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The Health Effects of
Air Pollution in Delhi, India

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Particulate air pollution has
less overall impact on
nontraumatic deaths in Delhi,
India, than in U.S. cities. But
the deaths occur earlier in life
in Delhi, which could mean a
larger loss in life-years.

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Summary findings

Cropper, Simon, Alberini, and Sharma report the results of a time-series study of the impact of particulate air pollution on daily mortality in Delhi. They find:

• A positive, significant relationship between particulate pollution and daily nontraumatic deaths as well as deaths from certain causes (respiratory and cardiovascular problems) and for certain age groups.

• In general, these impacts are smaller than those estimated for other countries, where on average a 100-microgram increase in total suspended particulates (TSP) leads to a 6-percent increase in nontraumatic mortality. In Delhi, such an increase in TSP is associated with a 2.3-percent increase in deaths.

• The differences in magnitudes of the effects are most likely explained by differences in distributions of age at death and cause of death, as most deaths in Delhi occur before the age of 65 and are not attributed to causes with a strong association with air pollution.

• Although air pollution seems to have less impact on mortality counts in Delhi, the number of life-years saved per death avoided is greater in Delhi than in U.S. cities — because the age distribution of impacts in these two places varies. In the United States particulates have the greatest influence on daily deaths among persons 65 and older. In Delhi, they have the greatest impact in the 15-to-44 age group. That means that for each death associated with air pollution, on average more life-years would be saved in Delhi than in the United States.

Large differences in the magnitude of effects do call into question the validity of the "concentration-response transfer" procedure. In that procedure, concentration-response relationships found for industrial countries are applied to cities in developing countries with little or no adjustment, to estimate the effects of pollution on daily mortality.

The Health Effects of Air Pollution in Delhi, India

by

Maureen L. Cropper, Nathalie B. Simon,
Anna Alberini, and P.K. Sharma

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I. INTRODUCTION

An important reason for controlling air pollutants such as particulate matter or sulfur dioxide is the damaging effects they have on human health. These effects include premature death, as well as increases in the incidence of chronic heart and lung disease. Estimates of the health damages associated with air pollution are important because they can provide both an impetus for environmental controls and a means of evaluating the benefits of specific pollution control policies.

To estimate the health damages associated with air pollution in developing countries, policy makers are often forced to extrapolate results from studies conducted in industrialized countries. These extrapolations, however, may be inappropriate for two reasons. First, it is not clear that the relationships found between pollution and health at the relatively low levels of pollution experienced in industrialized countries hold for the extremely high pollution levels witnessed in developing countries. Levels of particulate matter, for instance, are often three to four times higher in developing countries than in industrialized ones. Second, in developing countries, people die at younger ages and from different causes than in industrialized countries, implying that extrapolations of the impacts of air pollution on mortality may be especially misleading.

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This paper reports the results of a study relating levels of particulate matter to daily deaths in Delhi, India between 1991 and 1994. We focus on Delhi, the capital of India, because it is one of the world's most polluted cities. During the study period, the average total suspended particulate (TSP) level in Delhi was 378 micrograms per cubic meter--approximately five times the World Health Organization's (WHO) annual average standard. Furthermore, TSP levels in Delhi during this time period exceeded the WHO 24-hour standard on 97 percent of all days on which readings were taken.

In addition, the distributions of deaths by age and by cause in Delhi are very different from those in the U.S. In the U.S., over 70 percent of all deaths occur after the age of 65. In Delhi, over 70 percent of all deaths occur *before* the age of 65, with over 20 percent occurring before the age of five. Furthermore, 46 percent of all non-trauma deaths in the U.S. are attributable to cardiovascular disease compared to only 23 percent in Delhi.[1] Because the main effects of acute exposure to air pollution on daily deaths occur through impacts on cardiovascular and respiratory disease, for which age is a known risk factor, we expect these differences to affect the relationship between pollution and mortality.

Our estimates of health damages have policy implications for pollution control in Delhi, and permit us to compare extrapolations from U.S. studies with actual pollution impacts. We find that a given reduction in TSP reduces non-trauma deaths in Delhi by a smaller percentage

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[1] Statistics for the U.S. are taken from WHO's *World Health Statistics Annual, 1993*. Figures for Delhi are reported in Appendix I, Table A3 and are taken from the National Capital Territory of Delhi's *Registration of Births and Deaths Act - 1969: Annual Report 1991*.

than predicted by U.S. studies. Indeed, the percentage decrease in deaths corresponding to a 100 microgram reduction in TSP is 2.3 percent--about one-third of the effect found in the U.S. On the other hand, because the age distribution of impacts vary from Delhi to the U.S., so do the number of life-years saved. The largest impact of particulates on daily deaths in the U.S. occurs among persons 65 and older. In Delhi, the largest impact occurs in the 15 to 44 age group, implying that for each death associated with air pollution, more life-years will be saved in Delhi than in the U.S. on average.

II. ESTIMATING CONCENTRATION-RESPONSE RELATIONSHIPS FOR DELHI

The relationship between air pollution and premature mortality is most often studied using time-series analysis of daily observations of the number of deaths and pollution levels. These studies capture the effects of short-term exposure to pollution on the probability of dying. The underlying assumption is that there is a distribution of susceptibility to the effects of air pollution in any population. People who are in a weakened physical state or who have a history of chronic obstructive pulmonary disease (COPD) or cardio-pulmonary problems are thought to be the most vulnerable. In the case of a sharp rise in pollution, the most vulnerable people are more likely to die.

Clearly, this type of analysis does not capture all of the effects of pollution exposure. Long-term exposure to pollution can also reduce life expectancy by altering lung function and making people more susceptible to COPD. However, measuring the effects of chronic exposure requires a long-term prospective study in which a sample population is followed long enough for the chronic effects to manifest themselves. Two such studies have been completed to date: the

Harvard Six Cities study (Dockery et al., 1993) which followed participants over the course of 15 years and the American Cancer Society study (Pope et al., 1995) which lasted approximately eight years. Due to cost considerations and time constraints, our work focusses on the acute effects of air pollution.

Because time-series studies focus on a given geographic location over a number of years, factors that are often thought to influence the health of the population, such as percentage of smokers, income level, occupational exposure to pollutants, access to medical care and age distribution, do not need to be incorporated into the analysis as they are considered to remain relatively constant within the study area over time. Typically, the only other factors aside from pollution included in these models are weather variables and seasonal controls.

In measuring the effects of air pollution, most attention has been focussed on particulates, especially those particles measuring less than 10 microns in diameter (PM10), which penetrate the lungs more readily. Even though particulate matter tends to be the pollutant most strongly associated with premature mortality, the presence of other pollutants may be important as well.

A. Data

Mortality data for years 1991 through 1994 were obtained from the New Delhi Municipal Committee (NDMC), one of the three distinct regions which comprise the National Capital Territory.[2] Because the NDMC houses a large concentration of Delhi's hospitals, approximately one-fourth of the 60,000 deaths in Delhi each year occur in the NDMC, in spite of the fact that

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[2] While registration of vital statistics became mandatory in the National Capital Territory in 1957, only the NDMC maintained a sufficiently detailed, computerized data base suitable for time-series analysis of this type, with a full four years worth of data available as of January 1995. The other two regions, the Municipal Corporation of Delhi and the Delhi Cantonment Board, began their computerization efforts several years later and, at the time this study began, did not provide the same level of detail in their data as the NDMC.

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only 3.6 percent of the population resides there. Although the NDMC data represent only 25 percent of all deaths occurring in Delhi, the geographic distribution of the Delhi residents who died due to non-traumatic causes in the NDMC mirrors the geographic distribution of the population, as shown in Table 1.

In the Appendix, we compare the distributions of deaths by cause and by age for the NDMC and the National Capital Territory of Delhi. The distributions of deaths by cause are similar, with between 20 and 25 percent of all medically certified deaths attributable to causes associated with air pollution (respiratory illnesses and cardiovascular disease). Roughly the same percentage of deaths are attributable to infectious diseases and to perinatal causes. The distribution of deaths by age group differs somewhat between the NDMC and the National Capital Territory. Forty-three percent of deaths in the NDMC occur before the age of five, compared to 33 percent of deaths in Delhi. For this reason, we estimate impacts by age group, as well as for specific causes of death (respiratory illness and cardiovascular disease).[3]

We also estimate the impact of air pollution on all non-trauma deaths. Because of problems associated with pinpointing the precise cause of an individual's death, counts of total non-trauma deaths have often been used as the basis of time-series analysis of this type, even though the links are strongest between air pollution and both cardiac and respiratory disorders. Daily counts of total non-trauma deaths covering the study period are plotted in Figure 1. The

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[3] Respiratory illness includes ICD8 460-519, excluding 463, 464, and 474 while cardiovascular disease consists of ICD8 390-448.

data display a marked seasonal pattern, with the highest number of deaths occurring during the rainy monsoon seasons[4].

The Central Pollution Control Board (CPCB) provided daily data on air pollution levels collected at the nine monitoring stations located throughout the city. Six of these monitors have been in operation since 1987 and are operated directly by the CPCB. The other three monitors, added to the monitoring network in 1990, are operated on behalf of the CPCB by the National Environmental Engineering Research Institute (NEERI). Readings of total suspended particulates (TSP), sulfur dioxide (SO_2) and nitrogen oxides (NO_x) are taken at each station on a rotational basis approximately every three days. The data include average, maximum and minimum daily observations of these pollutants at each monitor. The monitors were not in operation on weekends or holidays during the study period. Daily means of TSP, SO_2, and NO_x, were calculated using all available readings on a given day.

Figure 2 shows average daily Total Suspended Particulate (TSP) levels for Delhi over the four years of the study. WHO established a guideline range several years ago of 150 to 230 micrograms per cubic meter per 24-hour period (WHO, 1992). As shown in Figure 2, TSP levels routinely fall well above this 24-hour guideline and, at times, reach as high as six times the guideline levels.[5] While two coal-fired power plants, a large motor vehicle fleet and chemical and cement industries located within the city all contribute to the high particulate levels in Delhi, we suspect that much of the TSP is currently attributable to resuspended dust and natural sources,

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[4]With its semi-arid climate, Delhi experiences only three seasons: (1) the dry season from April through June; (2) the monsoon season from July through September and (3) winter from October through March.

[5]Note that two observations greater than 1200 micrograms per cubic meter were omitted from Figure 2 to make the graph more legible.

primarily because sulfur dioxide (SO_2) and nitrogen oxide (NO_x) levels remain well below the WHO guidelines (see Figures 3 and 4). Even so, available data on the size composition of particles suggest that the ratio of particles less than or equal to 10 microns in diameter (PM10) to TSP is about the same as in the United States (0.53).

Daily meteorological data covering all four years of the study period were obtained from the National Climatic Data Center in Asheville, NC. These data, collected on a daily basis at Delhi's International Airport located in the southwest of city, include average daily temperature, maximum and minimum temperature, mean daily dew point temperature, rainfall and visual range. The seasonality demonstrated by the data are shown clearly in Figures 5 and 6. Temperatures never fall below freezing and typically range between 60 and 100 degrees Fahrenheit. During the study period, fewer than five percent of the days fell below 55 degrees and fewer than one percent exceeded 100 degrees.

Descriptive statistics for all of the variables are provided in Table 2.

B. The Econometric Model

Daily mortality figures are considered counts of rare events and are therefore often modeled using Poisson regression analysis. We fit Poisson regressions to the Delhi mortality data using the method of maximum likelihood. Formally, the log likelihood function is:

$$\log L = \sum_{t=1}^{T} [-\lambda_t + y_t \log \lambda_t - \log(y_t!)] \tag{1}$$

where y_t is the count of deaths occurring on day t, $\lambda_t = \exp(X_t \beta)$ is both the mean and the variance of deaths, X_t is a matrix of covariates on day t, and β is a vector of regression

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coefficients. The predicted count of deaths on day t is therefore $\hat{y}_t = \exp(X_t\beta)$, implying that, if

pollution is entered in a linear fashion in the right-hand side of the model, the percentage change

in mortality following a given change in pollution levels is--holding all other factors unchanged--

$\Delta C \cdot \beta_C$, where C is the pollution concentration variable and β_C is the coefficient associated

with this variable. The maximum likelihood estimate of β is obtained by applying the method

of iteratively re-weighted least squares (IRLS) to minimize the quadratic form:

$$[Y-\lambda] \Omega^{-1} [Y-\lambda] \tag{2}$$

where Y is the T×1 vector of daily deaths, $\lambda = \exp(X\beta)$, X is the T×1 matrix of covariates, and

$\Omega = \text{diag}\{\exp(X_t \beta)\}$ (Farhmeir and Tutz, 1994).

We exploit this equivalence to modify expression (2) to correct for serial correlation.

Specifically, we assume that daily deaths follow a serially correlated process of the first order

with autocorrelation parameter ρ, and implement the generalized estimating equation (GEE)

approach devised by Liang and Zeger (1986), replacing the matrix Ω in equation (2) with the

matrix $\Lambda = A^{1/2} P A^{1/2}$ where $A = \text{diag}\{\exp(X_t\beta)\}$, $P = \{r_{ts}\}$, and $r_{ts} = \rho^{|t-s|}$, for t, s = 1, 2, ..., T.

Coefficient estimates are obtained from an IRLS step nested within a grid search over values of ρ

ranging between -1 and 1.[6]

As is often the case with Poisson models, we are also concerned about the possible

presence of over dispersion, which may signal omitted variables and tends to result, when

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[6]Liang and Zeger (1986) and Prentice (1988) show that for large samples the GEE coefficient estimates are normally distributed, and provide the expression for their asymptotic covariance matrix. Had we not accounted for serial correlation, the estimates of β from the Poisson model that assume serial independence would remain consistent under general assumptions, but their standard errors would not be reliable.

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ignored, in unrealistically low standard errors (Agresti, 1996). To avoid such a problem, the

Poisson standard errors can be multiplied by a correction factor equal to $\sqrt{\chi^2/dof}$, where χ^2 is

the value of the Pearson chi square goodness of fit statistic (see Agresti, 1996 and McCullagh

and Nelder, 1989) and *dof* is the number of degrees of freedom, i.e., the number of observations

minus the number of independent variables.

III. MODEL SPECIFICATION

A. Development of the Core Model

We estimated the autoregressive Poisson model described above for total non-trauma

deaths, as well as for deaths by selected cause (respiratory and cardiovascular deaths) and age

group. Our modeling strategy was carried out in four steps. We began by accounting for the

variability in the number of total non-trauma deaths using seasonal/cyclical terms, a daily time

trend and year dummy variables. Then, we added weather variables to control for the impact of

temperature and humidity. Next, we added pollution variables to see if they had any additional

explanatory power. Because of the complexity of the autoregressive Poisson model, we used a

log-linear specification and ordinary least squares to build the models, using the Akaike

Information Criterion (AIC) at each step to select additional regressors. Finally, we corrected the

model for serial correlation using IRLS as described above.

Following Schwartz et al. (1996), we have controlled for the seasonality in the data by

including trigonometric terms for cycles ranging from one year to 2.4 months in length. A daily

time trend and dummy variables for the year of the study account for population increases and

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other unobserved factors thought to influence the number of deaths. We considered using indicator variables for both the month of the study and the season to control for the seasonality in the data but found that the trigonometric terms provided the best fit.

We accounted for the effects of weather on daily mortality by adding temperature and dew point temperature variables to the model. We considered both maximum and mean temperatures with various lag structures up to seven days in length as well as indicator variables for the hottest and most humid one, five and ten percent of the days during the study period. In the end, we found that contemporaneous mean weather variables and dummy variables for the most extreme 10 percent of the days were the best predictors.

With season and weather accounted for, we incorporated particulate pollution into the model. Again, we considered daily maximum, minimum and mean values of TSP as well as values lagged up to three days. While we did not find significant effects of contemporaneous levels of TSP on mortality, we did find that mean TSP lagged two days had a significant effect. Again, using AIC, we found that this specification provided the best fit.

The results of the autoregressive Poisson model using our core specification are presented in Table 3. Particulate pollution has a positive and significant impact on daily mortality ($\beta=0.00023$, se=0.0001) as does mean daily temperature ($\beta=0.011$, se=0.0047) and the dummy variable for the most humid days ($\beta=0.008$, se=0.0019). Mean daily dew point temperature also has a significant impact on daily mortality; however, the coefficient is negative ($\beta=-0.002$, se=0.0007). This same model is used to estimate the relationship between particulate pollution and the other mortality endpoints (see Tables 4 and 5).

B. Sensitivity Analyses

To examine the robustness of the core model, we conducted several sensitivity tests. First, we added dummy variables to the model to indicate which monitoring stations were included in the calculation of the TSP variable for a given day. As shown in Tables 4 and 5, the addition of these variables did not affect the significance of the pollution variable nor did it affect the magnitudes of the coefficients dramatically. An F-test of the joint significance of these variables, however, did not allow us to reject the null hypothesis that all the coefficients were equal to zero.

Since other studies have shown statistically significant impacts of SO_2 on daily mortality, we examined the impacts of SO_2 on daily deaths in Delhi. First, we considered the impact of SO_2 on mortality alone and then included it in the model with TSP. When considered alone, SO_2 was found to have a negative coefficient for every mortality endpoint except cardiovascular disease and was significant for all endpoints except respiratory deaths, cardiovascular deaths and deaths in the 0 to 4 age group. When considered jointly with SO_2, the effect of TSP on daily mortality retained its significance in all cases (except total non-trauma deaths) and, in general, did not change in magnitude.

While the negative coefficient on SO_2 is somewhat puzzling, we do not give much weight to these results. SO_2 levels during the study period were very low (see Figure 3) and the correlation coefficient between SO_2 and TSP, while positive, is not large (less than 0.3). In studies where SO_2 was found to have a significant and positive effect on daily mortality (Xu et al, 1994; Sunyer et al., 1996, Vigotti et al., 1996), SO_2 and TSP were much more highly correlated and SO_2 levels were in general much higher. We do not report the effects of NO_x on

daily deaths since levels during the study period were similarly low and the link with daily mortality is not well established in the medical literature.

We tested the model's sensitivity to outliers by removing the highest five percent of the TSP values and repeating the regressions. While admittedly the magnitudes of the coefficients were affected in some specifications of the model by the removal of these extreme values, in general, the significance of the TSP variable was not. In some instances, such as cardiovascular deaths, deaths among children aged 5 to 14, and among the elderly, the impact actually increased once the extreme values were removed.

Finally, to test for the effects of over dispersion, we estimated models for each endpoint using a serially independent Poisson model and then applied the correction used by McCullagh and Nelder (1989) and Agresti (1996). Correcting for over dispersion in this manner had only slight effects on the magnitudes of the coefficients on TSP and did not affect their significance.

IV. DISCUSSION

A. Comparison of Results with Other Studies

One of the striking features of the results reported in Table 3 is the fact that the impact of TSP, while statistically significant, is small when compared to results for other cities. Table 6 lists the results of daily mortality studies conducted in a number of cities in the U.S., Europe, and other developing countries. All of the studies listed find a significant and positive relationship between particulate pollution and daily mortality, with an average impact on daily mortality

(excluding Delhi) of six percent for a 100 $\mu g/m^3$ increase in TSP.[7] By contrast, in Delhi a 100

microgram per cubic meter change in TSP is associated with only a 2.3 percent change in total

non-trauma mortality.

There are many potential explanations for the seemingly small impact of particulate

pollution on mortality in Delhi. One line of reasoning focusses on differences in the particulate

matter itself. For example, it could be that the health effects of particulate pollution are lower in

Delhi because the size of the particulates is larger than in western cities, thereby impeding

penetration into the lungs and causing fewer detrimental effects. In 1992, however, NEERI

measured PM10 at the three monitoring stations that they operate (NEERI, 1994). Results

indicate that the ratio of PM10 to TSP at these monitoring stations is only slightly smaller than

the average ratio occurring in the U.S. (0.53 compared to 0.55 in U.S. cities). Even after

converting the mean TSP value of 378 $\mu g/m^3$ to PM10 using the local ratio to account for the

slight difference in particle size, we find that, on average, PM10 over the four year period

reached 200 $\mu g/m^3$, a value well above even the 24-hour standard set by the U.S. of 150 $\mu g/m^3$.

It may be however that, because a large proportion of particulate pollution in Delhi arises

from natural sources rather than combustion of fossil fuels, the chemical composition of the

particulates is such that they pose a lower risk to health. Unfortunately, not enough is known

about the chemical composition of particulates in the various cities to make a comparison.

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[7] Bachárová et al. (1996) recently completed a daily mortality study for the Slovak Republic and find no significant relationship between particulate pollution and daily mortality. In a similar study conducted in Poland, Wojtyniak and Piekarski (1996) find mixed results for four cities. Zmirou et al. (1996), on the other hand, find no significant relationship between particulates and total non-trauma mortality in Lyon, France but do find significant results for respiratory deaths.

Another line of reasoning, and in our opinion a more compelling one, focusses on demographic differences. Deaths in Delhi tend to occur at much younger ages than in the U.S. and, also, for much different reasons. To place our results in context, we compare our estimates of the impact of TSP on mortality in Delhi with similar estimates for Philadelphia (Schwartz and Dockery, 1992a), presented in Table 7. The Philadelphia results are based on an econometric model similar to ours and use TSP as the measure of air pollution. Average TSP levels in Philadelphia during the time of the study were, however, 300 micrograms lower on average than levels in Delhi.

The difference in the impact on total non-trauma deaths is no doubt due in part to the continued importance of infectious diseases in Delhi (accounting for close to 20 percent of deaths in our sample) as well as to the smaller role played by cardiovascular and respiratory deaths. The latter account for only a quarter of the deaths in our sample (see Appendix), whereas they account for approximately half of all deaths in Philadelphia.

This, however, is not the entire story. Table 7 indicates that the impact of TSP on cardiovascular and respiratory deaths is also smaller in Delhi than in Philadelphia. This result is most likely driven by differences in the nature of these illnesses between the two cities. For example pneumonia, which has a weaker association with particulate matter than COPD, comprises a larger fraction of respiratory deaths in Delhi.

The differences in the effects of TSP by age are also striking. In Philadelphia, the impact of TSP on deaths *before* the age of 65 is not statistically significant. The main impact of TSP is on persons who die after the age of 65. In Delhi the impact of TSP on deaths *after* the age of 65 is not statistically significant. Peak impact occurs between 15 and 44, with significant positive

effects also found for the 5 to 14 and 45 to 64 age groups. A clear implication of this finding is that more life-years are likely to be lost per person due to the impacts of air pollution.

B. Policy Implications

One of the implications of our findings is that extrapolations of the mortality impacts of air pollution to developing countries from U.S. studies are likely to be misleading. If one applies the coefficients from Schwartz and Dockery's study to the population of Delhi, the number of premature deaths associated with air pollution is over estimated. As shown in Table 7 using vital statistics for 1991, deaths would increase by 1,385 in Delhi if TSP were to increase by 100 micrograms, whereas the Schwartz and Dockery coefficient for total non-trauma deaths predicts an increase of 3,524 deaths[8, 9].

If one cares about life-years lost, however, the impacts of a 100 microgram increase in TSP in Delhi are more startling. As illustrated in Table 8, weighting each of the 1,385 lives lost by remaining life expectancy implies a loss of 51,403 life-years. To put this number in perspective, we use Table 8 to contrast the impact of increasing TSP by 100 micrograms in Philadelphia and in Delhi. Although the impact of the change in air pollution on total non-trauma deaths is lower in Delhi than in Philadelphia, the same increase in air pollution causes more life-years to be lost in Delhi. This is because more deaths occur at younger ages in Delhi

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[8] The number of lives lost per 100 µg/m³ increase in TSP is calculated by multiplying the total number of non-trauma deaths in Delhi (52,601) by 0.067, the coefficient on the TSP variable from the Philadelphia study.

[9] Brandon and Hommann (1995) estimate the number of deaths that could be avoided in Delhi using the accepted metric (computed from U.S. studies) that a 10 µg/m³ change in PM10 leads to a one percent change in mortality. They estimate, for a 141.16 µg/m³ change in PM10 (a change large enough to reduce levels to the lower end of WHO guideline range), that 7,490 deaths would be avoided. Using our estimates, a change in PM10 of this magnitude would result in only 3,430 avoided deaths, less than half of what they predict.

than in Philadelphia and because the impact of air pollution on deaths is greater at younger ages in Delhi than in Philadelphia.

VI. CONCLUSIONS

We draw two conclusions from this study: (1) The impact of particulate matter on total non-trauma deaths in Delhi, India is smaller than effects found in the U.S. This is due to the fact that in Delhi a greater proportion of deaths occurs at younger ages and from causes not associated with air pollution than is the case in the U.S. Estimating the number of non-trauma deaths associated with air pollution in a developing country city based on U.S. studies may therefore yield misleading results. (2) The impacts of air pollution on deaths by age group may be very different in developing countries than in the U.S. In the U.S., peak effects occur among people 65 and older. In Delhi, peak effects occur in the 15 to 44 age group, implying that a death associated with air pollution causes more life-years to be lost.

We recognize, however, that our results are based on data representing only 25 percent of the deaths that occurred in Delhi during the study period. When data for the remainder of the city become available, this study should be replicated to confirm our findings.

TABLE 1:
Distribution of the Population of Delhi vs the Distribution of the NDMC Deaths
Among the Three Areas of Delhi by Place of Residence

Region	Census Population, 1991		NDMC Non-Trauma Deaths, 1991-94	
	Number	Percent of Total	Number	Percent of Total
Municipal Corporation of Delhi -- Urban	8,075,935	95.3	34,455	94.4
New Delhi Municipal Committee	301,297	3.6	1,999	5.5
Delhi Cantonment Board	94,393	1.1	49	0.1
Total	8,471,625	100	36,503	100

Source: National Capital Territory of Delhi, 1991.
Current Study.

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TABLE 2:

Descriptive Statistics for Variables Used in Regression Analysis

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Variable	N	Mean	Standard Deviation	Minimum	Maximum
Weather Variables:					
·Temperature	1393	76.32	12.73	45.4	102.5
· Dew Point	1392	57.91	12.34	28.3	80.2
Mortality (non-trauma)[1]:					
· Total Deaths per day	1461	24.98	7.07	6.0	50
· Respiratory Deaths	1461	2.22	1.68	0	14
· Cardiovascular Deaths	1461	3.86	2.10	0	13
· Ages 0 to 4	1461	10.61	4.63	0	31
· Ages 5 to 14	1461	1.41	1.25	0	7
· Ages 15 to 44	1461	4.86	2.45	0	15
· Ages 45 to 64	1461	4.78	2.39	0	14
· Ages 65 and over	1461	3.34	1.97	0	12
Pollution Measures:					
· Average Daily TSP	961	377.56	139.44	68	1714
· Average Daily SO_2	974	19.04	8.84	3.2	79.93
· Average Daily NO_x	974	32.74	11.80	6.2	127.54

[1] Included deaths occurring among Delhi residents only.

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TABLE 3:
Regression Results for Autoregressive Poisson Model
Dependent Variable=Total Non-trauma Deaths

Variable	Definition	Coefficient	Standard Error
Constant	Intercept	2.83*	0.3165
TSPLAG2	Mean daily TSP lagged two days	0.00023*	0.0001
TEMP	Mean daily temperature (°F)	0.011*	0.0047
HOT10	= 1 if temperature is in highest ten percent	0.105	0.0711
DEWPT	Mean daily dew point temperature (°F)	-0.002*	0.0007
HUMID10	=1 if dew point is in highest ten percent	0.008*	0.0019
_1991_	=1 if year is 1991	-0.374	0.5864
_1992_	=1 if year is 1992	-0.326	0.3606
_1993_	=1 if year is 1993	-0.097	0.3783
TREND	daily trend (increases by one for each day)	-0.0003	0.0005
SIN1YR	= sin((2*pi*trend)/365.25)	-0.249*	0.0322
COS1YR	= cos((2*pi*trend)/365.25)	0.058*	0.0208
SIN6MO	= sin((2*pi*trend*2)/365.25)	0.038*	0.0130
COS6MO	= cos((2*pi*trend*2)/365.25)	0.027	0.0880
SIN4MO	= sin((2*pi*trend*3)/365.25)	-0.21	0.0199
COS4MO	= cos((2*pi*trend*3)/365.25)	0.036	0.0380
SIN3MO	= sin((2*pi*trend*4)/365.25)	0.023	0.0190
COS3MO	= cos((2*pi*trend*4)/365.25)	-0.005	0.0831
SIN2_4M	= sin((2*pi*trend*5)/365.25)	-0.003	0.0071
COS2_4M	= cos((2*pi*trend*5)/365.25)	-0.023	0.0279

* indicates significance at 95 % confidence.

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TABLE 4:
Summary of Regression Results
for a 100 Microgram increase in TSP

Type of Regression	Percent Change in Mortality by Endpoint		
	Total Non-trauma Deaths	Cardiovascular Deaths	Respiratory Deaths
Model A	2.3** (2.28)	4.3** (3.51)	3.1** (8.58)
Model A + SO$_2$	2.8 (1.10)	4.4** (4.00)	3.4** (10.45)
Model A with outliers removed	1.8 (0.39)	5.3** (2.97)	0.7** (2.46)
Model B	2.3* (1.82)	4.3** (3.31)	3.8** (49.11)
Model B + SO$_2$	2.6 (0.98)	4.4** (3.82)	3.9** (34.02)
Model B with outliers removed	1.36 (0.27)	5.6** (2.68)	1.6** (25.69)
Model C	2.3 (0.78)	4.6** (6.49)	3.1** (14.87)

Model A = constant + TSP(-2) + temperature + dew point + hot10 + humid10 + year dummies + trend + trigonometric terms.
Model B = Model A + monitoring station dummies.
Model C = Model A - trigonometric terms + month dummies.
** Indicates significance at 95% confidence level; * Indicates significance at 80% confidence level

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Summary of Regression Results by Age Group
for a 100 microgram increase in TSP

Type of Regression	Percentage Change in Mortality by Endpoint				
	0 to 4	5 to 14	15 to 44	45 to 64	65 & up
Model A	2.4 (0.47)	2.6** (3.14)	4.3** (16.13)	2.0** (3.37)	0.8 (0.92)
Model A + SO$_2$	2.7 (0.40)	3.3** (6.91)	4.9** (67.49)	2.8** (3.78)	1.1 (1.19)
Model A with outliers removed	1.1 (1.02)	2.9** (2.75)	3.8** (11.36)	1.8* (1.41)	1.1** (2.02)
Model B	2.4 (0.36)	2.5** (17.23)	3.7** (4.00)	2.7** (3.07)	0.8 (0.73)
Model B + SO$_2$	2.6 (0.35)	na	4.2** (7.90)	3.1** (3.86)	1.0 (0.82)
Model B with outliers removed	0.9 (1.25)	2.6** (2.74)	2.9** (4.44)	2.8** (2.09)	1.3** (2.29)
Model C	2.1 (0.41)	2.6** (2.53)	4.1** (6.89)	2.3** (3.55)	1.0 (0.60)

Model A = constant + TSP(-2) + temperature + dew point + hot10 + humid10 + year dummies + trend + trigonometric terms.
Model B = Model A + monitoring station dummies.
Model C = Model A - trigonometric terms + month dummies.
**Indicates significance at 95% confidence level; * Indicates significance at 80% confidence level
na=not available (i.e. convergence not achieved)

TABLE 6:
Comparison of Daily Mortality Studies for Selected Cities

City	Percentage Change in Daily Mortality per 100 μg/m³ increase in TSP	Particulate Measure Used in Analysis	Mean Daily TSP[1] (μg/m³)
U.S. Studies:			
Steubenville, OH (Schwartz & Dockery, 1992b)	4	TSP(-1)	111
Birmingham, AL (Schwartz, 1993)	6	PM10	87
Detroit, MI (Schwartz, 1991)	6	TSP(-1)	87
Utah Valley (Pope et al., 1992)	9	PM10(5-day MA)	85
Philadelphia, PA (Schwartz & Dockery, 1992a)	7	TSP(2-day mean)	77
St. Louis, MO (Dockery et al., 1992)	8	PM10(-1)	50
Kingston/Harriman, TN (Dockery et al., 1992)	9	PM10(-1)	55
European Studies:			
Athens, Greece (Touloumi et al., 1996)	3 (winter)	BS(-1)	153
Paris, France (Dab et al., 1996)	4 9	ln(BS) ln(PM13)	58 93
Erfurt, Germany (Spix et al., 1993)	7	ln(BS)	106 (median)
Barcelona, Spain (Sunyer et al., 1996)	4	BS	64-91 (median)
Developing Country Studies:			
Santiago, Chile (Ostro et al., 1996)	4	ln(PM10)	210
Bangkok, Thailand (Chestnut et al., 1997)	6	PM10(-3)	118
Beijing, China (Xu et al.,1994)	4 (summer)	TSP(-1)	375
Delhi, India (this study)	2	TSP(-2)	375

[1]PM13, PM10, PM7, and BS values were converted to TSP using the following relationship: PM13=PM10=PM7=BS= 0.55TSP.

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Comparison of Delhi and Philadelphia Results

Mortality Endpoint	Percent Increase in Mortality per 100 $\mu g/m^3$ increase in TSP	
	Delhi [1]	Philadelphia (Schwartz & Dockery)
By Selected Cause:		
Total Deaths	2.3 *	6.7 *
CVD	4.3*	9.2 *
Respiratory [2]	3.1*	Pneumonia: 10.2 COPD: 17.8 *
By Age group:		
ages 0 to 4	2.4	
ages 5 to 14	2.6 *	2.7
ages 15 to 44	4.3 *	
ages 45 to 64	2.0 *	
ages 65 and up [3]	0.8	9.1 *

Notes: *   Indicates significance at 95% confidence.
         [1]   Poisson model: with trigonometric terms, weather, year and trend.
         [2]   Schwartz and Dockery compute dose response functions for pneumonia and chronic obstructive pulmonary disease.
         [3]   Schwartz & Dockery divide deaths into two age groups: < 65 and 65<.
              NA=not available
Sources: Schwartz & Dockery, 1991
              Current Study.

TABLE 8:
Number of Life-years Saved
for a 100 microgram reduction in TSP

Mortality Endpoint	Delhi, 1991		Philadelphia, 1989	
	Number of Deaths Avoided	Number of Life-years saved	Number of Deaths Avoided	Number of Life-years saved
By Age group:				
ages 0-4	278	16,680	370	13,320
ages 5-14	63	3,591		
ages 15-44	651	26,040		
ages 45-64	268	5,092		
ages 65 and up	125	0	3,149	37,788
TOTAL	1,385	51,403	3,519	51,108

Sources: Schwartz and Dockery, 1991
U.S. Department of Commerce, 1995
National Capital Territory of Delhi, 1991
World Bank, 1993
Current Study.

Figure 1:
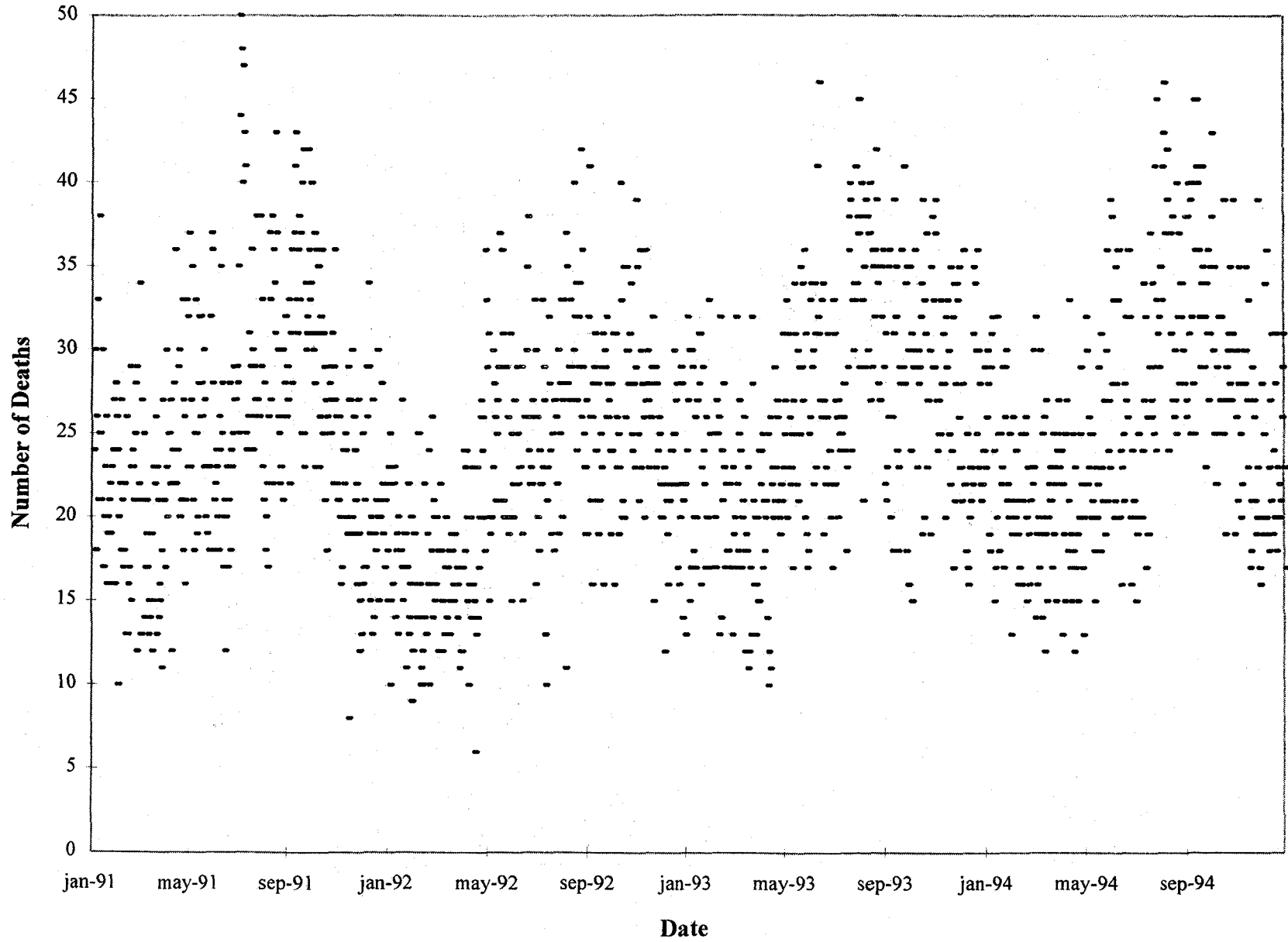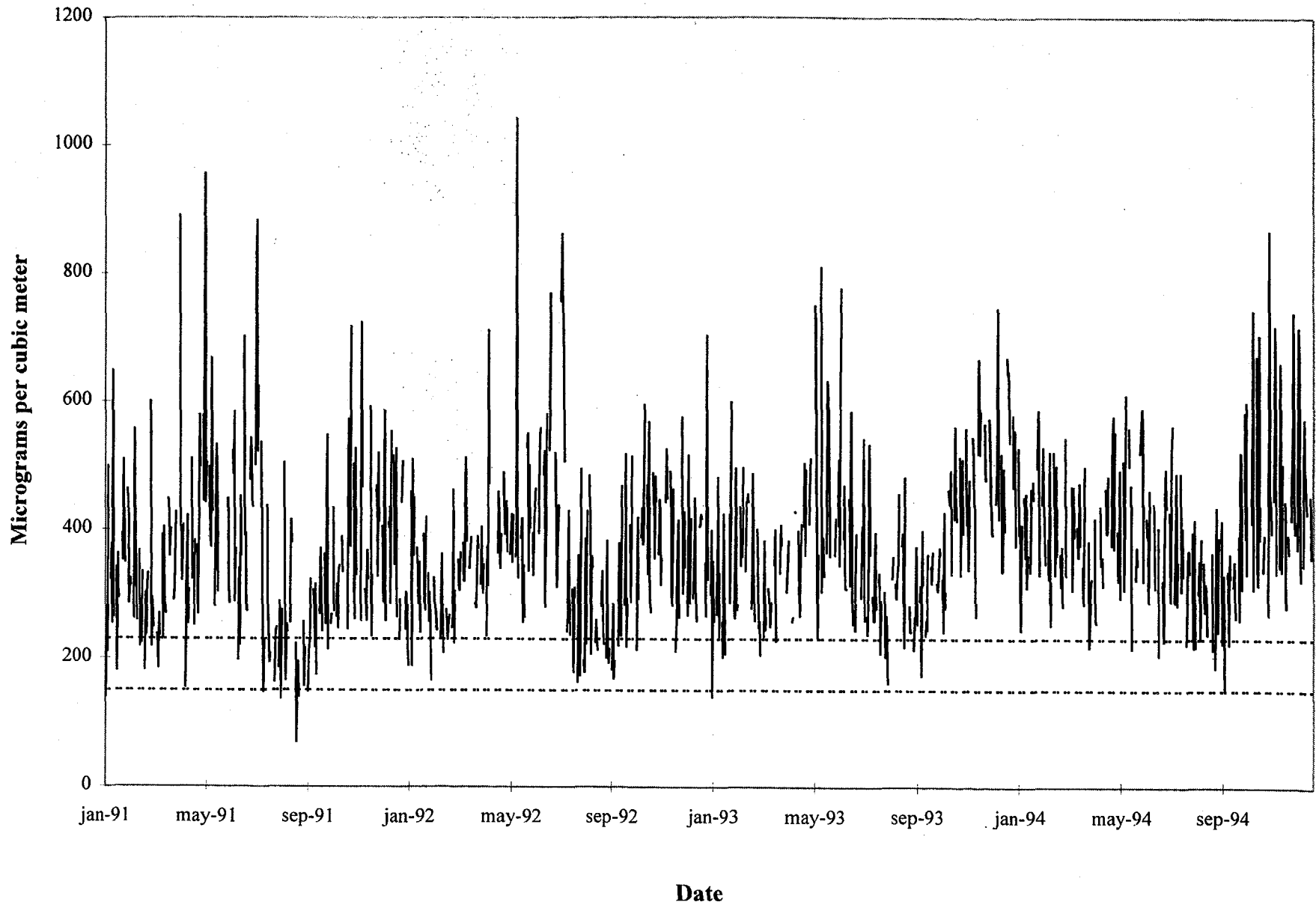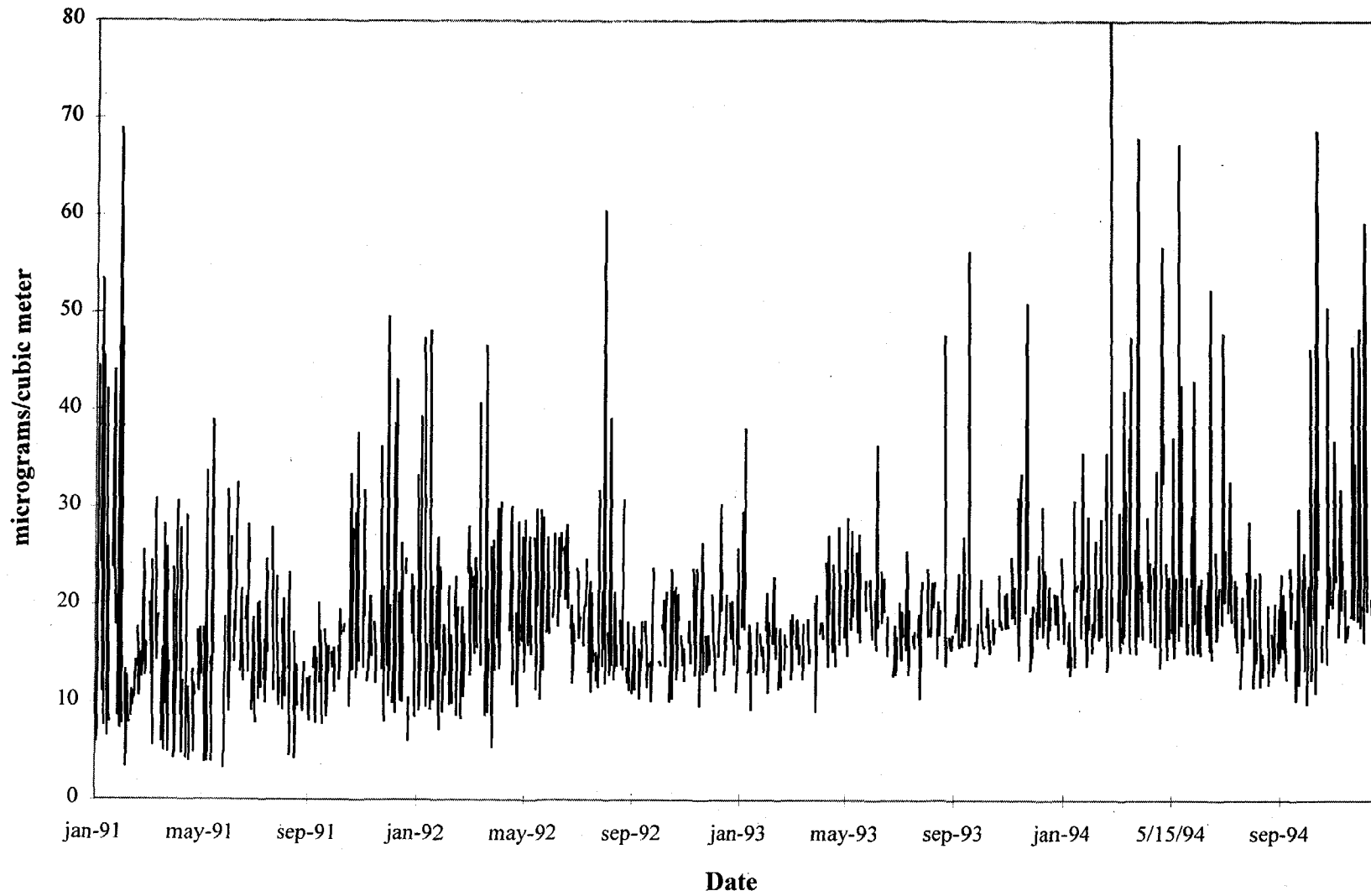**Daily Non-Trauma Deaths Among Delhi Residents, 1991-94**

Figure 2:
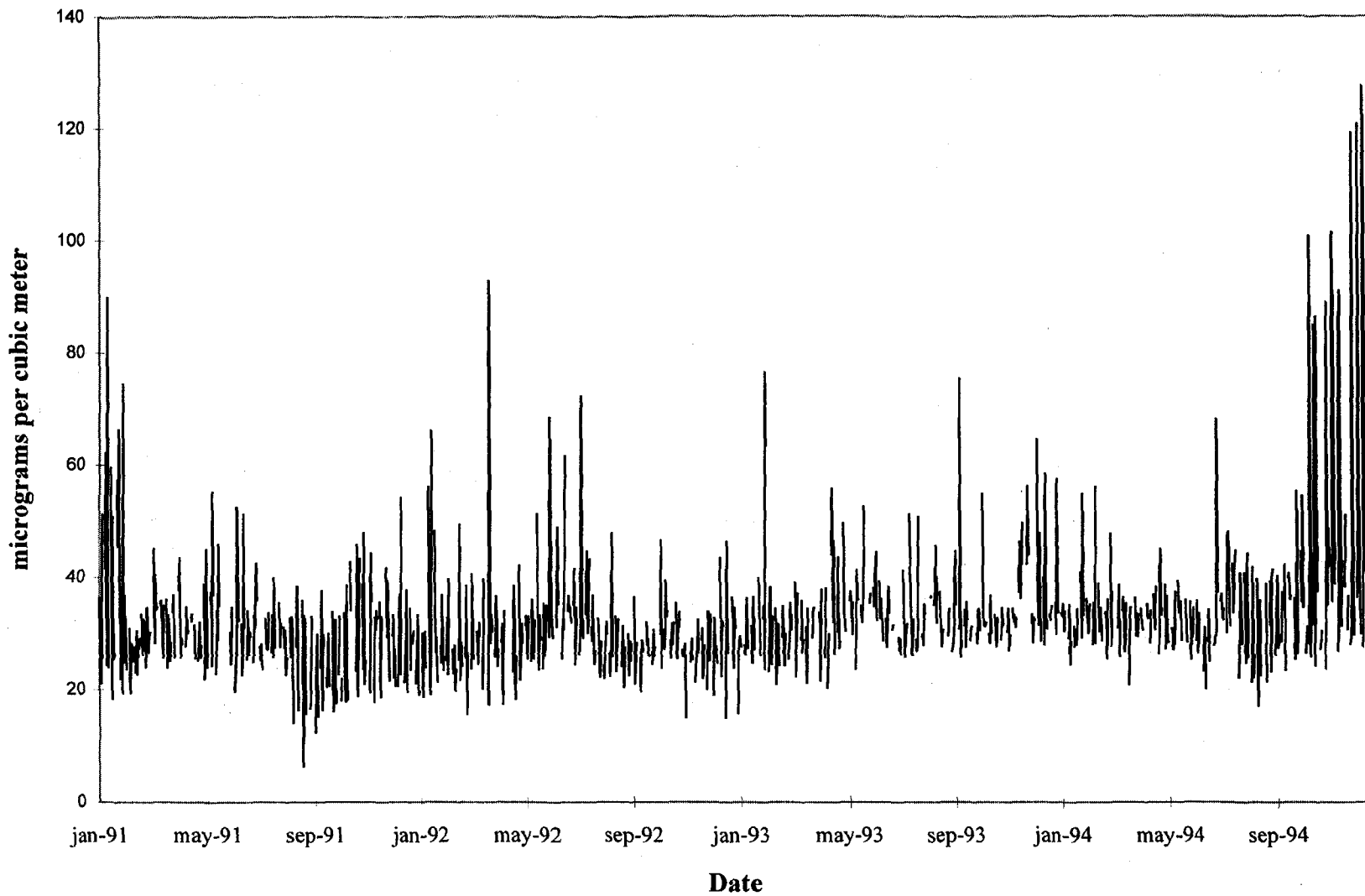**Mean Daily SPM: Delhi, 1991-94**

WHO Guideline: 150-230 micrograms per cubic meter per 24 hour period; indicated by dashed lines.

Figure 3:
Average Daily SO2: Delhi, India, 1991-94

WHO 24-hour guideline = 125 micrograms per cubic meter

Figure 4:
Average Daily NOx: Delhi, India, 1991-94

WHO 24-hour guideline = 150 micrograms per cubic meter

Figure 5:
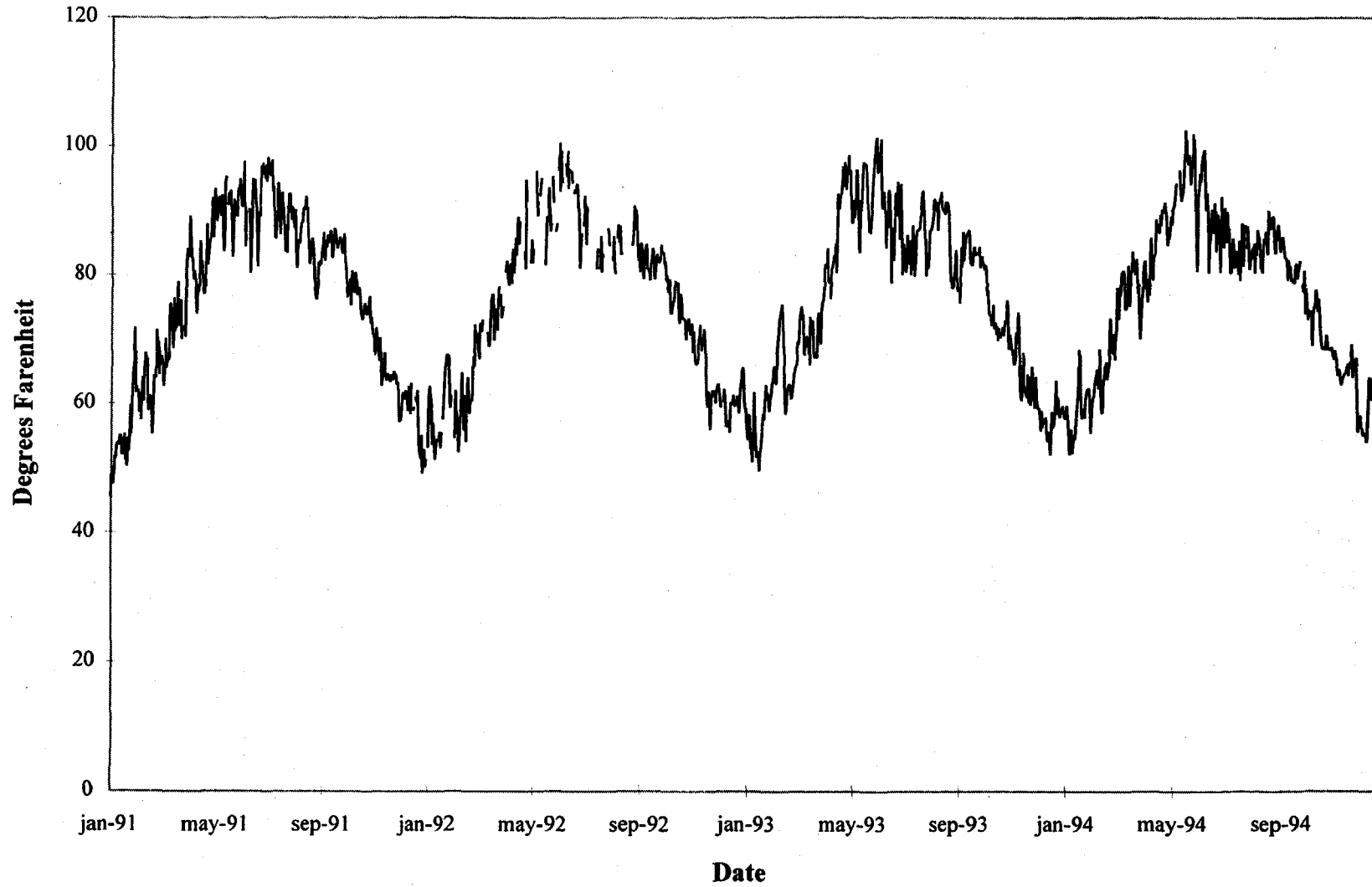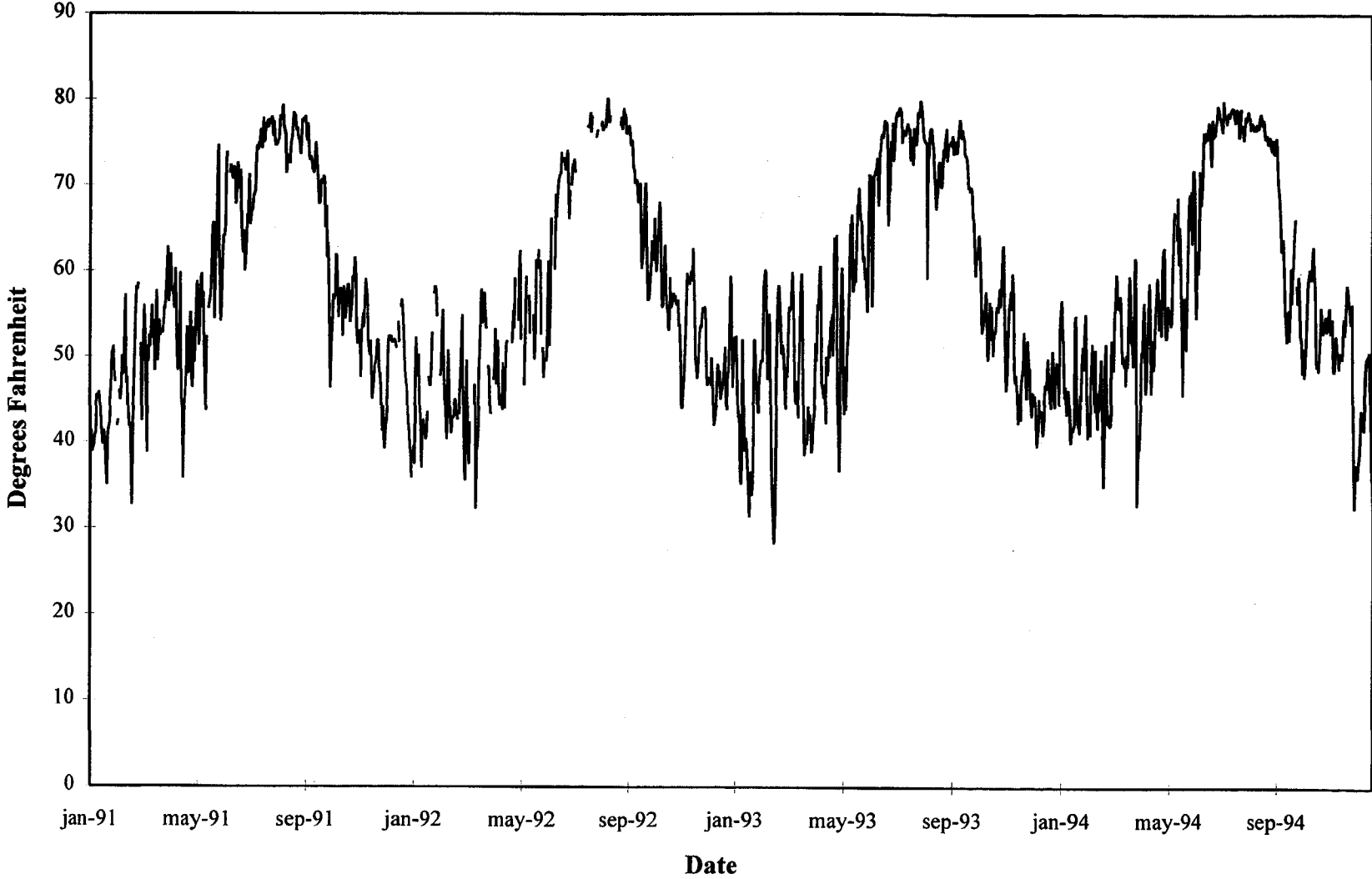**Mean Daily Temperature, Delhi 1991-94**

Figure 6:
Mean Daily Dew Point, Delhi 1991-94

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APPENDIX I:
Distribution of Deaths by Cause in the Study Data vs. the National Capital Territory

As illustrated in Tables A1 and A2, the distributions of deaths by cause in the data

provided by the NDMC for this study are very similar to those of the urban area of the National

Capital Territory. There are two large differences between the region as a whole and the NDMC,

however. First, a larger proportion of deaths are attributed to a specific cause in the NDMC data

compared to the statistics for the National Capital Territory. This occurs regardless of whether or

not we restrict the counts of death to those that are medically certified (Table A1) or whether we

consider all non-trauma deaths (Table A2).

Second, if we compare the distributions for the NDMC data in both tables, we find that

they are virtually identical whereas the distributions for the National Capital Territory in Tables

A1 and A2 are somewhat different. For instance, a much higher proportion of medically certified

deaths in the National Capital Territory are attributed to "Other Causes of Non-trauma deaths"

(27.1 percent) compared to those that are "medically certified or otherwise" (9.8 percent).

These two phenomena may simply be artifacts of hospital location. Many hospitals in the

National Capital Territory are located in the NDMC. Over 99 percent of the deaths in the

NDMC data are medically certified compared to 61 percent in the National Capital Territory.

The increased medical attention in the NDMC could also account for the higher incidence of

diagnoses.

If we assume that the deaths with unknown cause are distributed in a similar fashion

among the broad categories of death as those deaths with known cause, we find that the

distributions for the NDMC data become even closer to those of the National Capital Territory.

In Table A3, we show the number of deaths (both medically certified deaths and total deaths) by broad category of death after appropriately redistributing the deaths with unknown cause among the categories. Comparing the NDMC data to the medically certified figures for the National Capital Territory, we find that the largest difference occurs in the infectious disease category. Whereas only 19.7 percent of deaths in the NDMC data are attributed to infectious diseases, 25.4 percent of deaths in the National Capital Territory are attributed to this cause, a difference of only 5.7 percent.

The distribution of medically certified, non-trauma deaths in the NDMC is also similar to that for the entire region as reported in Table A4. We should note that while the NDMC is located entirely in the urban area of Delhi, the figures reported for medically certified deaths are not broken out by type of region (urban or rural). As shown in the table, a slightly larger percentage of deaths in the NDMC occurs in the youngest age group compared to the National Capital Territory. Differences in the age distributions, however slight, make our analyses of the mortality data by age group that much more important.

TABLE A1:
Distribution of Non-trauma Deaths (Medically Certified Only)
by Selected Cause

Cause of Death	NDMC data[1] 1991-94	National Capital Territory, 1991[2]
Infectious Disease, Total	18.7	18.6
Tuberculosis	6.4	7.7
Others	12.3	10.9
Associated with Air Pollution	22.6	14.5
Cardiovascular Disease	15.3	9.4
Pneumonia	5.1	4.3
Bronchitis and Asthma	2.2	0.8
Perinatal/Childbirth Deaths	21.4	13.0
Complications related to pregnancy	0.3	0.2
Perinatal causes	21.1	12.8
Other Causes of Non-trauma deaths	32.2	27.1
Cancer	4.9	2.6
Diabetes Mellitus	3.3	1.7
Anemias	3.4	2.0
Meningitis	3.5	1.8
Chronic Liver Disease and Cirrhosis	1.7	1.0
Other known causes	15.4	18.0
Deaths with Unknown Cause	5.1	26.8
TOTAL	100	100

[1] Includes Delhi residents only.
[2] Includes rural area of National Capital Territory and non-residents who expired in Delhi.

Sources: National Capital Territory of Delhi , 1991 and Current Study.

TABLE A2:
Distribution of Non-Trauma Deaths (Medically Certified or Otherwise)
by Selected Cause

Cause of Death	NDMC data[1] 1991-94	National Capital Territory (Urban)[2] Annual Report, 1991
Infectious Disease, Total	18.7	9.6
Tuberculosis	6.4	6.5
Others	12.3	3.1
Associated with Air Pollution	22.6	15.3
Cardiovascular Disease	15.3	10.4
Pneumonia	5.1	3.1
Chronic Bronchitis and Asthma	2.2	1.8
Perinatal/Obstetric causes	21.2	9.4
Perinatal causes	20.9	9.2
Obstetric causes	0.4	0.2
Other Causes of Non-trauma deaths	32.3	9.8
Cancer	5.2	2.7
Diabetes Mellitus	3.3	1.3
Anemias	3.4	1.9
Meningitis	3.5	1.3
Chronic Liver Disease and Cirrhosis	1.7	0.7
Other known causes	16.8	1.9
Deaths with Unknown Cause	5.2	55.9
TOTAL	100	100

[1] Included Delhi residents only.
[2] Includes non-residents who expired in Delhi.
Source: National Capital Territory of Delhi, 1991.
        Current Study.

TABLE A3:
Distribution of Non-trauma Deaths by Cause
After Inflating Categories to Include Deaths with Unknown Cause

Cause of Death	NDMC data, 1991-94	National Capital Territory (Urban) Annual Report, 1991
Medically Certified:	100.0	100.0
Infectious Diseases	19.7	25.4
Associated w/ Air Pollution	23.8	19.8
-Cardiovascular Disease	16.1	12.8
-Pneumonia	5.4	5.9
-Chronic Bronchitis/Asthma	2.3	1.1
Perinatal/Obstetric causes	22.6	17.8
Other Causes	33.9	37.0
Medically Certified or Otherwise:	100.0	100.0
Infectious Diseases	19.7	21.8
Associated w/ Air Pollution	23.8	34.7
-Cardiovascular Disease	16.1	23.6
-Pneumonia	5.4	7.0
-Chronic Bronchitis/Asthma	2.3	4.1
Perinatal/Obstetric causes	22.4	21.3
Other Causes	34.1	22.2

Source: National Capital Territory of Delhi, 1991.
    Current Study.

TABLE A4:
Distribution of Medically Certified Deaths
Due to Non-traumatic Causes by Age Group

Age Group	NDMC data, 1991-94	National Capital Territory, 1991 (Includes Rural Area)[1]
0-4	42.7	32.6
5 to 14	5.7	5.7
15 to 44	19.5	25.3
45 to 64	18.9	21.7
65 and up	13.2	14.5
Age not stated	--	0.2
Total	100.0	100.0

[1] Medically Certified Deaths are not reported separately for the Urban area of the National Capital Territory.

Source: National Capital Territory of Delhi, 1991.
         Current Study.

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