Air Pollution and Daily Mortality in Seoul and Ulsan, Korea

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The relationship between air pollution and daily mortality for the period 1991–1995 was examined in two Korean cities, Seoul and Ulsan. The observed concentrations of sulfur dioxide (SO_2; mean = 28.7 ppb), ozone (O_3; mean = 29.2 ppb), and total suspended particulates (TSP; mean = 82.3 μg/m^3) during the study period were at levels below Korea's current ambient air quality standards. Daily death counts were regressed separately in the two cities, using Poisson regression on SO_2, O_3, and/or TSP controlling for variability in the weather and seasons. When considered singly in Poisson regression models controlling for seasonal variations and weather conditions, the nonaccidental mortality associated with a 50-ppb increment in a 3-day moving average of SO_2 concentrations, including the concurrent day and the preceding 2 days, was 1.078 [95% confidence interval (CI), 1.057–1.099] for Seoul and 1.051 (CI, 0.991–1.115) for Ulsan. The rate ratio was 1.051 (CI, 1.031–1.072) in Seoul and 0.999 (CI, 0.961–1.039) in Ulsan per 100 μg/m^3 for TSP, and 1.015 (CI, 1.005–1.025) in Seoul and 1.020 (0.889–1.170) in Ulsan per 50 ppb for 1-hr maximum O_3. When TSP was considered simultaneously with other pollutants, the TSP association was no longer significant. We observed independent pollution effects on daily mortality even after using various approaches to control for either weather or seasonal variables in the regression model. This study demonstrated increased mortality associated with air pollution at both SO_2 and O_3 levels below the current World Health Organization recommendations. *Key words*: air pollution, daily mortality, O_3, Seoul, SO_2, total suspended particulates, Ulsan. *Environ Health Perspect* 107:149–154 (1999). [Online 14 January 1999]
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During the last few decades, Korea has given priority to economic development. As a result of this effort, Korea has been very successful in both economic growth and development. Beyond this prosperity, however, several negative issues have also arisen. One of these is environment-related problems. Residents living in polluted areas have requested specific information on the quality of their environment. They have begun to realize the possibility of causal inferences between changes in health status and deteriorating environments, including ambient air pollution and contaminants from drinking water and food. Our 1994 report showed that sulfur dioxide (SO_2) and total suspended particulate (TSP) levels had been continuously decreasing over the previous 10 years, but ozone (O_3) and nitrogen dioxide (NO_2) levels had not (*1*). For the past 10 years, the government has advocated and enforced the use of low-SO_2-contaminant fuel or natural gas for industry. At the same time, the amount of traffic in Korea has skyrocketed in most cities. For this reason, NO_2 and O_3 levels have not decreased as much as other regulated air pollutants. This study, therefore, was conducted to provide useful information on these matters to Koreans. An epidemiologic study has its own merits over laboratory studies. Its flexibility and generalization are easy to interpret, and the findings can be shared with people who have little knowledge in this area. In Korea, only one observation has been reported accounting for the daily mortality effect of ambient air pollution (*2*). Even though public concern has increased, few quantitative data are available in Korea.

The famous London fog of 1952 demonstrated the alarming deadly potential of high levels of urban air pollution, particularly for the elderly and for those already suffering from sickness (*3*). Several later studies in London reported associations between daily mortality and ambient air pollution at much lower pollution levels (*4–6*). After the experience of the London fog episode, people began to realize the necessity of regulating ambient air pollution levels. Nowadays, as pollution levels have been reduced, increased mortality directly attributed to air pollution is rarely observed. However, recent epidemiologic studies have shown the possible causal relationship between adverse health effects and ambient air pollution for levels well below the national ambient air quality standards of many developed countries. Extensive literature has developed concerning the effects of outdoor air pollution on human health. Human epidemiologic studies of acute health effects have found decreased lung function (*7*), increased respiratory symptoms and illnesses (*8*), an increased incidence of hospital admissions and emergency visits (*9,10*), and an increased mortality associated with current levels of air pollution in many urban areas (*11–15*).

More recent studies have examined mortality with respect to daily particulate and SO_2 air pollution levels (*13,14,16,17*). These studies have observed changes in daily death counts associated with short-term changes in ambient levels of those air pollutants.

Ozone is generally regarded as one of the most toxic components of the photochemical air pollution mixture. Epidemiological studies (*18–21*) have reported significant effects of exposure to O_3 on lung function decrements, respiratory and nonrespiratory symptoms, exacerbation of asthma, and an increased number of hospital admissions. A few studies have specifically investigated the short-term effects of O_3 on mortality (*22–25*).

Our purpose was to determine the relationship between ambient air pollution and mortality. Data from two cities in Korea provided an opportunity to evaluate the association between daily mortality and air pollution, including TSP, SO_2, and O_3, in two different study areas, the cities of Seoul and Ulsan.

Materials and Methods

The study areas consisted of two cities (Seoul and Ulsan) in Korea (Fig. 1). Seoul is the capital of Korea with a population of about 12 million. Few major industrial sources of ambient air pollution are located within this huge city. Traffic and domestic space heating are thought to be the sources of ambient air pollution, as in many other large cities around the world. Ulsan is a highly industrialized city located on the southeastern part of the Korean Peninsula near the Bay of Ulsan (Fig. 1). This city is a symbol of success in Korean economic development because there are two enormous industrial complexes within the borders of the city, namely, the Ulsan petrochemical complex and the Ulsan Mipo industrial complex. A key feature of this study is that the areas being compared are widely different from each other.

The number of deaths occurring in the two cities between 1 January 1991 and 31 December 1995, according to the day on which the deaths occurred, were supplied by the National Statistics Office of Korea. Until 1994, the causes of death were coded according to the *International Classification of*

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Disease, 9th Revision (ICD-9) by a certified nosologist. Since 1995, the National Statistics Office has followed the *International Classification of Disease, 10th Revision* (ICD-10). Deaths due to accidents were excluded, as were all deaths of residents outside the Seoul or Ulsan area.

Air pollution data were provided by the Ministry of Environment, Republic of Korea. Exposure measurements during the study period were based on 20 monitoring stations in Seoul and 4 stations in Ulsan. Ambient concentrations of TSP (β-ray absorption method), SO_2 (pulsed ultraviolet fluorescence method), NO_2 (chemiluminescent method), O_3 (ultraviolet photometry method), and carbon monoxide (CO; nondispersive infrared photometry method) were measured at each monitoring station during the study period. In the Ulsan area, the levels of specific pollutants (e.g., SO_2, TSP) often exceeded the World Health Organization (WHO) air quality guidelines (*26*). Daily mean pollution levels for each pollutant were calculated and filed during the study period. To have a representative 24-hr average pollution level, except for O_3 levels, we included the data only if at least 20 hr of daily data were available. If the number of hours of observed data were <20, then we treated that day as missing. We took the highest hourly measured O_3 concentration as the representative level for the day. We also observed a lead-lag relationship between air pollution and mortality. Therefore, we assumed that the increased mortality occurred concurrently or within 1–3 days following an increase in air pollution. Daily variations in mortality have frequently been shown to be strongly associated with variations in outdoor air temperature and humidity (*27*). Information on the 24-hr average temperature (°C) and relative humidity (%) of the same calendar year was available from the National Meteorological Office and was measured at a central location in both cities. Although seasonal variation in mortality is partly reflected by temperature, we decided to include an additional nominal variable for the season to remove any residual confounding from this source. There have also been observations that mortality varies by day of the week (*28,29*). Unlike previous reports, mortality in this study was generally consistent over the week, so we did not consider weekday variation in the regression equation.

Figure 1. Location of Seoul and Ulsan, Korea.

The death counts per day were matched to the daily-averaged levels of TSP, SO_2, and the 1-hr daily maximum level of O_3 on the same day. Poisson distribution may have been appropriate to model the distribution of mortality rates and daily death counts.

In this study, the impacts of environmental factors (i.e., ambient air pollutants, especially the effect of TSP, SO_2, and O_3, weather, and season) on mortality rates were our main concern, as in previous studies. We chose these factors because they were suggested as significant predictors in the previous analyses as to the number of daily deaths. It is assumed that daily death counts were correlated in days. Therefore, we applied generalized estimation equations (GEEs) developed by Liang and Zeger (*30*).

The model can be expressed as

$$\log E(Y) = \beta X$$

where $E(Y)$ is the expected number of deaths on a day and X is the vector of air pollution and other indicator variables on the same day. We also assumed the exchangeable correlation structure on consecutive death counts, which can be expressed as

$$Corr\left(Y_{ij}Y_{ik}\right) = \begin{cases} 1, j = k \\ \alpha, j \neq k' \end{cases}$$

where i =1991, 1992, 1993, 1994, and 1995 (the calendar year), and j = 1, 2, ..., 365 (day of the year).

The regression coefficients were estimated, using GEEs, and the variances were estimated robustly. Regressions were done in PROC GENMOD of SAS software (*31*).

After establishing the full model, TSP, SO_2, or O_3 was considered a main risk factor. Air pollution levels were generally treated as a continuous variable in the Poisson regression analysis.

Results

Table 1 presents the mean and percentile distribution of variables in this study. Total suspended particulates and O_3 levels were higher in Seoul than in Ulsan. Sulfur dioxide was negatively associated with O_3 and air temperature (Fig. 2). Figure 2 shows that clear seasonal patterns existed in air temperature, SO_2, and O_3. The seasonal patterns were stronger in Seoul than in Ulsan. It can also be seen in Figure 2 that SO_2 and TSP levels decreased over a calendar period. However, O_3 did not show any trend by calendar year (Fig. 2).

A descriptive analysis indicated that the correlation among air pollutants and weather conditions was not high, except the correlation between TSP and SO_2 in Seoul (Table 2). Daily death counts showed seasonal variation: during the winter season (December, January, and February) mortality was the highest.

The population size of Seoul (5-year average = 10,801,622) remained at similar levels from year to year, but seemed to be slightly decreasing. However, in Ulsan (5-year average = 792,422) the population was increasing. In 1995, the district of Ulsan expanded its area, so the population rapidly increased by 26%. Daily death counts in the two cities were, therefore, different according to the size of population (Table 1).

Previous studies suggested that air pollution may affect mortality with some lags, and

Table 1. Descriptive statistics of mortality counts, weather, and air pollution in two study cities, Seoul and Ulsan, 1991–1995

	Ulsan							Seoul						
		Percentile							Percentile					
Variable	No. of days	10	25	50	75	90	Mean	No. of days	10	25	50	75	90	Mean
Air pollutants														
TSP (μg/m³)	1,642	39	49	65	89	117	72.1	1,646	45	61	85	115	149	92.5
SO_2 (ppb)	1,794	17	22	29	39	49	31.4	1,794	8	11	19	34	54	26.0
O_3 (ppb)	1,795	16	19	24	31	39	26.0	1,764	14	21	29	41	55	32.4
Weather														
Temperature (°C)	1,826	2.5	6.3	14.5	20.8	25.0	14.0	1,826	-1.1	3.6	13.7	21.6	24.9	12.6
Humidity (%)	1,826	40	53	67	77	85	64.3	1,826	46	56	66	76	84	65.5
Deaths (per day)	1,807	2	3	5	7	10	5.7	1,826	68	75	83	92	100	83.7

Abbreviations: TSP, total suspended particulates; SO_2, sulfur dioxide; O_3, ozone.

the appropriate averaging time for exposure may exceed 24 hr; therefore, concurrent exposure, lagged exposure (up to the previous 3 days), and 3-day moving averages (including the concurrent day or not) were considered. The 3-day moving averages of SO_2 and TSP levels resulted in the highest relationship with daily mortality. Therefore, the final model for daily mortality included air temperature, relative humidity, seasonal dummies, 3-day moving averages of SO_2 and TSP, and 1-hr maximum O_3 levels.

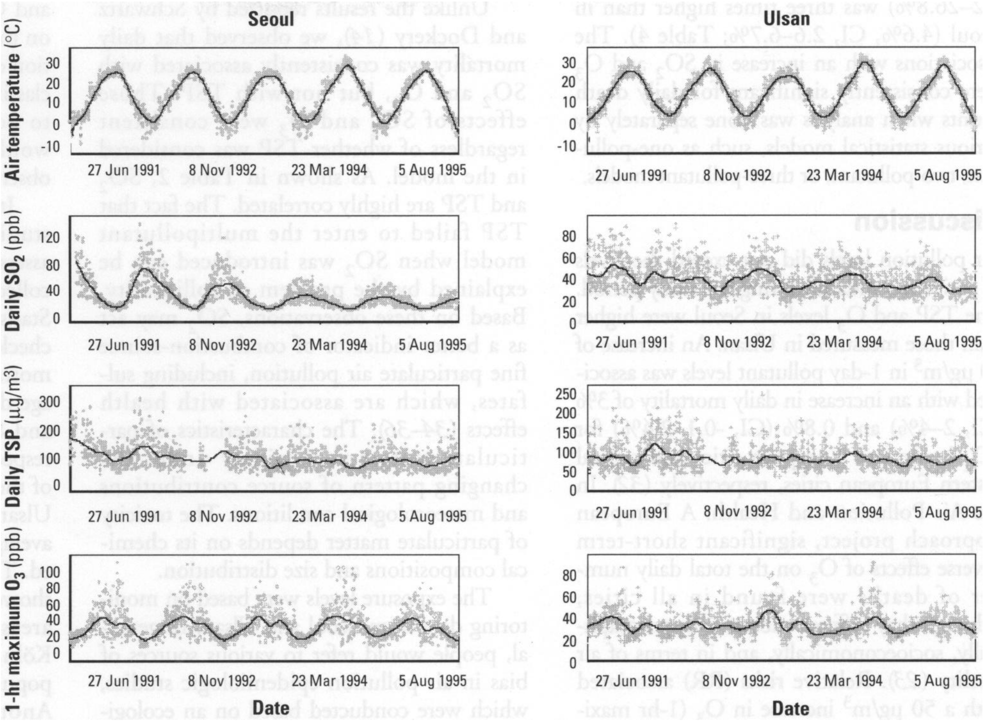

Figure 2. Distribution of daily mean temperature (°C), daily mean SO_2 (ppb), daily mean total suspended particulates (TSP; µg/m³), and 1-hr daily maximum O_3 (ppb) concentration in Seoul and Ulsan, 1991–1995.

Table 2. Pearson correlation coefficients for ambient air pollutants and weather conditions, including temperature (°C) and humidity (%) in Seoul and Ulsan

		Seoul				
		TSP (µg/m³)	SO_2 (ppb)	O_3 (ppb)	Temperature (°C)	Humidity (%)
Ulsan	TSP (µg/m³)		0.72***	0.01	-0.19***	-0.05*
	SO_2 (ppb)	0.42***		-0.34***	-0.55***	-0.22**
	O_3 (ppb)	0.17***	0.14***		0.58***	-0.04
	Temperature (°C)	0.02	0.03	0.33**		0.42***
	Humidity (%)	-0.04	0.02	-0.03	0.57***	

Abbreviations: TSP, total suspended particulates; SO_2, sulfur dioxide; O_3, ozone.

*$0.01 \leq p \leq 0.05$; **$0.001 \leq p \leq 0.01$; ***$p \leq 0.001$.

One pollutant model controlling for either weather conditions (temperature and relative humidity) or seasonal variations showed that each pollutant was highly associated with daily mortality (Table 3). The estimate for the single TSP effect in Seoul is 0.0007 (Ulsan, 0.0005), with a standard error of 0.0001 (Ulsan, 0.0001). Hence, an increase of 10 µg/m³ of TSP corresponded to approximately 7% more deaths in Seoul (Ulsan, 1%), given a constant level of weather conditions. Based on the results from a one-pollutant model and previous studies, our full model consisted of the levels of three air pollutants (TSP, SO_2, and O_3) as a continuous variable, the weather conditions such as air temperature and relative humidity, and seasonal indicators. In these multipollutant models, the TSP effect on mortality was no longer significant ($p = 0.7557$ and 0.8775 for Seoul and Ulsan, respectively). Thus, we excluded TSP from the full model. Table 4 shows the results of two-pollutant models (SO_2 and O_3) considering either weather conditions or seasonal variations. In both cities, the model III gave the best fit (the smallest ratio of deviance value to degree of freedom). Seasonal variation affected the estimation of O_3 effect on mortality more than weather conditions did (comparison of model I to model II). The risk of all-cause mortality was estimated to increase by 12–13% [95% confidence interval (CI), 9–16% and 6–20% for Seoul and Ulsan, respectively] with an increase in 3-day moving average SO_2 levels equal to 50 ppb. The effect of O_3 increase by 50 ppb on mortality in Ulsan (14%, CI,

Table 3. Poisson regression of daily mortality and each ambient air pollutant with year treated as a random effect, Seoul and Ulsan, Korea, 1991–1995 (one-pollutant models)

	Not adjusted		Adjusted for temperature and humidity		Adjusted for temperature, humidity, and season[a]	
Pollutant	Seoul	Ulsan	Seoul	Ulsan	Seoul	Ulsan
TSP (100 µg/m³)[b]	1.105	1.001	1.073	1.010	1.051	0.999
	(1.063–1.149)	(0.962–1.040)	(1.052–1.094)	(0.972–1.050)	(1.031–1.072)	(0.961–1.039)
SO_2 (50 ppb)[c]	1.145	1.062	1.094	1.073	1.078	1.051
	(1.111–1.179)	(0.991–1.137)	(1.062–1.127)	(1.031–1.115)	(1.057–1.099)	(0.991–1.115)
O_3 (50 ppb)[d]	0.932	0.980	1.025	1.062	1.015	1.020
	(0.888–0.979)	(0.863–1.113)	(1.015–1.035)	(0.926–1.218)	(1.005–1.025)	(0.889–1.170)

Abbreviations: TSP, total suspended particulates; SO_2, sulfur dioxide; O_3, ozone. Values shown are relative risk (95% confidence interval).

[a] Three indicators for spring, fall, or winter months.

[b] Effect of a 100-µg/m³ increase in the 3-day mean, including a current day.

[c] Effect of a 50-ppb increase in the 3-day mean, including a current day.

[d] Effect of a 50-ppb increase in the 1-hr daily maximum concentration of a current day.

2.2–26.8%) was three times higher than in Seoul (4.6%, CI, 2.6–6.7%; Table 4). The associations with an increase in SO_2 and O_3 were consistently significant for daily death counts when analysis was done separately by various statistical models, such as one-pollutant, two-pollutant, or three-pollutant models.

Discussion

Air pollution levels did not exceed the levels of national standards during the study period. The TSP and O_3 levels in Seoul were higher than those measured in Ulsan. An increase of 50 µg/m^3 in 1-day pollutant levels was associated with an increase in daily mortality of 3% (CI, 2–4%) and 0.8% (CI, -0.1–2.4%) for SO_2 in western European cities and central eastern European cities, respectively (*32*). In the Air Pollution and Health: A European Approach project, significant short-term adverse effects of O_3 on the total daily number of deaths were found in all cities, although they differed substantially geographically, socioeconomically, and in terms of air quality (*23*). Relative risks (RR) associated with a 50 µg/m^3 increase in O_3 (1-hr maximum) ranged from 1.3 to 8.6%, with a pooled estimate of 2.9% (CI, 1.0–4.9) (*23*). The correlation between O_3 and TSP was poor, ranging from 0.11 to 0.25. Table 4 compares the results from this study with those from European cities (*23,32,33*). Because individual studies necessarily have methodological restrictions, judgments concerning the validity of our study must involve evaluating the body of research as a whole. As shown in Table 5, the consistency of findings from various study areas makes it unlikely that the observed overall air pollution effects on daily mortality could be due to systemic methodologic or analytic bias.

Unlike the results reported by Schwartz and Dockery (*14*), we observed that daily mortality was consistently associated with SO_2 and O_3, but not with TSP. Those effects of SO_2 and O_3 were consistent regardless of whether TSP was considered in the model. As shown in Table 2, SO_2 and TSP are highly correlated. The fact that TSP failed to enter the multipollutant model when SO_2 was introduced can be explained by the problem of collinearity. Based on these observations, SO_2 may act as a better indicator of combustion-source fine particulate air pollution, including sulfates, which are associated with health effects (*34–36*). The characteristics of particulate matter vary widely under the changing pattern of source contributions and meteorological conditions. The toxicity of particulate matter depends on its chemical compositions and size distribution.

The exposure levels were based on monitoring data from Seoul and Ulsan. In general, people would refer to various sources of bias in air pollution epidemiologic studies, which were conducted based on an ecological study design. It is usually difficult to control many confounding variables in air pollution epidemiologic studies. Most studies have used an area monitored for air pollution data as an alternative measure for personal exposure assessment. This practice implies that all of the residents living near the monitoring site are exposed to the same level of air pollution, which is unrealistic. For this reason, results from these kinds of studies cannot be given too much weight. All these limitations imply the existence of a probable causal relationship between mortality and ambient air pollutants, such as TSP, SO_2, and O_3. We had no systematic information on the reliability of routinely collected pollution data. However, even if there were a misclassification of exposure levels, it is unlikely to be related to mortality, so any effect would dilute the strength of the effects observed for particulate pollution.

It is general procedure in epidemiologic studies to have information on exposure assessment and health outcomes. This study collected mortality data from the National Statistics Office of Korea. It is important to check the validity and completeness of the mortality data. As seen in Table 1, the average death counts of the two cities were 5.3 and 89.3 deaths/day in Ulsan and Seoul, respectively. Considering the population size of these two cities (Seoul about 10,800,000; Ulsan about 792,000), we realize that the average death counts were less than expected. This was also revealed in Table 5, which showed the average death count in different areas. The average daily death count in Köln, Germany, was 18 (Table 6), with a population size of 740,000, similar to Ulsan. Another comparison can be made with Korea's national mortality statistics. The crude mortality in Korea was 520 × 10^{-5}. The expected daily deaths in Seoul and Ulsan would be about 154 and 10, respectively, if we applied the crude mortality rate. It is, therefore, important to find a reasonable explanation for this discrepancy.

What we considered in this regard was the age distribution of the two cities and the proportion of deaths caused by accidents, which was excluded from our analysis. The age distribution of the two cities was similar to that of the general Korean population, except in the proportion of elderly subjects (>60 years old). The number of persons

Table 4. Poisson regression analysis of daily mortality and sulfur dioxide (SO_2) and ozone (O_3) with year treated as a random effect, Seoul and Ulsan, Korea, 1991–1995

	Seoul			Ulsan		
Variable	Model I	Model II	Model III	Model I	Model II	Model III
SO_2 (ppb)^a	0.0023 (0.0003)***	0.0020 (0.0003)***	0.0019 (0.0003)***	0.0013 (0.0004)**	0.0011 (0.0005)*	0.0012 (0.0007)
O_3 (ppb)^b	0.0006 (0.0001)***	0.0004 (0.0003)	0.0005 (0.0001)***	0.0009 (0.0013)	0.0001 (0.0014)	0.0001 (0.0013)
Temperature (°C)	-0.0023 (0.0014)	–	-0.0009 (0.0022)	-0.0047 (0.0021)*	–	-0.0006 (0.0056)
Humidity (%)	-0.0005 (0.0003)	–	-0.0002 (0.0003)	-0.0002 (0.0014)	–	-0.0002 (0.0014)
Spring^c	–	0.0838 (0.0259)**	0.0712 (0.0150)***	–	0.1280 (0.0617)*	0.1180 (0.0813)
Fall^c	–	0.0309 (0.0178)	0.0218 (0.0151)	–	0.1113 (0.0268)***	0.1053 (0.0240)***
Winter^c	–	0.0797	0.0583 (0.0171)***	– (0.0344)	0.1316 (0.0448)**	0.1142 (0.0947)
Deviance value	1.8301	1.7787	1.7723	1.5877	1.5897	1.5721

Values shown are parameter estimates (standard error).

[a] Three-day moving average including a current day.

[b] One-hour daily maximum concentration of a current day.

[c] Indicator for spring (March, April, and May), fall (September, October, and November), or winter (December, January, and February) months.

*0.01≤p<0.05; **0.001≤p<0.01; ***p<0.001.

Table 5. Estimated mortality rate ratio and 95% confidence intervals associated with increases in the levels of total suspended particulates (TSPs), sulfur dioxide (SO_2), and ozone (O_3) in various sites

Variable	Seoul^a	Ulsan^a	APHEA^a	Ref	Mexico City^b	Ref
TSP (100 µg/m^3)	1.051 (1.031–1.072)	0.999 (0.961–1.039)	1.022 (1.013–1.031)	(*32*)	1.050 (1.030–1.067)	(*23*)
SO_2	1.029 (1.021–1.037)	1.019 (0.997–1.042)	1.023 (1.017–1.028)	(*32*)	1.024 (0.984–1.062)	(*23*)
O_3	1.008 (1.003–1.013)	1.010 (0.942–1.083)	1.029 (1.010–1.049)	(*33*)	1.024 (1.011–1.039)	(*23*)

Abbreviations: APHEA, Air Pollution and Health: A European Approach project; Ref, reference.

[a] Mortality increases of 50 µg/m^3 (= 19.1 ppb for SO_2 and 25.5 ppb for O_3) in SO_2 and O_3.

[b] Mortality increases of 100 ppb (= 262 µg/m^3 for SO_2 and 196 µg/m^3 for O_3) in SO_2 and O_3.

Table 6. Comparisons of daily average death counts (deaths from external causes were excluded) in several cities

City	Time period	Population	Average daily death counts	Reference
Athens	1987–1991	2,000,000	35^a	(*23*)
London	1987–1991	7,200,000	176	(*23*)
Paris	1987–1990	6,140,000	130	(*23*)
Köln	1977–1989	740,000	18	(*23*)
Southwest Mexico City	1990–1992	2,082,000	22	(*33*)
Utah County	1985–1989	260,000	2.7	(*40*)
Philadelphia	1973–1980	1,688,710	48.2	(*14*)
Seoul	1991–1995	10,800,000	89.3	This study
Ulsan	1991–1995	792,000	5.3	This study

[a] Deaths from external causes were included.

Table 7. Comparisons of mortality characteristics between Korea as a whole and the study cities

Area	No. in population ≥60 years of age (%)	No. of deaths defined as ICD<800 (%)
Whole country	3,861,859 (8.7)	198,661 (86.1)
Seoul (1991–1995)	724,068 (6.9)	152,825 (88.6)
Ulsan (1991–1995)	30,662 (4.0)	6,785 (77.8)

ICD, *International Classification of Disease.*

older than 60 years in the whole population comprises about 9%, while those >60 years in the study cities comprised only 4–7% (Table 7). Because of this, we believe that Seoul and Ulsan show a lower mortality than Korea as a whole. In addition, the proportion of deaths by accident (ICD>800) in Ulsan was 22%, while the proportion in the whole country was 14%. These figures can explain the discrepancy, although they are not fully explanatory. For the completeness of mortality data, a recent survey (*37*) indicated that more than 90% of death counts were reported and filed. It is reasonable, therefore, to consider that the completeness of mortality data in Korea is satisfactory.

We observed a clear seasonal variation in air pollutants in Seoul, but not in Ulsan (Fig. 2). This difference can be explained by the air pollution sources in the two cities. Major air pollution sources in Seoul are traffic and space heating during the winter season. In addition to these sources, industrial sources must be a contributing factor in Ulsan. However, we still do not know exactly why the trend and levels of air pollution were different in the two cities. This must be studied separately. Like other ecological studies, the present study permits only a limited control of confounding variables. As Pope and Schwartz (*38*) stated, covariates that vary within subject, but whose day-to-day variation is unlikely to associate with air pollution, can be excluded as potential confounders. The main potential confounders in this time-series analysis are factors that vary in time, such as air temperature, humidity, and seasonal variations. This seasonal variation was controlled in the regression model in which seasonal indicators (winter, spring, and fall months) were included. Figure 3 shows residuals from Poisson models using SO_2 as a main predictor of daily mortality controlling for either weather conditions (air temperature and humidity) or seasonal variation. The analysis indicates that seasonal variation is effectively controlled. We observed independent pollution effects on daily mortality even after using various approaches to control for either weather or seasonal variables in the regression model.

Exposure measurement error is a concern in environmental epidemiologic studies. As in previous studies, we assigned air pollutant levels from fixed, outdoor monitoring stations to individuals who died to estimate their exposure. Despite limitations, the consistency and strength of these findings were striking, and further in-depth studies are required to confirm the existence of the effects. However, priority should be given to individual-based studies in which data on key covariates such as smoking, occupation history, indoor air pollution, and family circumstances can be collected, and in which the validity of the pollution exposure measurements can be investigated. It is highly unlikely that such concordance across so many locations could have occurred due to confounding or by chance.

In summary, the present study contributes to a growing body of literature that reports associations between ambient air pollution and mortality and morbidity. As Bates (*39*) has pointed out, the consistent and coherent findings in evaluating the evidence on the effects of air pollution play an important role in establishing the causal pathway in mortality and air pollution. Given the coherency of the observed associations between SO_2 and O_3 and daily mortality across different geographic locations and ethnic populations, the association reported here indicates that these pollutants are probable contributors to premature death. The association is observed at pollution levels common to many cities, including levels well below the national ambient air quality standards of many developed countries. We observed that the regression against mortality on a daily basis was strong. This observation, along with other previously published results, becomes strong grounds for arguing that the relationship is causal, even in the absence of any confirmed biological mechanism. Air pollution could be a good example of an involuntary risk. There is little basic biological plausibility and a clearly demonstrated dose–response relationship to mortality. Nevertheless, considering that the groups exposed to air pollution are among the general population, the findings of this study have significant implications.

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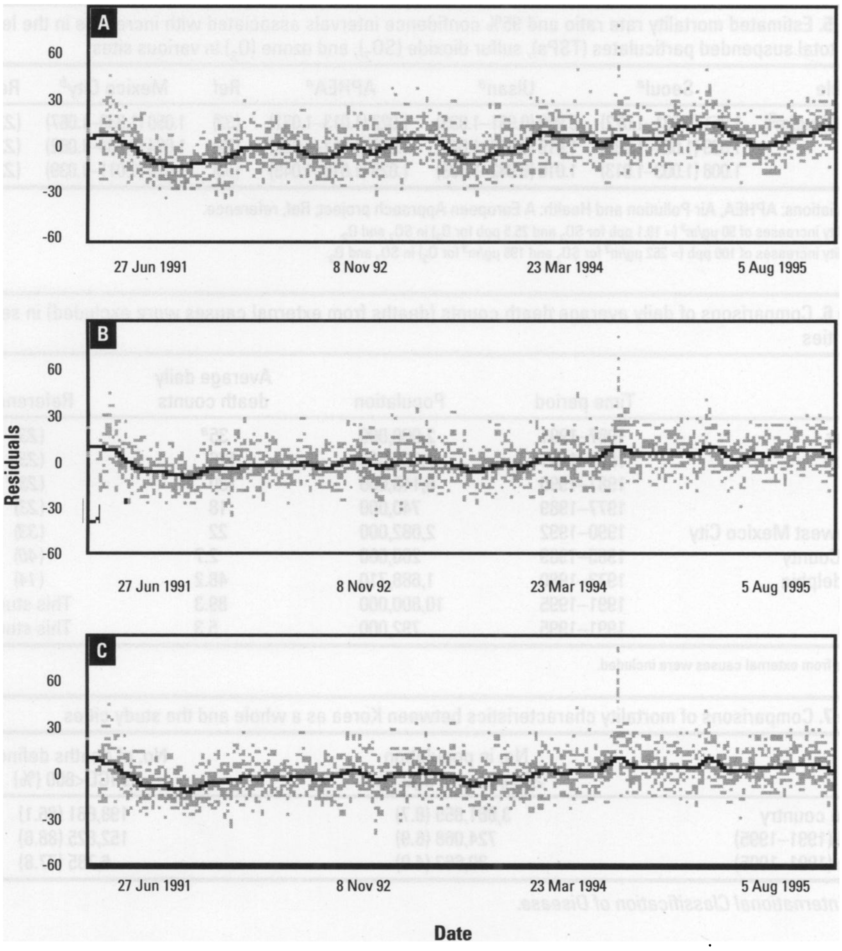

Figure 3. The residual plots versus date. (A) The regression model includes only SO_2 concentration. The smoothed curve (Loess) shows the substantial seasonal pattern. (B) The regression model includes weather condition (temperature and humidity) as well as SO_2 levels. (C) The adjustment was by regression including weather conditions (temperature and humidity), seasonal indicators, as well as SO_2 levels.

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