA on 6 Jan–15 Feb 2003 (PST), and for RNMA on 1 Dec 2008–31 Mar 2009.

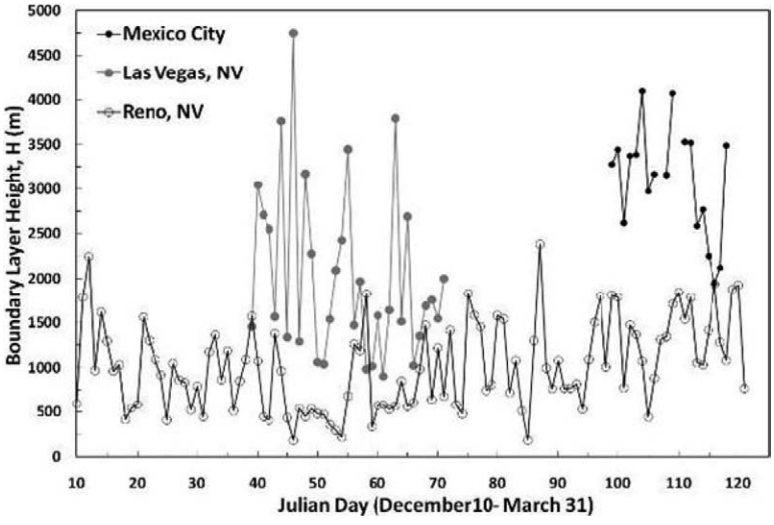

Fig. 5. PBL height above ground level at 0000 UTC as a function of day for MCMA, LVMA, and RNMA.

processes, such as sea breezes or mountain drainage (Pino et al. 2004). Figure 5 shows the 0000 UTC PBL height above ground level from 9 to 28 March 2006 for MCMA, from 10 December 2009 to 31 March 2010 for RNMA, and from 8 January to 9 February 2003 for LVMA obtained by analyzing the local station atmospheric soundings collected by the University of Wyoming. The average PBL heights for Reno, Las Vegas, and Mexico City were 1,019, 2,014, and 3,099 m, respectively. We determined a PBL height for MCMA that compares quite reasonably to the value of 3,057 m, obtained by Zelaya-Angel et al. (2010) for Mexico City at 2100 local time from 19 to 23 March 2001. In Reno the balloon soundings are launched at the National Weather Service (NWS) office, which is about 175 m above the valley floor; thus we may be underestimating the PBL depth somewhat.

Average diurnal aerosol light scattering and absorption. Figure 6 shows the average daily variation of the absorption coefficient, B_{abs}, for all three cities. For every hour, the values were averaged over all days where the measurements were carried out. As expected, because of a lower PBL height, the absorption coefficient is larger during the morning for all three cities. As the PBL height increases during the day, the absorption coefficient continually decreases, reaching a minimum at about 1400–1600. The maximum value for B_{abs} is reached in MCMA at about 0700 in the morning and a few hours later in LVMA and RNMA. During the night, the PBL height starts decreasing, which leads to a significant increase in absorption in LVMA (probably also related to the intense nightlife). In MCMA absorption is stable during the night but it starts to increase dramatically at about 0200. MCMA ventilates more at night than the other cities, as shown in Fig. 4.

Figure 7 shows the daily variation of the scattering coefficient, B_{sca}, for the three cities. The effect of a large increase in pollutant concentration during the night for LVMA is even more pronounced for scattering than for absorption, possibly explained by the fact that the plethora of spark ignition vehicles are potent emitters of organic carbon. The effect of evening use of wood burning stoves in the vicinity of the site may also be important. For LVMA, the maximum scattering coefficient was registered at about 2200. The morning scattering peak is reached later than the absorption peak (e.g., in MCMA the absorption peak is reached at about 0700, while the scattering peak appears about 1100). A partial

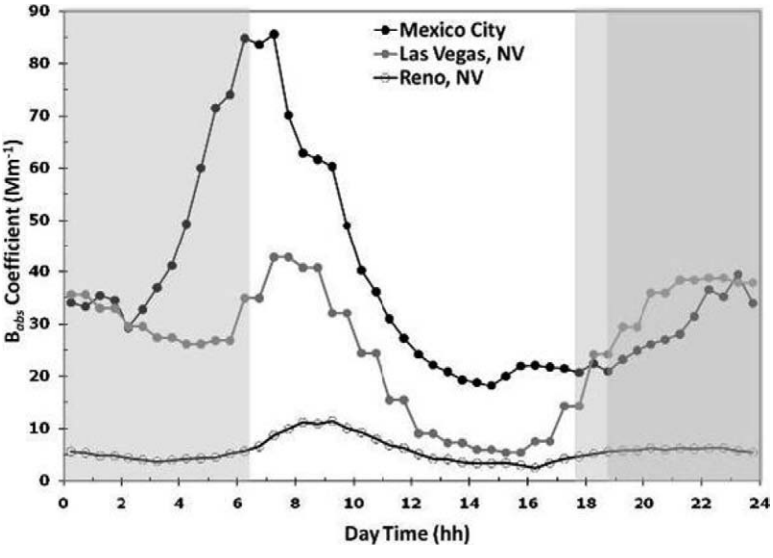

Fig. 6. Absorption coefficient B_{abs}, as a function of the time of day, for three different cities. The B_{abs} are averaged over all days where measurements were carried out. For MCMA on 9–28 Mar 2006 (CST), for LVMA on 6 Jan–15 Feb 2003 (PST), and for RNMA on 1 Dec 2008–31 Mar 2009.

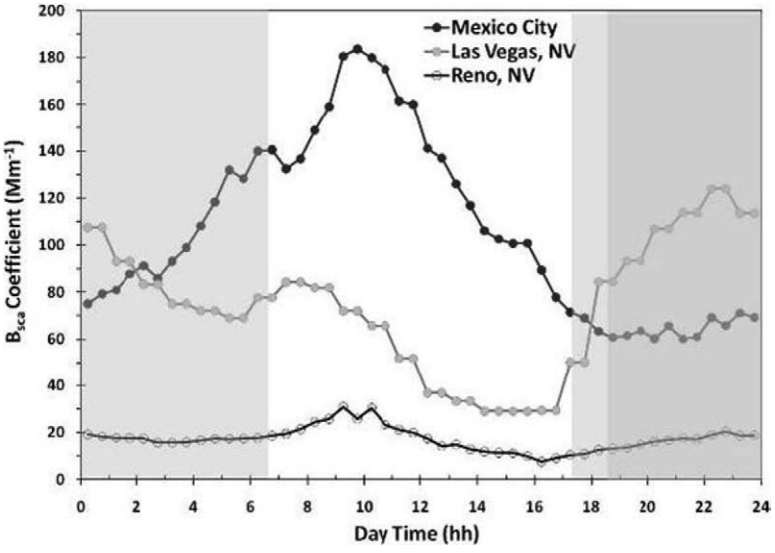

Fig. 7. Scattering coefficient B_{sca}, as a function of the time of day, for three different cities. The B_{sca} are averaged over all days where measurements were carried out. For MCMA on 9–28 Mar 2006 (CST), for LVMA on 6 Jan–15 Feb 2003 (PST), and for RNMA on 1 Dec 2008–31 Mar 2009.

exception is Las Vegas, where both the absorption and scattering peaks seem to occur at about the same time, between 0700 and 0800. This difference is mostly due to the production of secondary aerosols with the increasing solar radiation and temperature. Patterns similar to those reported here for Mexico City have previously been found in other cities such as Beijing (He et al. 2009). The average absorption coefficient for MCMA is 38 inverse megameters (Mm^{-1}) while the average scattering coefficient is 106 Mm^{-1}. The averages for LVMA are 26 and 74 Mm^{-1}, respectively. Reno's averages are 5.8 Mm^{-1} for the absorption coefficient and 17.2 Mm^{-1} for the scattering coefficient.

Comparison between measurements and model. The model discussed in the "A model for the city-size dependence of urban atmospheric pollution" section suggests that the absorption coefficient, B_{abs}, and the scattering coefficient, B_{sca}, should approximately scale with the city population as $N^{1/2}$. It is easier to check the approximate validity of this relation on a log–log scale, where one would expect a linear relation with a slope equal to ~0.5; that is,

$$\mathrm{Log}(B_{abs}) \sim 0.5 * \mathrm{Log}(N) \text{ and}$$
$$\mathrm{Log}(B_{sca}) \sim 0.5 * \mathrm{Log}(N).$$

Here, in order to simplify the problem, we consider only the dependence on the city size N and ignore terms that are assumed to be (statistically) independent on N (or in other words they are assumed to be uncorrelated with N; see the "A model for the city-size dependence of urban atmospheric pollution" section).

In Fig. 8 we show a log–log plot of the absorption coefficient, B_{abs}, averaged over all days considered, as a function of the city population for the three cities where measurements were carried out. Here B_{abs} data were added for Beijing, during the period 2005/06 (as reported by He et al. 2009), and Delhi, during April 2008–March 2009 (as reported by Soni et al. 2010). In Beijing the city population is 22 million people and the average absorption coefficient is 56 Mm^{-1} (at 532 nm), while in Delhi the population is near 13 million people, and the average value of B_{abs} is 98 Mm^{-1} (at 520 nm). The resulting slope and its standard deviation obtained from the linear regression in log–log space are 0.51 ± 0.15, which is in accord with the theoretical value of 0.5. While the sample of cities is small and should be increased for a better empirical test of this scaling

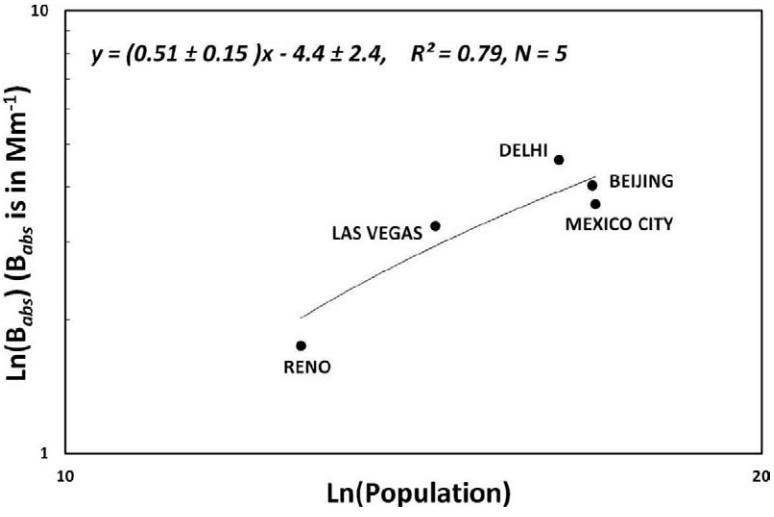

Fig. 8. Log–log plot of the absorption coefficient B_{abs}, over all days considered, versus the city population N. The slope obtained from a linear regression is close to 0.5 as expected from the very simple model described in the section "A model for the city-size dependence of urban atmospheric pollution."

rule, these results are encouraging with respect to the usefulness of the rule. The corresponding p value of statistical significance was estimated to be 4.4%.

In Fig. 9 we show a log–log plot of the scattering coefficient, B_{sca}, over all days considered, as function of city population, for the three cities considered. Once again, we include the data for Beijing in the period 2005/06 for B_{sca} (at 525 nm), as reported by He et al. (2009), as well as data for Delhi in the period April 2008–March 2009 obtained at 550 nm for B_{sca} as reported by Soni et al. (2010). The average value of B_{sca} in Beijing is 288 Mm^{-1} while in Delhi it is 252 Mm^{-1}. The log–log slope and its standard deviation are found to be equal to ~0.54 ± 0.15. The corresponding p value of statistical significance is estimated to be 3.4%. Note also that in both graphs the correlation between the light extinction coefficients and the city population is found to be high. MCMA ventilates the best, and therefore is likely why it lies below the trendline.

Table 1 shows a summary of the three-city comparison. In a previous study (Paredes-Miranda et al. 2009), an MSE, of 3.8 $m^2 g^{-1}$ at a wavelength of 532 nm, was determined for Mexico City, coinciding also with the value obtained by DeCarlo et al. (2008). For MAE, the same value is used for all three cities. The daily averaged values for the absorption and scattering coefficients, B_{abs} and B_{sca}, are also reported in the table.

The black carbon surface emission flux, ε_{BC}, and the $PM_{2.5}$ surface emission flux, $\varepsilon_{PM2.5}$, both in units of $\mu g\ m^{-2}\ s^{-1}$, are estimated using Eqs. (4a) and (4b). A value of 8.8 $m^2 g^{-1}$ for the MAE at a wavelength of 532 nm is consistent with our previous measurements of elemental carbon (EC) by thermal optical reflectance methods and photoacoustic light absorption for fresh compression ignition emissions measured during source-sampling experiments (Arnott et al. 2005). Black carbon net surface flux in grams per person per day, E_{BC}, is calculated by

$$E_{BC} = \frac{\varepsilon_{BC}}{n}\left(86,400\frac{s}{Day}\right) g \times 10^{-6}\,\mu g^{-1},$$

where n is the city population density in units of number of persons per square meter. Analogously, the total $PM_{2.5}$ net surface flux in grams per person per day, identified as $E_{PM2.5}$, is calculated by the following formula:

$$E_{PM2.5}\frac{\varepsilon_{PM2.5}}{n}\left(86,400\frac{s}{Day}\right) g \times 10^{-6}\,\mu g^{-1}.$$

While the absorption and scattering coefficients are highest in MCMA, the corresponding values for E_{BC} and $E_{PM2.5}$ turn out to be considerably smaller than in LVMA. The higher pollution concentration (linked to higher values of B_{abs} and B_{sca}) should therefore be attributed mostly to differences in the population size. That is, people are affected not just by the pollution they produce themselves locally, but by that produced in other regions of the city and transported by the wind. Note also that both the BC and $PM_{2.5}$ surface emission fluxes, as well as the BC and $PM_{2.5}$ mass emission per person per day, is by far higher in Las Vegas than in the other two cities. This might be due to the intense Vegas nightlife [approximately 40 million tourists each year according to Goossens and Buck (2011)].

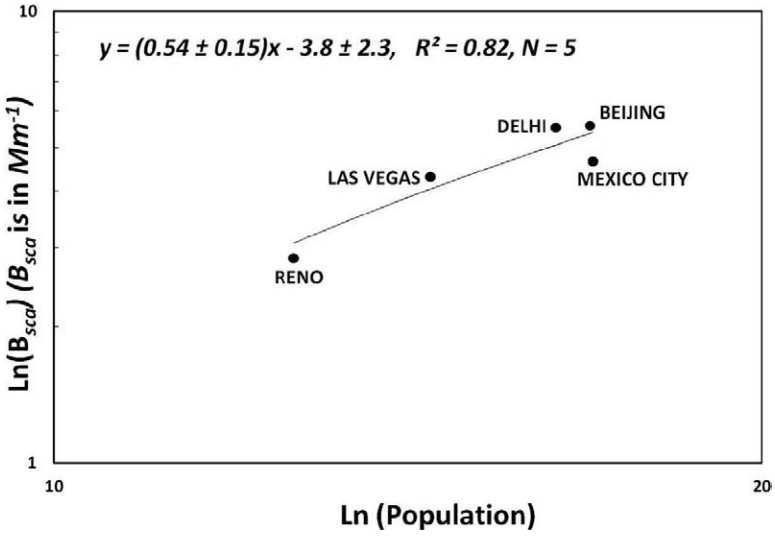

FIG. 9. Log–log plot of the scattering coefficient B_{sca}, over all days considered, versus the city population N. The slope obtained from a linear regression is close to 0.5 as expected from the very simple model described in the section "A model for the city-size dependence of urban atmospheric pollution."

CONCLUSIONS. The daily variation of the absorption and scattering coefficients is similar in MCMA, LCMA, and RNMA. There is a higher pollutant concentration in the early morning due to the nocturnal decrease in PBL height caused by the lack of solar radiation and wind. After that, there is a continuous decrease in pollution during the day. In the case of Mexico City and Reno, the values

of B_{abs} and B_{sca} are observed to be approximately stationary during the night. On the other hand, in Las Vegas a strong increase on both coefficients seems to indicate higher emissions due to the intense nightlife activity in casinos, hotels, etc. (although it may be also due to a decrease in PBL height at night). The morning scattering peak occurs a few hours later than the absorption peak, probably because of the formation of secondary aerosols. The average absorption coefficient for MCMA is 38 Mm^{-1} while the average scattering coefficient is 105 Mm^{-1}. The averages for LVMA are 26 and 74 Mm^{-1}, respectively. Reno's averages are 5.8 Mm^{-1} for the absorption coefficient and 17.2 Mm^{-1} for the scattering coefficient.

Table 1. Summary of pollution results for the cities.

City	Reno, Nevada	Las Vegas, Nevada	Mexico City, Mexico
Area (km^2)	242	1,600	7,815
Population	310,047	1,902,834	23,000,000
PBL: H (m)	1,019	2,014	3,099
Average wind speed (m s^{-1})	1.91	1.37	1.81
B_{abs} (Mm^{-1})	5.78	25.96	38.52
B_{sca} (Mm^{-1})	17.20	74.03	105.97
ε_{BC} (μg BC m^{-2} s^{-1})	0.16	0.41	0.56
$\varepsilon_{PM2.5}$(μg $PM_{2.5}$ m^{-2} s^{-1})	1.13	2.69	3.54
n, total population/total area (km^{-2})	1.28×10^{-3}	1.19×10^{-3}	2.94×10^{-3}
E_{BC} g/(person × day)	11.08	29.57	16.30
$E_{PM2.5}$ g/(person × day)	76.33	195.26	103.89

Since much of the growing world population continues to concentrate in large cities, it is interesting to establish a relationship between city size and the parameters characterizing air pollution concentration. We described a very simple model that assumes steady-state conditions and suggests that both the absorption coefficient, B_{abs}, and the scattering coefficient, B_{sca}, should scale approximately with city population, N, as $B_{abs} \sim N^{1/2}$ and $B_{sca} \sim N^{1/2}$. This scaling may be considered a useful metric that depends on the assumption that specific city conditions (such as latitude, altitude, local meteorological conditions, degree of industrialization, population density, air pollution emissions controls/regulations, city shape, etc.) vary randomly, independent of city size. We compare this predicted scaling behavior with empirical values measured in the three mentioned cities [as well as data from Beijing reported by He et al. (2009) and data from Delhi reported by Soni et al. (2010)] and find agreement. This relatively weak dependence on the city population might help to explain why the worsening of urban air quality does not directly lead to a decrease in the rate of growth in city sizes, especially if people curtail activity during peak pollution events. While MCMA is the more polluted of the three cities, this turns out to be largely due to the effect of city size; that is, people are affected not just by the pollution produced by themselves locally, but by that generated in other regions of the city and transported by the wind. LVMA turned out to be the city with the most BC and $PM_{2.5}$ pollution generated per person per day, probably as a side effect of the tourist and gaming industry.

A general scaling law, such as the proposed $N^{1/2}$ law, connecting air pollution concentrations to total city population allows urban planners and air pollution management specialists to deconvolve the influence of city size and per capita emission rates on air pollution concentrations. This makes it possible to project, for example, what decrease in per capita emissions is necessary to allow for a certain increase in city population while keeping air pollution concentrations constant. In a more general sense, it allows for a very simple and intuitive analysis of different scenarios balancing goals for air pollution concentrations (such as attainment of standards), projected or desired changes in city population, and projected or necessary changes of per capita emission rates.

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