

Measurements and analysis of criteria pollutants in New Delhi, India

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Abstract

Ambient concentrations of carbon monoxide (CO), nitrogen oxides (NO_x), sulfur dioxide (SO₂), and total suspended particulates (TSP) were measured from January 1997 to November 1998 in the center of downtown [the Income Tax Office (ITO) located on B.S.G. Marg] New Delhi, India. The data consist of 24-h averages of SO₂, NO_x, and TSP as well as 8 and 24-h averages of CO. The measurements were made in an effort to characterize air pollution in the urban environment of New Delhi and assist in the development of an air quality index. The yearly average CO, NO_x, SO₂, and TSP concentrations for 1997 and 1998 were found to be 4810 ± 2287 and 5772 ± 2116 μg/m³, 83 ± 35 and 64 ± 22 μg/m³, 20 ± 8 and 23 ± 7 μg/m³, and 409 ± 110 and 365 ± 100 μg/m³, respectively. In general, the maximum CO, SO₂, NO_x, and TSP values occurred during the winter with minimum values occurring during the summer, which can be attributed to a combination of meteorological conditions and photochemical activity in the region. The ratio of CO/NO_x (~50) indicates that mobile sources are the predominant contributors for these two compounds in the urban air pollution problem in New Delhi. The ratio of SO₂/NO_x (~0.6) indicates that point sources are contributing to SO₂ pollution in the city. The averaged background CO concentrations in New Delhi were also calculated (~1939 μg/m³) which exceed those for Eastern USA (~500 μg/m³). Further, all measured concentrations exceeded the US National Ambient Air Quality Standards (NAAQS) except for SO₂. TSP was identified as exceeding the standard on the most frequent basis. © 2001 Elsevier Science Ltd. All rights reserved.

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1. Introduction

To protect air quality in the US, the US Environmental Protection Agency (EPA) has mandated air quality standards for the following six air pollutants (called the criteria pollutants): ozone (O₃), lead (Pb), total suspended particulates (TSP/PM fine), carbon monoxide (CO), sulfur dioxide (SO₂), and nitrogen oxides (NO_x = NO + NO₂). Collectively, these standards are called the National Ambient Air Quality Standards (NAAQS) (Table 1). The results for the analysis of CO, SO₂, NO_x, and TSP measurements made at the Income Tax Office (ITO) located on B.S.G. Marg in New Delhi, India will include the US NAAQS for comparison purposes.

CO is an important trace gas in the earth's atmosphere, which performs several important roles in the troposphere.

There are a variety of sources, both natural and anthropogenic, for ambient CO. Natural sources include oxidation of methane and natural hydrocarbons, ocean emissions, and emissions from vegetation. In rural areas, these are the most dominant sources; therefore, in a remote location, CO is one of the most dominant precursors for photochemical ozone production (Crutzen, 1973; Chameides and Walker, 1973; Parrish et al., 1991). In urban areas, however, anthropogenic sources, including fossil fuel combustion, industrial activities, biomass burning, and oxidation of anthropogenic hydrocarbons, contribute far more to the concentration of CO than the natural sources.

CO regulates the hydroxyl radical (OH) concentration in areas of less than a few parts per billion by volume (ppbv) of NO_x = NO + NO₂ (Weinstock et al., 1980; Parrish et al., 1991). The lifetime of CO is approximately 1–3 months, representing the slow rate of mixing and the consumption by reaction with OH (Seinfeld, 1986; Warneck, 1988; Parrish, 1991). As a result of its long lifetime, it can be used as an inert tracer of most recent CO emissions in an airmass. In the

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Table 1
US NAAQS in effect as of December 1999

Pollutant	Primary standard (health related)		Secondary standard (welfare related)	
	Type of average	Standard level concentration ^a	Type of average	Standard level concentration ^a
CO	8 h ^c	9 ppm (10 mg/m ³)	No secondary standard	
	1 h ^c	35 ppm (40 mg/m ³)	No secondary standard	
Pb	Maximum quarterly average	1.5 µg/m ³	Same as primary standard	
NO ₂	Annual arithmetic mean	0.053 ppm (100 µg/m ³)	Same as primary standard	
O ₃	Maximum daily 1-h average ^{a,b}	0.12 ppm (235 µg/m ³)	Same as primary standard	
	Fourth maximum daily ^d 8-h average	0.08 ppm (157 µg/m ³)	Same as primary standard	
<i>Particulate matter</i>				
PM ₁₀	Annual arithmetic mean	50 µg/m ³	Same as primary standard	
	24 h ^c	150 µg/m ³	Same as primary standard	
PM _{2.5}	Annual arithmetic mean	15 µg/m ³	Same as primary standard	
	24 h ^c	65 µg/m ³	Same as primary standard	
SO ₂	Annual arithmetic mean	0.03 ppm (80 µg/m ³)	3 h ^c	0.50 ppm (1300 µg/m ³)
	24 h ^c	0.14 ppm (365 µg/m ³)		

Source: US EPA National Air Quality and Emissions Trends Report (2000).

^a Parenthetical value is an approximate equivalent concentration (See 40 CFR Part 50).

^b The standard is attained when the expected number of days per calendar year with maximum hourly average concentrations above 0.12 ppm is equal or less than one, as determined according to Appendix H of the Ozone NAAQS.

^c Not to be exceeded more than once per year.

^d Three-year average of the annual fourth highest daily maximum 8-h average concentration.

troposphere, a significant CO background concentration exists (~150 ppbv in the Northern Hemisphere and ~50 ppbv in the Southern Hemisphere) based on continuous CO production from the oxidation of methane and its long lifetime (Warneck, 2000). The background concentration is defined here as the annual mean surface-mixing ratio advected into an airshed at a particular location. The rural/remote CO concentration levels display a pronounced seasonal cycle associated

with a theoretical seasonal cycle in the hydroxyl radical concentration (Seiler et al., 1976; Dianov-Klokov and Yurganov, 1989). Studies have shown a direct link between the increase in anthropogenic emissions and a continuous increase in the background concentration level of CO (Rinsland and Levine, 1985; Khalil and Rasmussen, 1988).

The history of a sampled airmass parcel may be explored further by the simultaneous measurements of CO with other

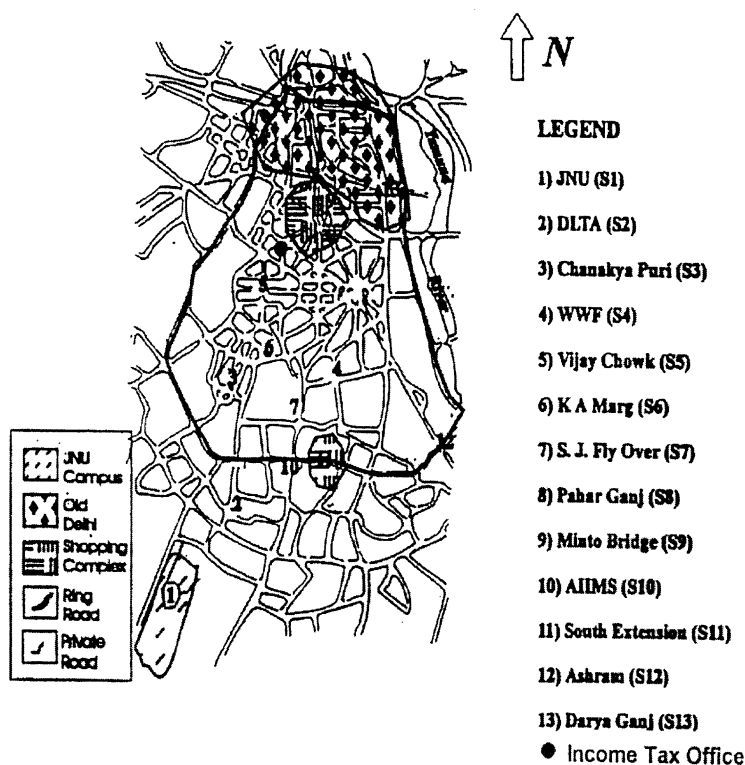


Fig. 1. Road map of Delhi showing approximate sampling site location.

atmospheric trace gases. This analysis allows for determining the emissions that the airmass has received and the photochemical transformation to which it has been subjected. In a situation where the photochemical transformations, including removal mechanisms, are negligible or can be accounted for adequately, a check of emission inventories is theoretically possible.

Both sulfur and nitrogen in the atmosphere originate either from natural processes or anthropogenic activity. SO_2 is a prominent anthropogenic pollutant and contributes to the formation of sulfuric acid, the formation of sulfate aerosols, and the deposition of sulfate and SO_2 at the ground surface. In the lower atmosphere, nitric oxide (NO) is converted to nitrogen dioxide (NO_2) by reaction with peroxyradicals (RO_2) or O_3 . The NO_2 generated is then photolyzed in the atmosphere and the atomic oxygen released combines with molecular oxygen to form O_3 .

TSPs are the general term used for a mixture of solid particles and liquid droplets found in the air. These particles, which come in a wide range of sizes, originate from many different stationary and mobile sources as well as from natural sources. They may be emitted directly by a source or formed in the atmosphere by the transformation of gaseous precursor emissions such as SO_2 and NO_x . Their chemical and physical compositions vary depending on location, time of year, and meteorology. Scientific studies show a link between inhale-

able particulates (i.e. PM fine) and a series of significant health effects. In addition, particulates cause adverse impacts on the environment via reduced visibility and changes in the nutrient balance through deposition processes (US EPA National Air Quality and Emissions Trends Report, 1997).

New Delhi, the capital of India, is the third most populated city of India and has a population of approximately 10 million. The city is located in central India (latitude $28^{\circ}39'N$, longitude $77^{\circ}13'E$) and approximately 715 ft above mean sea level (MSL). New Delhi is located in the subtropical belt with maximum temperature of $46^{\circ}C$ in summer and minimum values of $1^{\circ}C$ in winter. This area is under the influence of monsoonal winds (ranging from NE to NW in winter and ranging from SE to SW in the summer) (Varshney and Padhy, 1998), with average yearly rainfall of approximately 73 cm.

The city has grown at a phenomenal rate from 1971 to 1991. Automobiles have increased from 200,000 to 850,000 during this 20-year period. In addition to this large source of fossil fuel combustion, the increase in power production, biomass burning, number of landfills, and sewage treatment plants all contribute to the deterioration of ambient air conditions in New Delhi during the past 20 years (Sharma and Roychowdhury, 1996).

The data presented were collected by the Central Pollution Control Board (CPCB) from January 1997 through

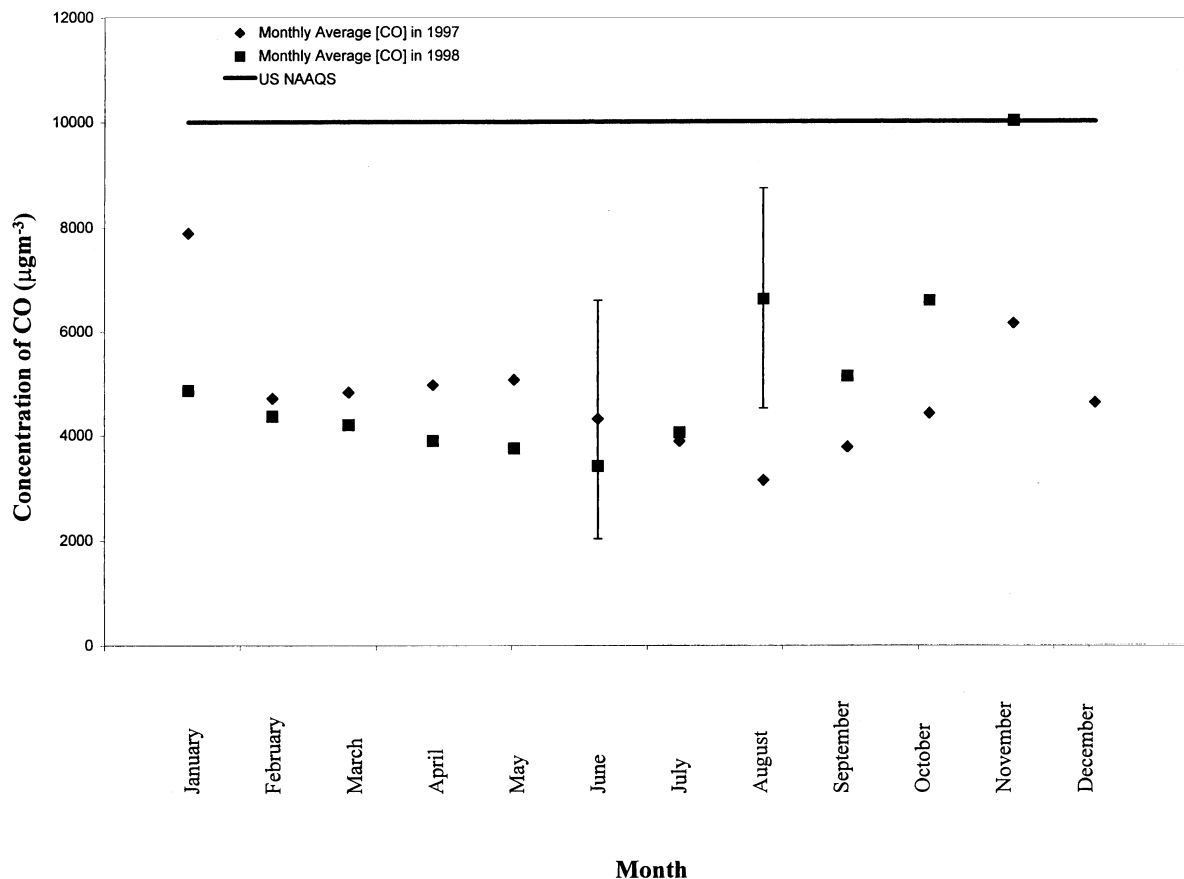


Fig. 2. Monthly average CO concentrations for 1997 and 1998 in New Delhi, India.

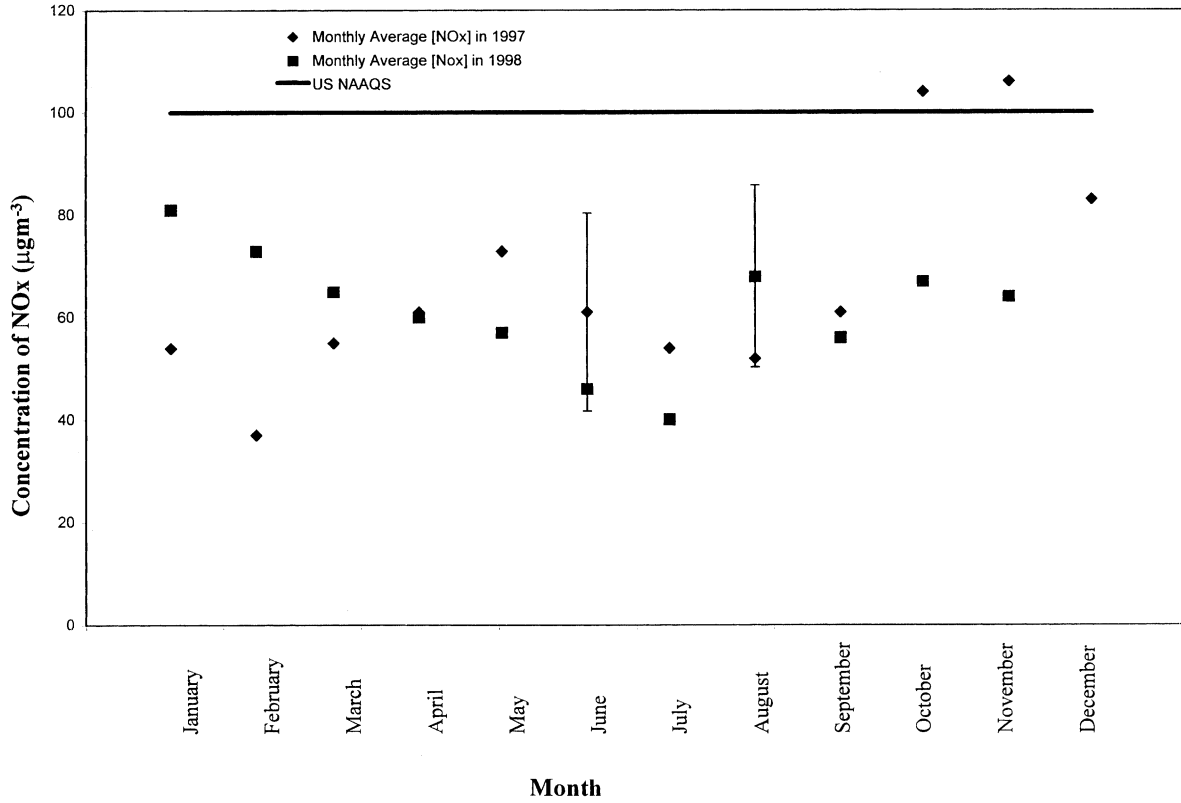


Fig. 3. Monthly average NO_x concentrations for 1997 and 1998 in New Delhi, India.

November 1998 at the ITO located on B.S.G. Marg in downtown New Delhi (Fig. 1). This data set was provided

by Centre for Science and Environment, India. The objective of this analysis is to present findings linking pollutant

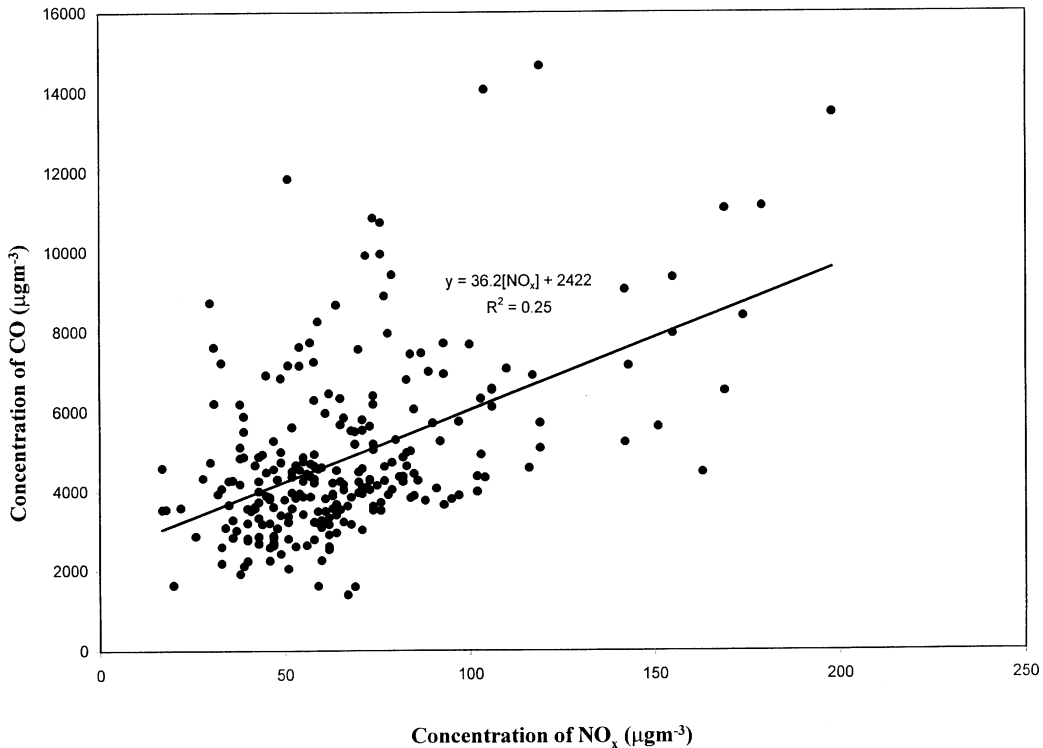


Fig. 4. Daily CO concentrations vs. daily NO_x concentrations for 1997.

concentrations, in terms of trends, to meteorology and anthropogenic activities in and around New Delhi as well as to determine the severity of the pollution from each source when compared to US NAAQS.

2. Results and discussion

Monthly average carbon monoxide concentrations ($1 \mu\text{g}/\text{m}^3 \text{CO} = 0.86 \text{ ppbv}$) are plotted in Fig. 2 for 1997 and 1998. The data sets for both plots reveal a general trend of wintertime maximum concentrations and summertime minimum concentrations. A plausible explanation for these results may be found by examining meteorological conditions and photochemical activity at the site.

The general meteorology of the region during the winter is dominated by high pressure usually centered over western China causing increased atmospheric stability, which in turn allows for less general circulation and thus more stagnant air masses. Stagnant air masses allow more accumulation of pollutants in any given area. During the winter, atmospheric dispersion is typically at a minimum, and therefore, the pollutants will not be as widely dispersed throughout the planetary boundary layer. Conversely, during the summer months, the average PBL height is typically at its greatest, resulting in increased mixing through a greater volume of the troposphere and hence lower pollutant concentrations. Additionally, a lack of precipitation during the winter months reduces the potential for wet deposition and associated cleansing mechanisms. Moreover, the availability of enhanced OH during summer months may also act to consume CO.

Table 2

Average emissions from NAPAP inventory

Region	CO/NO _x	SO ₂ /NO _x
Eastern US ^a	4.3	0.94
Mobiles	8.4	0.05
Point sources	0.95	1.8
Pennsylvania area ^b	2.6	1.7
Mobiles	7.8	0.05
Point sources	0.8	2.3
Western US ^c	6.7	0.41
Mobiles	10.2	0.05
Point sources	1.2	1.1
Denver metropolitan area ^d	7.3	0.19
Mobiles	10.5	0.05
Point sources	0.18	0.44
Raleigh, NC ^e	16.3	–
This study (New Delhi, India)	50	0.58

In each category, the sum of the mobile and point sources is less than the total given; the difference is the stationary area sources.

^a East of 95.9°W longitude, south of 45°N latitude.

^b 76.5–81°W longitude, south of 49°N latitude.

^c West of 104°W longitude, 39.5–41°N latitude.

^d 104–105.5°W longitude, 39.5–41°N latitude.

^e Aneja et al. (1997).

During the late summer and fall months (July–September), minimums in pollutant concentrations can be ascribed to the monsoons. The monsoons bring large amounts of precipitation, high wind velocities, and changes in general wind direction. The large amounts of precipitation reduce atmospheric pollution via associated wet deposition processes. Further, wind velocities will allow for pollutant transport away from sources; increase mixing processes and the winds coming from the marine

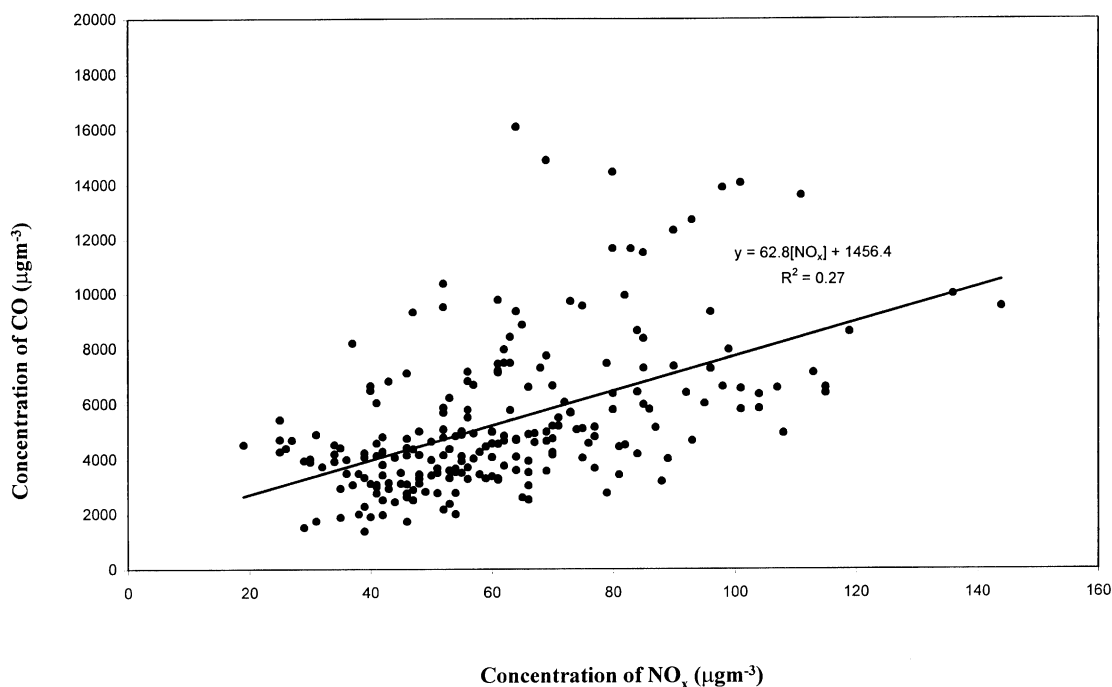


Fig. 5. Daily CO concentrations vs. daily NO_x concentrations for 1998.

environment will have less background concentrations than that of continental air masses. Included on Fig. 2 is also the US NAAQS, which shows that throughout both years the monthly average CO concentration has been below this threshold except for 1 month (November 1998). Although only one monthly average approached the US NAAQS, the 8-h US NAAQS for CO ($10,000 \mu\text{g}/\text{m}^3$) was exceeded 54 times in 1997 and 69 times in 1998. These numbers far exceed the standard set by the US EPA, which requires that the US NAAQS not be exceeded more than once in a given year.

Monthly average NO_x concentrations ($1 \mu\text{g}/\text{m}^3$ $\text{NO} = 0.80$ ppbv) for New Delhi are plotted in Fig. 3. Similarly to Fig. 2, maximum pollutant concentrations occur during the winter months, and a general trend of minimum values occurs in the summer. Meteorological conditions and photochemical activity are again presumed to be the primary cause of this profile. Plotting the US NAAQS on this profile reveals that based on US standards, this city would have met the requirements throughout the majority of both years.

It is well known that mobile emission sources are predominantly characterized by high CO and NO_x concentrations while point source emissions are characterized by high SO_2 and NO_x concentrations. Given these character-

istics, mobile sources will often have high CO/NO_x ratios and low SO_2/NO_x ratios. Lower CO/NO_x ratios and higher SO_2/NO_x ratios will typically characterize point sources. Therefore, the relationship between CO and nitrogen oxides for 1997 and 1998 in New Delhi, India was investigated (Figs. 4 and 5) and compared to published values in Raleigh, NC (Aneja et al., 1997). A linear regression of the plotted data reveals statistically significant correlations ($P < .05$) between CO and the nitrogen oxide species: New Delhi 1997: $[\text{CO}] = 36.2 * [\text{NO}_x] + 2422$, $r^2 = .25$; New Delhi 1998: $[\text{CO}] = 62.8 * [\text{NO}_x] + 1456$, $r^2 = .27$; Raleigh, NC 1991: $[\text{CO}] = 16.3 * [\text{NO}] + 470$, $r^2 = .53$. From this ratio analysis, it is possible to determine relative source strengths (i.e., mobile vs. point sources) by examining the slope of the regression lines and also to determine relative background concentrations (as defined previously) by examining the intercept of the regression lines.

The regression curves reveal background $[\text{CO}]$ of $546 \mu\text{g}/\text{m}^3$ for Raleigh concentrations while the New Delhi data had an average background concentration of approximately $1939 \mu\text{g}/\text{m}^3$. The CO/NO_x ratio for this data and similar studies are given in Table 2. Parrish et al. (1991) conducted a similar ratio analysis and reported values of 8.4, 7.8, and 10.2 for mobile sources in the Eastern US,

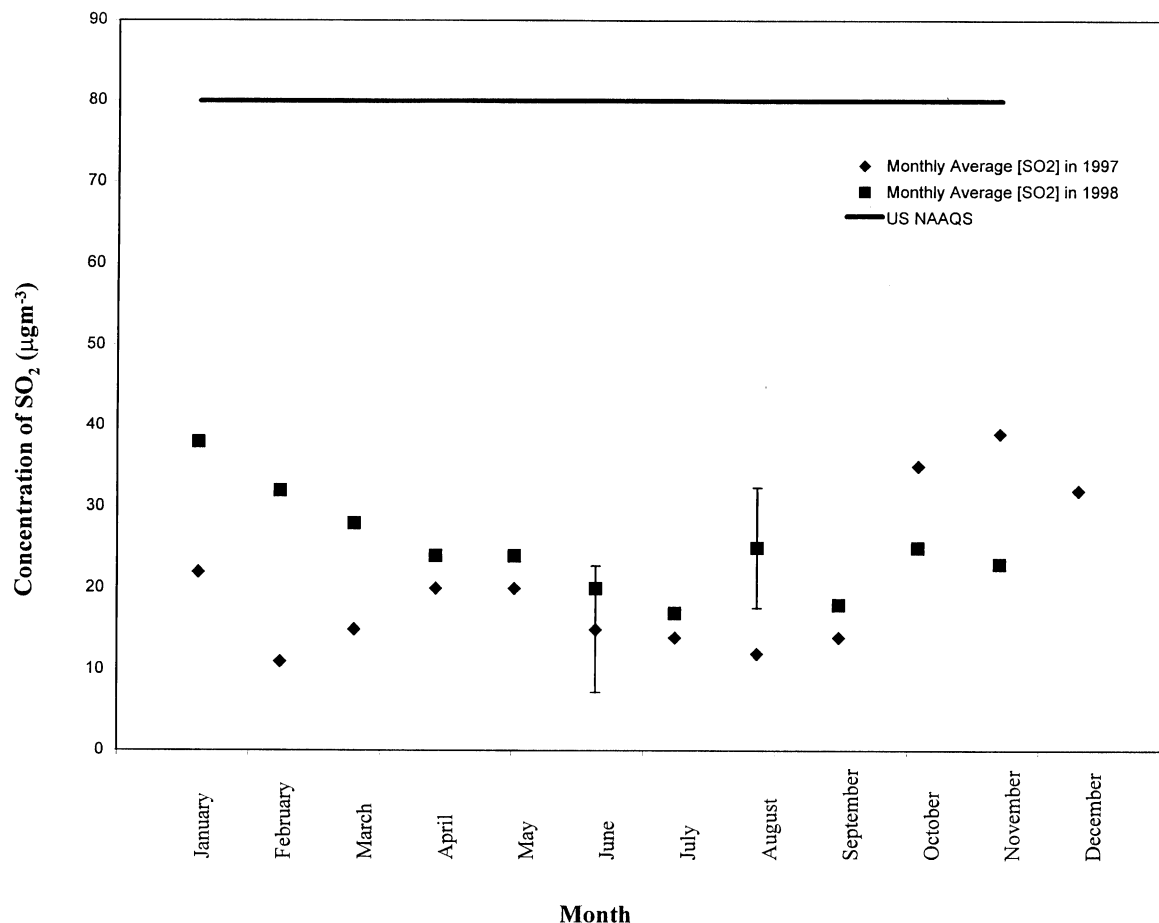


Fig. 6. Monthly average SO_2 concentrations for 1997 and 1998 in New Delhi, India.

Pennsylvania area, and Western US, respectively. Given the average ratio of 50 in New Delhi, it appears that mobile sources are larger contributors of CO and NO_x to the urban air pollution problem than point sources.

Monthly averages of sulfur dioxide concentrations ($1 \mu\text{g}/\text{m}^3$ SO₂=0.38 ppbv) are plotted in Fig. 6 and also include the US NAAQS. Sulfur dioxide concentrations appear to be in control, with annual concentrations below the NAAQS of $80 \mu\text{g}/\text{m}^3$. Additionally, sulfur dioxide concentrations never exceeded the 24-h standard of $365 \mu\text{g}/\text{m}^3$ during the measured period. Conducting similar ratio analysis of SO₂/NO_x (New Delhi ~ 0.6 ; Table 2) indicates that point sources are contributing to SO₂ in the city.

Fig. 7 is a plot of the monthly averaged TSP in New Delhi for 1998. Included on Fig. 7 is also the US NAAQS, which is set at $75 \mu\text{g}/\text{m}^3$ (the 24-h standard is set at $260 \mu\text{g}/\text{m}^3$). It is clear that TSP concentrations in New Delhi are significantly above the annual standard with an approximate annual average concentration of $400 \mu\text{g}/\text{m}^3$. The daily 24-h standard was exceeded 340 days out of the year in 1997.

3. Integrated assessment

Solutions to the air quality problem must include a fully integrated assessment to include emission inventories, atmos-

pheric modeling, environmental effects modeling, ambient concentration measurements, and socioeconomic analysis (Fig. 8). Emission inventories are needed to characterize pollutants and their sources, while the atmospheric modeling provides broad spatial and temporal coverage of the region and allows simulation of air quality during selected episodes. When the modeling provides adequate representation of the measurements made through the ambient monitoring program, then the process can continue with modeling both primary (human health) and secondary (welfare) effects and associated socioeconomic impacts. Only through this innovative and integrated approach can policy and decision makers reach beyond the boundaries of geography and divergent interests to develop effective, balanced, and widely supported recommendations to accomplish improved air quality.

4. Conclusions

Continuous measurements of CO, NO_x, SO₂, and TSP were made in downtown New Delhi, India. All measured concentrations exceeded the US NAAQS except for SO₂, while TSP was identified as exceeding the standard on the most frequent basis. This study revealed that background CO concentrations in New Delhi ($\sim 1939 \mu\text{g}/\text{m}^3$) were much larger than background concentrations in the Eastern US

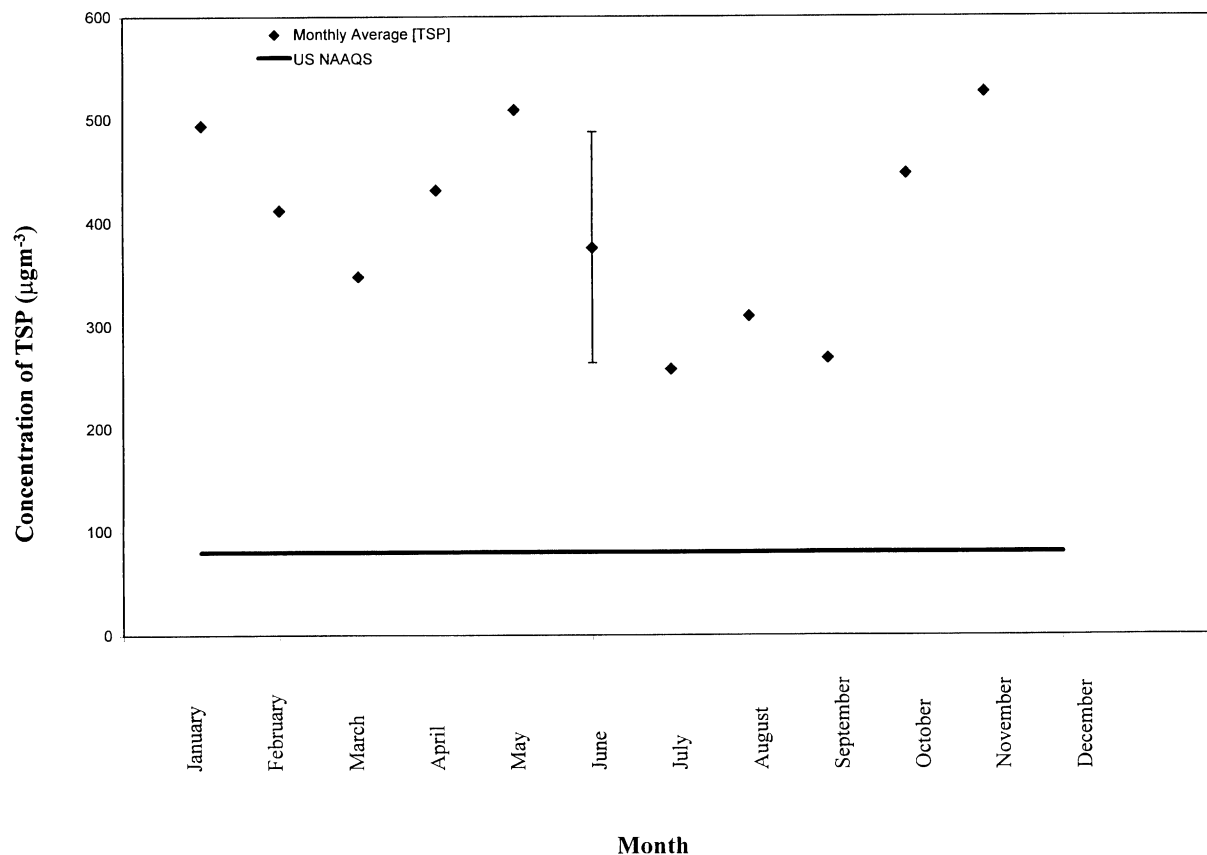


Fig. 7. Monthly average total suspended particulate concentrations for 1998 in New Delhi, India.

Integrated Assessment

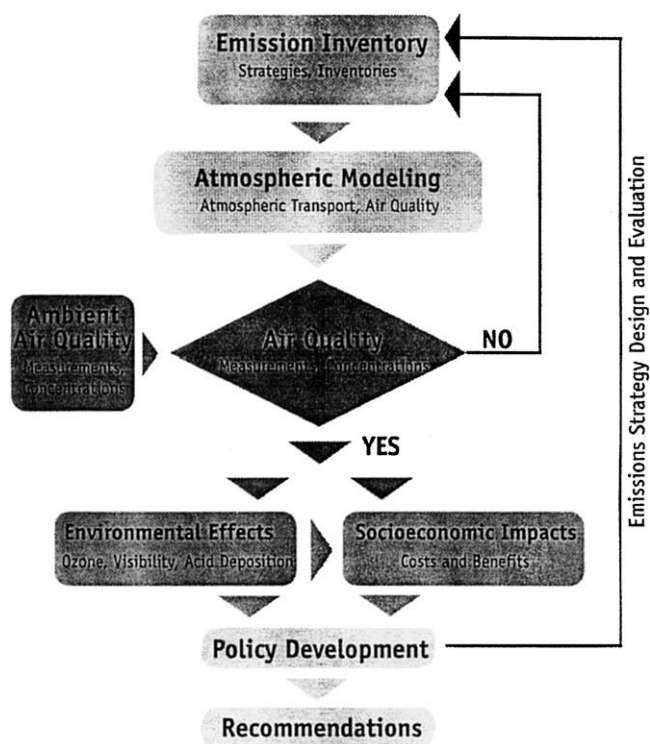


Fig. 8. Integrated assessment.

($\sim 500 \mu\text{g}/\text{m}^3$) and Western US ($\sim 200 \mu\text{g}/\text{m}^3$) and TSP concentrations were identified as being the largest violator of the US NAAQS. The ratio of CO/NO_x (~ 50) indicated that mobile sources are the predominant contributors of these two compounds, while the SO_2/NO_x ratio (~ 0.6) indicated that point sources are contributing to SO_2 pollution in the city. Admittedly, this analysis is based on measurements made at one urban location. Undoubtedly, there is a need for a more comprehensive study based on increased spatial and temporal coverage, which is coupled with photochemical/air quality modeling. Increasing both the spatial and temporal coverage of ambient air quality measurements/modeling and developing an integrated assessment will be instrumental in fostering a truly comprehensive solution to the air quality concerns of New Delhi, India.

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