Air Pollution and Daily Mortality in Erfurt, East Germany, 1980–1989

Claudia Spix,[1] Joachim Heinrich,[2] Douglas Dockery,[3] Joel Schwartz,[4] Gisela Völksch,[5] Kurt Schwinkowski,[6] Christel Cöllen,[7] and H. Erich Wichmann[1,2]

[1]Labor Safety and Environmental Medicine, University Wuppertal, Wuppertal, Germany; [2]GSF-Research Center for Environment and Health, Epidemiology Institute, Neuherberg, Germany; [3]Environmental Epidemiology Program, Harvard School of Public Health, Boston, MA 02115 USA; [4]Environmental Protection Agency, Washington, DC 20024 USA; [5]Center for Hygiene, Preventive and Environmental Medicine, Medical Academy Erfurt, Erfurt, Germany; [6]Ministry for the Environment in Thüringen, Erfurt, Germany; [7]Magistrate of the City of Erfurt, Health Department, Erfurt, Germany.

In Erfurt, Germany, unfavorable geography and emissions from coal burning lead to very high ambient pollution (up to about 4000 µg/m^3 SO_2 in 1980–89). To assess possible health effects of these exposures, total daily mortality was obtained for this same period. A multivariate model was fitted, including corrections for long-term fluctuations, influenza epidemics, and meteorology, before analyzing the effect of pollution. The best fit for pollution was obtained for log (SO_2 daily mean) with a lag of 2 days. Daily mortality increased by 10% for an increase in SO_2 from 23 to 929 µg/m^3 (5% quantile to 95% quantile). A harvesting effect (fewer people die on a given day if more deaths occurred in the last 15 days) may modify this by ± 2%. The effect for particulates (SP, 1988–89 only) was stronger than the effect of SO_2. Log SP (daily mean) increasing from 15 µg/m^3 to 331 µg/m^3 (5% quantile to 95% quantile) was associated with a 22% increase in mortality. Depending on harvesting, the observable effect may lie between 14% and 27%. There is no indication of a threshold or synergism. The effects of air pollution are smaller than the effects of influenza epidemics and are of the same size as meteorologic effects. The results for the lower end of the dose range are in agreement with linear models fitted in studies of moderate air pollution and episode studies. *Key words:* mortality, particulates, Poisson regression, short-term effects, sulfur dioxide, time series. *Environ Health Perspect* 101:518–526(1993)

Episodes of very high levels of air pollution have been associated with excess mortality in anecdotal reports for centuries (*1*). In this century, winter smog episodes have led to increased mortality in severe episodes in 1930 in the Meuse Valley, Belgium, in 1948 in Donora, Pennsylvania, and in London in 1952. For most of those episodes, no continuous measurements of air pollution were available. Early episode analyses pointed to SO_2 and the resultant acid aerosols as the responsible agents (*2–7*). In the 1950s and 1960s, when air pollution was still considerably higher in western countries than it is currently, SO_2 and particulates were highly correlated (*2–5,8*). Larsen (*2*) pooled various episode data and concluded that there is a stronger influence of particulates plus a kind of synergism between SO_2 and particulates. Later studies have not confirmed this suggestion of synergism (*9*).

Historically, smog episodes provided the first incentive to look closely at the short-term relationship between air pollution and mortality. It was not necessary to specify the pollution concentrations to demonstrate an association, but only necessary to show the temporal correlation of a mortality increase with the pollution episode. On the other hand, this analytic approach requires that episodes are isolated with a recovery time with relatively low pollution between episodes so that the baseline mortality rate can be determined.

Subsequent analyses have attempted to quantify associations over a broader range of exposure and to differentiate the influence of specific pollutants by analyzing long time series of mortality and pollution observations. Such time-series analyses have reported associations of daily mortality with SO_2 [e.g., in Hannover, Germany (*10*) or in Athens (*11*)]. Most later analyses of longer time series indicate that the effect may be caused by suspended particulates (measured as British smoke, COHs, smoke shade, total suspended particulates, PM_{10}, etc.), while SO_2 acts mostly as an indicator of increased air pollution (*4,5,8,9,12–14*). These studies have found no or greatly reduced relationships with SO_2 when measures of particulates were incorporated in the time-series model. Results suggest that SO_2 acts as an indicator for general air pollution, though it is probably not the best indicator.

Early studies also suggested threshholds for observable increases in mortality between 150 µg/m^3 and 750 µg/m^3. These threshholds have not been observed in recent studies (*9,15*). In West Germany, increased mortality was observed in connection with episodes in the Ruhr area (part of North-Rhine Westfalia, Germany) in 1962 and 1985 (*16–20*). During episodes in the Ruhr area in 1979 (*21*) and in 1981–82 in Berlin (*22*), no relationship with mortality was found. In East Germany (*23*), across three episodes in the 1980s in Leipzig, an increase was observed as well. Although these analyses came to different conclusions about the order of magnitude of the effect, practically none found more than about 20–30% excess deaths in the given range of pollutants. Lower levels of pollution usually resulted in increases of about 5–10% or less.

The health endpoint in these studies, total mortality (sometimes minus accidental deaths), has the advantage of being reliable, retrospectively available, and usually complete, but it may reflect only the "tip of the iceberg" with regard to health effects. In studies where morbidity data (e.g. emergency room visits or diary data) were also available, there was good agreement among the various measures with respect to the effects of air pollution (*3,4,18,19,24,25*). This paper presents the results of analyses of total daily mortality and air pollution data collected in Erfurt, Thüringen, in the former German Democratic Republic during the 1980s.

Materials and Methods

Study Area

Erfurt is one of the most polluted cities in eastern Germany. It is located on the northern slope of the Thüringer Wald, a mountainous area up to 1000 m above sea level about 60 km south of Erfurt. Erfurt lies at approximately 200 m above sea level and is surrounded by ridges approximately 100 m higher in all directions except north where the terrain is flat. There are frequent inversions and trapping of air pollutants in this bowl.

About 30–40% of the homes in Erfurt are newer appartment buildings on the outskirts of town which are heated by central heating plants situated to the north just outside the city, although one is in the city center. After the oil shortage early in the 1980s, all central and domestic heating was switched from oil or gas to brown coal, low-quality coal, briquettes, or, in a limited amount, coke. These solid fossil fuels have a high sulfur content and emit large amounts of particulates. More recently, increased use of sulfur-reduced coal and the mild winters from 1986 onwards led to a decrease in air pollution. Political changes, which led to the shutdown of industries, resulted in substantially lower air pollution concentrations in 1989.

Address correspondence to C. Spix, University Wuppertal, FB 14, FG Arbeitssicherheit und Umweltmedizin, Gaussstrasse 20, D-42097 Wuppertal, Germany.

This study was supported by a grant from DAAD (German Academic Exchange Service), no. DAAD 312 402 590/1.

Received 29 March 1993; accepted 10 August 1993.

Mortality and Morbidity Data

Erfurt has a total population of about 217,000 with little change over recent years, with the possible exception of 1989. Total daily deaths for 1980–1989 were obtained from the local health authorities by counting death certificates. This includes accidental deaths and deaths of residents occurring outside of Erfurt. Age- and cause-specific data were not available for all years, and the number of deaths per day in Erfurt was too small to permit further splitting (Table 1).

Data were obtained regarding influenza epidemics during the study period. In 1985, 1986, and 1988, major epidemics were identified by the authorities. Weekly reports of influenza cases (morbidity) for the region ranged from approximately 10,000 to 33,000 cases per week [see also Höpken and Willers (*26*)].

Air Pollution and Weather Data

We measured daily SO_2 concentrations in Erfurt at a station situated in the middle of the town by continuous coulometric titration of low-volume samples. Daily means for the period from 7 AM to 7 AM the next day and daily half-hour maximum concentrations were recorded. Data were available for 92% of the study days. A drawback of these data is the location of the measuring station inside a closed courtyard of five-story buildings at about the fourth-floor level. However, comparisons with data from Weimar, located about 25 km east of Erfurt with similar emissions and a comparable geographic and climatic situation, for 3 of the study years showed remarkable correlation in the daily averages ($r = 0.87$) at an almost identical SO_2 level.

For the last 2 years of the study period, 1988 and 1989, particulate concentrations measured by a simplified low-volume (10 m^3/hr) gravimetric method at the same site were also available. The opening is about 0.5 m from the wall of the building. The method does not differentiate by particle size, and there was no inlet cutoff. Filters were cut by hand; weighing was also done by hand. We took 24-hr mean samples Monday–Thursday from 8 AM to 8 AM the next day. Measurements are similar to, but do not fully fit, the well-defined term total suspended particulates (TSP), so results are best described by the generic term suspended particulates (SP). Seventy-nine percent of the possible data was available.

Daily temperature and relative humidity were available between 1985 and 1989 and precipitation between 1985 and 1987. During the periods where meteorologic data could be obtained, it was quite complete (Table 1).

Statistical Methods

Mortality is a rare event which can be modeled by Poisson regression. This Poisson assumption is especially important for small numbers of daily deaths, as in Erfurt. Small daily numbers of deaths do allow one to obtain consistent regression results, especially with a large number of observations as provided by 10 years of data. The chance of not being able to statistically prove a result that is of visible size is relatively larger than for large numbers, as is the chance of getting randomly significant results. Both are typical for a study of this size, whose results have to be verified by more data. However, the amount of data allows a certain extent of internal verification.

The model has the form

$$\log\{E[\text{mort}(t)]\} = X(t)\,ß + e$$

where $E[\text{mort}(t)]$ is the expected mortality at time t, $X(t)$ is a daily vector of influences, ß is the vector of parameter estimates, and the error (e) is Poisson distributed. The exponentials of ß can be interpreted as risk ratios (RR); (RR – 1)100 corresponds to the percent change in risk.

Mortality data are usually slightly overdispersed (that is, variance > expectation) and somewhat positively autocorrelated. In ecological models, a source of overdispersion can be that the population under study consists of different sets of subpopulations, homogenous within but with extra variation between the populations. In this type of time series, the unit of observation is the day, and variation between days or groups of days caused by varying external circumstances introduces overdispersion. So if we could fit an optimal model, which explains all the differences between the study days, all that would be left in the residuals would be random variation of the expected size and no overdispersion (overdispersion factor = 1). The degree to which overdispersion is reduced is thus a criterion of model fit.

Table 1. Distribution of daily data on mortality, meteorology and air pollution in Erfurt, 1980–89

	Period[a]	Available	% Missing	Minimum	5%	25%	50%	75%	95%	Maximum
SO_2, daily mean ($\mu g/m^3$)	All	1980–89	8	10	27	79	197	406	952	3569
	Winter		5	11	103	202	364	620	1206	3569
	Summer		11	10	20	45	81	178	376	899
SO_2, daily max ($\mu g/m^3$)	All	1980–89	6	10	60	170	420	890	2200	4960
	Winter		3	50	200	440	800	1350	2700	4960
	Summer		8	10	40	100	180	390	840	2660
Suspended particulates, daily mean ($\mu g/m^3$)	All	1988–89	21	10	30	60	106	170	390	650
	Winter	Mon–Thu	23	21	37	67	120	201	484	650
	Summer		18	10	20	60	98	140	270	600
Temperature, daily mean (°C)	All	1985–89	1	-19	-6	3	9	15	20	29
	Winter		1	-19	-10	-1	4	7	12	22
	Summer		1	-3	6	12	15	18	22	29
% Relative humidity	All	1985–89	0	32	57	69	77	84	94	100
	Winter		0	45	66	76	82	88	96	100
	Summer		0	32	53	64	71	78	87	100
Precipitation (mm)	All	1985–87	0	0	0	0	0	1	8	42
	Winter		0	0	0	0	0	1	5	42
	Summer		0	0	0	0	0	2	10	36
Total mortality (deaths/day)	All	1980–89	0	0	3	5	6	8	11	20
	Winter		0	0	3	5	7	9	12	20
	Summer		0	0	2	4	6	8	10	16

[a]Winter; October through March; summer; April through September.

Autocorrelation in a mortality time series is not necessarily a feature of daily deaths themselves. Positive autocorrelation implies that observations that are closer together are more similar than more distant ones. But the number of deaths on a given day is not directly influenced by the number of deaths on previous days; rather, successive days are correlated by autocorrelated, underlying influences on the risk of mortality. Thus, appropriate modeling of underlying risks should reduce autocorrelation in the daily mortality residuals.

Autocorrelation can also be introduced by "harvesting" vulnerable individuals. A high number of deaths on one day may leave a smaller number of vulnerable individuals at risk of dying on succeeding days. This harvesting effect might introduce a certain amount of negative autocorrelation, which can also be modeled after correcting for other influences.

A two-stage analysis was undertaken. In the first stage, Poisson regression was performed to obtain an optimal model. In the second stage, additional terms were added to adjust for autocorrelated errors. The goal of this stage was not to fit an autocorrelation model for forecasting but rather to check whether adjustment for autocorrelation changes parameter estimates of interest and their variance estimates (efficiency). A negligible difference between the results with and *without adjustment for autocorrelation* would indicate a good fit. If the results differed noticeably, the results correcting for remaining autocorrelation would be reported. Fitting lagged residuals (AR-model for the error) acts as an instrumental variable for an autocorrelated influence which may be unknown or on which there may be no information available. The estimates then will become more efficient (*9,27,28*).

The complete model for daily counts of mortality consists of the following elements: 1) long-term changes such as trend, season, and slightly shorter long-term fluctuations, 2) impact of influenza epidemics (1–2 months' duration), 3) short-term effects of meteorology, and 4) short-term effects of air pollution measured by SO_2, particulates, or both. The model was built in a stepwise fashion, obtaining an optimal model for each of the above elements before fitting the next. In each case it was necessary to determine the functional form for each covariate and possible lagged relationships.

For those years when meteorologic measurements were not available, we used an indicator for missing values in place of the measured value ("availability interaction"). This means that meteorology is only fitted in the years where data are available, while the parameters for trend, season, influenza, and air pollution (see below) can still be based on the whole period. This makes correction for those terms and parameter estimation more reliable than splitting the data would allow, which is an important issue for data with such a low signal-noise ratio.

The internal verification of results is obtained by a sensitivity analysis that includes variations of confounder control and pollutant parameter interactions with subsets of the data as months (of the year) and years. This allows the regression slopes of a pollutant to vary between months or years. Systematic deviations from the overall parameter estimate can thus be detected.

To disentangle the pollutant effects, the results of a two-pollutant model are compared to the single-pollutant models. Interaction between pollutants is also checked. Harvesting is present if the parameter of an interaction term, (last k days mortality) × (pollutant), is negative. This means the pollutant effect is less visible if there have been more deaths than usual in the last k days and vice versa. The value of k is determined by model fit.

The results are corrected for all long- and medium-term relationships and are intended to describe only the short-term relationship between air pollution and death. Short-term means imminent deaths occur a few days earlier under unfavorable conditions than they would have otherwise. This relationship does not depend on the general level of air pollution, though the shape of the relationship may change with the level. A linear relationship means that an increase in risk occurs with every fixed increase in air pollution. A logarithmic relationship means it occurs with every fixed factor or ratio, e.g., any doubling of air pollution. The logarithm linearizes those ratios, i.e., $\log(x/y)$ is just as far away from $\log(1)$ as $\log(y/x)$.

Results

Descriptive Analysis

Table 1 shows the distribution of the available data. Temperature was mild in summer (5% above 20°C) and low in winter (25% below 0°C). Humidity and precipitation were relatively high; winters were more humid, but the days with extreme precipitation were primarily in summer. Daily mortality rates were low: median 6 deaths per day and high variability (range 0–20 deaths/day).

Year-specific median values (Table 2) suggest a slight decrease in mortality over the years, probably due to a slight decrease in population. The SO_2 level in the 10 study years decreased from a winter median of 604 $\mu g/m^3$ in 1980 to 208 $\mu g/m^3$ in 1989. Suspended particulates are only available for 1988 and 1989 with winter medians of 140 and 107 $\mu g/m^3$.

Time-Series Analysis

Before starting the analysis, the mortality series was inspected for features that might be important for a time-series analysis. The overdispersion ratio of variance to mean was only 1.1. A periodogram (of log-mortality) showed only one clear peak for frequency 1/365 days; that is, a 1-year cycle. The correlogram, partial and inverse correlation plots, showed no hints of an autoregressive (AR) or moving average (MA) serially correlated structure. Autocorrelation at lag one was remarkably low at $r = 0.07$. There was no evidence of a day-of-week pattern, which is sometimes found in mortality data. The annual cycle was present but was barely visible to the eye in a time-series plot (see also Fig. 1) because of the large day-to-day variation. Thus, the series under study presented no difficult properties except for small values and thus a large amount of noise.

Sulfur dioxide has a very distinct seasonal pattern with a relatively sharp rise in values with the beginning of the heating season (Fig. 1). The SO_2 series was highly autocorrelated; $r = 0.85$ for the daily means and $r = 0.77$ for daily maxima (1-day lag). The limited particulate data showed somewhat less autocorrelation ($r = 0.60$). The

Table 2. Mortality and air pollution over the study years

	Median mortality	% Missing	Daily SO_2 ($\mu g/m^3$) Median	Winter median[a]	Maximum
1980	7	5	346	604	2673
1981	7	12	190	394	2425
1982	6	7	277	352	3569
1983	6	11	128	316	2553
1984	6	4	197	445	2352
1985	7	7	177	459	2947
1986	6	6	180	355	1973
1987	6	1	182	376	1949
1988	6	9	178	275	1576
1989	6	15	145	208	1002
			Daily suspended particulates ($\mu g/m^3$)		
1988	6	25	120	40	650
1989	6	16	98	107	618

[a]Winter: October through March.

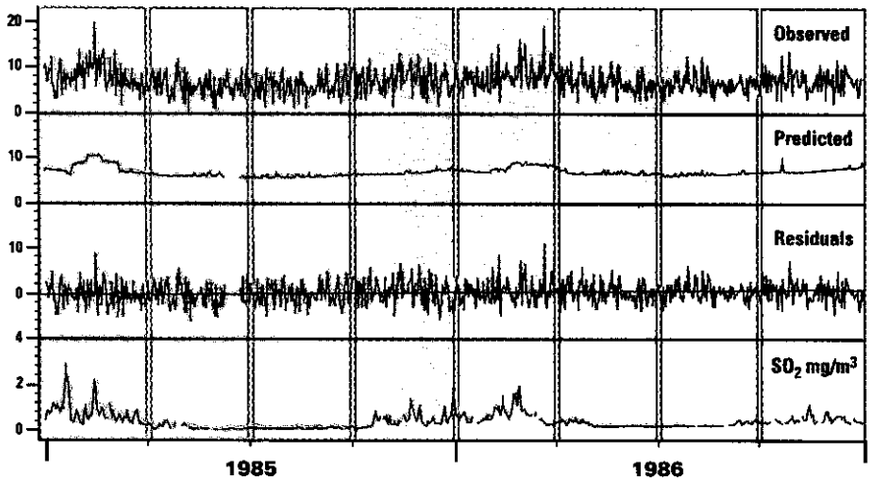

Figure 1. Daily data for 2 out of 10 years; 1985 and 1986 chosen as examples. The top time series shows the observed daily mortality; the fitted line shows the long-term fluctuations, the impact of two influenza epidemics (February 1985, February–March 1986) and small peaks and dips due to weather. There is large, unexplained variation left in the raw residuals, but no obvious structure.

same day correlation of particulates with daily mean SO_2 was not very strong (r = 0.55), but the relationship appeared to be linear.

Regression Analysis

The daily mortality was first fitted to Fourier terms (sines and cosines) of time with periods of one, one-half, one-quarter, and one-fifth year (~2.5 months). There was no evidence for cycles shorter than a year in these data, including day-of-week effects. Inclusion of shorter than annual wavelength terms permits the estimated shape of the annual cycle to have a more complicated pattern than a pure sine wave. There was a slight linear downward trend over the entire period (0.15% per year).

In the next step, the influence of known influenza epidemics in 1985, 1986, and 1988 was modeled. Weekly reports of number of influenza cases (morbidity) were included in the model with various lags. The best fit was observed between daily mortality and weekly influenza reports 8 days before. In addition, mortality during the 1985 epidemic was 18% higher than expected based on the 1986 or 1988 epidemics. Thus an additional indicator was included for the 1985 epidemic. There was an estimated 21% increase in daily mortality associated with the peak week in 1986 or 1988, and a 46% increase in 1985.

In the third step, the influence of meteorologic variables plus an indicator for years of missing data was included. Linear and nonlinear functions (including various threshold values) and lagged relationships were evaluated for temperature and humidity. A model with indicators for very cold days (mean temperature less than -5°C, daily mortality increased by 8%) and hot days (greater than 19°C, mortality increased by 12%) fit the data well after adjusting for long-term cycles and influenza epidemics as described above. Daily precipitation was also associated with daily mortality (+ 8% per 9 mm precipitation per day; 95% quantile; Table 3). Slight discrepancies between quantiles here and in Table 1 result from using only days with complete data as used in the regression analysis for expressing results.

Relative humidity was not associated with mortality after adjusting for all the above variables. There was no indication of associations with these meteorologic variables on prior days, nor any indication of interactions between them. Figure 1 illustrates the observed daily mortality, the predicted mortality from the above model, and the residuals for comparison with the SO_2 series. As showing the full 10-year period is technically difficult and makes effects less visible, 1985 and 1986 were chosen as examples because they demonstrate all important features (temperature effect, two influenza epidemics of different lethality and a smog episode).

Inspection of the functional form and lag structure of SO_2 showed 4 days in January 1982 with daily mean SO_2 greater than 3000 µg/m^3 to be very influential. Including an indicator for $SO_2 \geq 3000$ µg/m^3 on the same day increased the fit considerably, no matter how the rest of the days were fitted. Various measures of SO_2 exposure including daily mean or maximum, logarithmic, or linear scaling and lags from 0 to 3 days were checked. A precheck with splines had indicated the association would not be steeper than linear.

The best fit was obtained with logarithm of mean daily SO_2 lagged by 2 days, although this model is only slightly better than a 1-day lag (Table 4). This lag may partly be due to the SO_2 data being collected starting at 7 AM as compared to the midnight–midnight definition of mortality. This observed lag cannot be explained with the data and type of analysis used here. The parameter is 0.0268 with p = 0.01 (highly significant). This means an RR of 1.10 for the comparison of the 95% quantile versus 5% quantile (929 µg/m^3 versus 23 µg/m^3 SO_2; Fig. 2, Table 4). This may not be linearly extrapolated.

For days with $SO_2 \geq 3000$ µg/m^3, we predict 73% more deaths than expected under the logarithmic model, nearly 100% more than on days with very low pollution (5% quantile = 23 µmg/m^3 SO_2; Fig. 2). Leaving out days with $SO_2 \geq 3000$ µg/m^3 or treating them the same as the other days slightly increases the parameter size for $\log(SO_2)(t\text{-}2)$, so including an indicator for those days is rather more conservative.

An earlier analysis of only 3 years (1985–87) by month of year had suggested stronger effects in October (beginning of annual polluted season). Refitting interactions between months and SO_2 gave slight-

Table 3. Regression results for confounding and additional influences

Influence on mortality[a]	Parameter ß	p[b]	95% quantile vs 5% quantile[c]	RR[d]
Trend (per day)	-4.1×10^{-6}	0.81	10 study years	0.99
Season			January vs July	1.13
Influenza cases[e] (t-8)	6.7×10^{-6}	0.00	Worst week '86,88	1.21
			Worst week '85	1.46
Temperature	0.0766	0.06	>19°C vs ≤ 19°C	1.08
	0.1159	0.00	<-5°C vs ≥ -5°C	1.12
Precipitation	0.0088	0.01	9 vs 0 mm	1.08

[a]Same day except for influenza, where mortality follows morbidity by an average of 8 days.
[b]p value for test regression parameter = 0; thus implicitly p value for test RR = 1.
[c]For continuous influences, the RR denotes the ratio of mortality during high exposure (95% quantile) versus low exposure (5% quantile). The respective values are given. Where quantiles are not appropriate, RR refers to the range given. For influences of yes/no type RR denotes the ratio of mortality during "yes" compared to "no."
[d]RR denotes the ratio of mortality expected by a change in the influence as indicated.
[e]Case counts refer to Erfurt area. In 1985 lethality per case was increased as compared to 1986/88 by a (significant) factor of 1.18.

ly steeper parameters for October and February through April, but the difference between months is far from being significant [comparing parameters for August (lowest) and April (highest) is not significant at $p = 0.11$), see Table 4]. This kind of monthwise regression also stands for an analysis that has been proposed in other papers: breaking the data down by pollution-level categories. We prefer this monthwise interaction procedure because the effect is checked on comparable, continuous days under identical control for possible confounders.

To check the consistency of results over years, the regression was refitted with SO_2–year interactions, as the general pollution level changes noticeably over the study years. Especially in 1989 we might expect a change in relationship because of a change in circumstances. This is not the case; generally results are quite consistent. The difference between the year with the strongest effect (1987) and the weakest (1988) is just close to being significant ($p = 0.06$; Table 3). There is no systematic change of the relationship over the years. In 1982 the same as for the full study period is true for the treatment of days with $SO_2 \geq 3000$ µg/m^3.

The complete analysis including air pollution was repeated without any meteorologic information to check whether this was a major confounder. After fitting long-term fluctuations the short-term effects of meteorology explain some more variation in the data, but they have no considerable confounding effect with regard to air pollution and do not change the pollution parameter estimates noticeably. This may be due to meteorology being only available for part of the study years. On the other hand, no systematic differences between meteorology-corrected years and uncorrected years show up in the SO_2 parameters by year (Table 4).

As earlier studies suggested (*10,29*), a harvesting effect caused by previous effects on mortality can modify the effect of the influence under study. Including previous mortality as a confounding factor makes little sense, as this would have a similar effect to a moving average of mortality competing with the already included Fourier filter and trend terms. So interaction (effect modification) terms of pollution with the mean number of deaths in the previous 2–21 days are checked. The marginally best fit is obtained for an interaction with the last 15 days' mean mortality. This is consistent with earlier findings from West Germany, which suggested a period of about 2 weeks for this effect. The term is not significant, but the effect of the difference between the 95% quantile and 5% quantile of SO_2, which increases mortality on average by 10% (see above) and can be modified from 8% to 12%, comparing days with a high mortality in the previous 15 days (about 12 deaths average) to days with low previous mortality (about 4 deaths average). Although not significant, the size of effect modification is noticeable and in agreement with the harvesting effect as described earlier. For a list of regression results, see Table 5.

Finally, the available data on suspended particulate matter (SP) was checked for its influence. Again, a model with all known data and fitting the interaction with SP availability was used because this makes controlling for other influences more reliable in the generally noisy data. The estimate of the SP parameter is only based on data from 1988 to 1989, collected on Mondays through Thursdays. For SP, no lagged effect could be observed; a log transform fits marginally better than a linear one, so it was chosen to make comparability with SO_2 easier. The parameter is 0.0631 (p value significant at 0.03). For an increase from 15 µg/m^3 to 331 µg/m^3 (5% quantile versus 95% quantile), this means an RR of 1.22 (Table 4).

Effect modification via the harvesting effect was much stronger for SP than for SO_2, although it was still not significant. The modification of the effect of 331

Table 4. Regression results for pollution variables after adjustment for trend, season, influenza epidemics, and meteorology

Influence on mortality[a]	Parameter ß	p[b]	95% quantile vs 5% quantile[c] (µg/m^3)	RR[d]
SO_2 daily mean(t-2)	0.0001	0.04	929 vs 23	1.05
log(SO_2 daily max)(t-2)	0.0224	0.03	2070 vs 50	1.09
log(SO_2 daily mean)(t)	0.0106	0.33	929 vs 23	1.04
log(SO_2 daily mean)(t-1)	0.0209	0.06	929 vs 23	1.08
log(SO_2 daily mean)(t-2)	0.0268	0.01	929 vs 23	1.10
log(SO_2 daily mean)(t-3)	0.0215	0.05	929 vs 23	1.08
SO_2 daily mean(t)	0.5491	0.00	≥ 3000 vs < 3000	1.73
log(SO_2 daily mean)(t-2)				
Jan	0.0240	0.10	1775 vs 105	1.07
Feb	0.0345	0.03	1346 vs 86	1.10
Mar	0.0411	0.01	978 vs 99	1.10
Apr	0.0370	0.03	584 vs 78	1.08
May	0.0294	0.10	394 vs 29	1.08
Jun	0.0110	0.56	284 vs 15	1.03
Jul	0.0216	0.26	206 vs 14	1.06
Aug	0.0061	0.75	212 vs 15	1.02
Sep	0.0238	0.17	310 vs 22	1.06
Oct	0.0349	0.03	576 vs 45	1.09
Nov	0.0272	0.08	957 vs 81	1.07
Dec	0.0214	0.13	1490 vs 98	1.06
1980	0.0180	0.28	1222 vs 65	1.05
1981	0.0227	0.14	1206 vs 50	1.07
1982	0.0275	0.04	1150 vs 93	1.07
1983	0.0332	0.03	939 vs 27	1.13
1984	0.0312	0.07	894 vs 39	1.10
1985	0.0356	0.03	1075 vs 34	1.13
1986	0.0320	0.04	831 vs 25	1.12
1987	0.0471	0.00	990 vs 21	1.20
1988	0.0081	0.65	674 vs 17	1.03
1989	0.0176	0.34	680 vs 19	1.06
1988–89 only				
log(SO_2 daily mean)(t-2)	0.0112	0.53	678 vs 17	1.04
Total suspended particulates daily mean (Mon–Thurs)				
Particulates daily mean(t)	0.0004	0.04	331 vs 15	1.13
log(particulates daily mean)(t)	0.0631	0.03	331 vs 15	1.22
Two-pollutant model 1988–89				
log(SO_2 daily mean)(t-2)	0.0049	0.79	678 vs 17	1.02
log(particulates daily mean)(t)	0.0543	0.09	331 vs 15	1.18

[a]Same day and lags of up to 3.
[b]p value for test regression parameter = 0; thus implicitly p value for test RR = 1.
[c]For continuous influences, the RR denotes the ratio of mortality during high exposure (95% quantile) versus low exposure (5% quantile). The respective values are given. For influences of yes/no type RR denotes the ratio of mortality during "yes" compared to "no."
[d]RR denotes the ratio of mortality expected by a change in the influence as indicated.

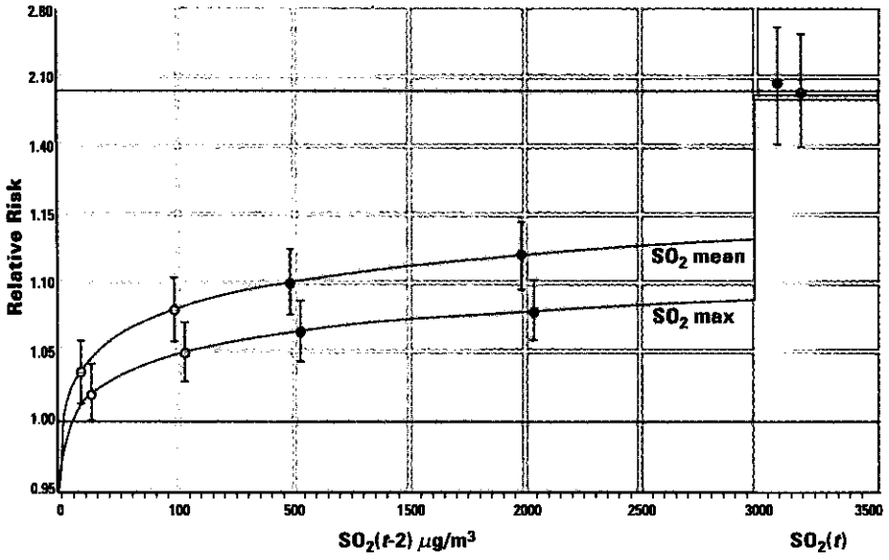

Figure 2. Exposure–response curve for daily mortality (t) depending on log (SO_2 daily mean) (t-2) and log (SO_2 daily max) (t-2). The response is expressed as relative risk compared to the respective 5% quantiles of SO_2. For some values a 95% confidence interval is shown. The large same-day effect on days with $SO_2 \geq 3000$ µg/m^3 is shown as part of the curve on a different scale.

µg/m^3 versus 15 µg/m^3 SP by days in 1988–89 with low previous mortality (five deaths) as compared to high previous mortality (9 deaths) is considerable: the effect changes from + 27% to + 14% (Table 5).

A two-pollutant model and fair comparison of SO_2 and SP could only be calculated for 1988–89. The SO_2 effect alone is much smaller (parameter 0.0112, p = 0.53) than for the whole period. In a two-pollutant model, the parameter for SO_2 is reduced to close to zero (p = 0.79), while the particulate parameter decreases slightly. There may be some collinearity problems here, but there is certainly no interaction. In earlier years SO_2 does seem to act as a proxy for particulates (Table 4).

Discussion

Modeling the mortality experience of the population in Erfurt from 1980 to 1989, we find a significant increase of daily deaths with log(SO_2) with a lag of 2 days, bearing in mind that the daily means for SO_2 were not defined midnight–midnight but shifted by 7 hr. The order of magnitude is relatively small (+10%) if comparing the 95% quantile (929 µg/m^3) to the 5% quantile (23 µg/m^3). This is about the same order of magnitude we find for meteorology and smaller than the effect of the influenza epidemics. The lagged logarithmic effect is fairly consistent over seasons and thus over the range of pollution as well as over the years. There are hints of a large, significant same-day effect for days with $SO_2 \geq 3000$ µg/m^3. The inference for this is based on only 4 days in January 1982 with 52 deaths instead of the expected 28, so this might as well be chance.

What few particulate data were available showed an effect with a larger order of magnitude. In a two-pollutant model, suspended particulates lost little of their effect, while SO_2, whose effect in 1988–89 was not very strong anyway, was reduced to close to zero. This result, which has been found in several previous studies (see below), is even more surprising considering the small quantity and possibly poor quality of the particulate data.

It is difficult to speculate on the kind of biological mechanism behind findings of such an associative nature. Certainly SO_2 or suspended particulates do not cause deaths in the sense of acute toxicity, but they may in some cases lead to the extra stress that causes the death of a moribund person on a certain day, instead of slightly later, and in some cases lead to the death of a seriously ill person who would otherwise have recovered (*3*). In agreement with this, a small harvesting effect could be shown to modify the effect of air pollution: high mortality about 2 weeks before an air pollution episode would lead to a smaller effect. While we can thus model a short-term harvesting effect, the logarithmic relationship points also to a possible long-term harvesting mechanism that presents itself as an adaptation of the population to high levels of air pollution.

Another explanation for the overall relatively small effect in spite of high concentrations and the logarithmic shape of the dose–response curve may be the relationship of the proxy SO_2 to the actual agent. One candidate is acid aerosols, of which SO_2 is an important precursor. Acid aerosols have been discussed previously as a possible cause of health effects (*6*). Current measurements of acid aerosols in the Erfurt area show surprisingly small amounts of acidity as compared to the amounts of SO_2, possibly due to meteorological mechanisms or neutralization.

Table 5. Regression results for harvesting effect modification of pollution variable parameters after adjustment for trend, season, influenza epidemics, and meteorology

Influence on mortality[a]	Parameter ß	p[b]	95% quantile vs 5%-quantile[c]	RR[d]
Harvesting effect modification of SO_2 1980–89				
Harvesting factor[d] log(SO_2 daily mean) (t-2)	-0.0011	0.50	929 vs 23 µg/m^3	
When mortality previous 15 days			Low = 4.3[e]	1.12
			Average = 6.6[e]	1.10
			High =11.7[e]	1.08
Harvesting effect modification of SP 1988–89				
Harvesting factor[f] log(SP daily mean) (t)	-0.0095	0.10	331 vs 15 µg/m^3	
When mortality previous 15 days			Low = 4.5[g]	1.27
			Average = 6.3[g]	1.22
			High = 8.7[g]	1.14

[a]Same day for SP, 2 days lag for SO_2.
[b]For continuous influences the RR denotes the ratio of mortality during high exposure (95% quantile) versus low exposure (5% quantile). The respective values are given.
[c]RR denotes the ratio of mortality expected by a change in the influence as indicated.
[d]Parameter for term log(SO_2)(t-2)*mean(mortality(t-1,...,t-15)). The p-value gives the test for this term.
[e]Lowest/highest observed numbers of deaths in previous 15 days of 1980-89 were 4.3 and 11.7, respectively; mean number of deaths is 6.6.
[f]Parameter for term log(SP)(t)*mean[mortality(t-1,...,t-15)].
[g]Lowest/highest observed numbers of deaths in previous 15 days of 1988–89 were 4.5 and 8.7, respectively; mean number of deaths is 6.3.

Comparisons with WHO LOEL and Other Studies

The WHO air quality guidelines for Europe 1987 (*30*) list a daily mean of 500 µg/m^3 SO_2 or British smoke (BS) as the lowest observed effect level (LOEL) for excess mortality. BS is known to underestimate SP by a relatively large amount (*31*), especially in smog situations, and very like-

Table 6. Excess mortality by WHO standards (*30*)

Period	Category (μg/m^3)	Days	% Excess mortality[a]
1980–89	SO_2[b] < 500	2752	0.0
	SO_2 ≥ 500	616	-0.1
1988–89[c]	SO_2 < 500 and SP < 500	260	-1.1
	SO_2 ≥ 500	26	6.7
	SP ≥ 500	9	8.8
	SO_2 ≥ 500 and SP ≥ 500	5	27.4

WHO LOEL (lowest-observed effect level) for excess mortality for 24-hr mean exposure: 500 μg/m^3 SO_2 or 500 μg/m^3 British smoke (BS). It is not possible to determine suspended particulates (SP) from BS, except that BS is usually much lower than SP.
[a]Observed mortality compared to expected mortality from the model including all influences except pollution variables (i.e., trend, season, influenza epidemics, and meteorology).
[b]SO_2 always from 2 days before.
[c]Only days where both SO_2 and particulate data were available.

ly the SP values observed in this study do not exceed this level. Still, 500 μg/m^3 SP may be a useful cutpoint for checking effects in a way comparable to episode studies. It is exceeded on less than 5% of the study days in 1988–89. Table 6 shows the percent increase in mortality by those cutpoints. While there is little increase by SO_2, there is a clear increase in mortality above 500 μg SP/m^3 (9% premature mortality), plus some more on the few days with SO_2 and SP increased jointly.

It is difficult to compare our results to other studies because of the different approaches chosen. But when some minimum information is given (i.e., baseline mortality, excess deaths, or a regression parameter for a certain period or pollution range), it is possible to estimate, albeit sometimes roughly, the percent increase in mortality for a period or pollutant range.

Brasser et al. (*7*) calculate the increase in deaths during the 1952 London episode as 72%. However, it is not quite clear how the number of expected deaths was actually determined, while excess deaths were counted in for up to 11 days after the episode. SO_2 and BS reached values of about 4000 μg/m^3. Steiger et al. (*16,17*) analyzed the 1962 Ruhr area episode with the help of a graph and saw a clear increase, which translates to a 13% increase in mortality over a 5-day period plus 1 or 2 days afterwards, which is in agreement with our analysis. What little was available in terms of pollution data in these days went up to 5000 μg/m^3 SO_2 and 2400 μg/m^3 TSP. A reanalysis of these data by Wichmann et al. (*19*) comparing the episode days to baseline mortality also points to a general 13% increase, 19% in the densely populated and highly industrialized Ruhr area.

During the 1985 episode, where SO_2 reached a daily mean of 830 μg/m^3 and TSP of 600 μg/m^3 in the Ruhr area, an 8% increase was observed for the 5 smog-alert days plus 2 following days. A linear regression pointed to a strongest effect at a 2-day lag; 8% is about what this analysis' regression coefficient would have predicted (see Fig. 2). A short period of unfavorable weather about 10 days before the smog episode made a harvesting effect observable, as the mortality increase during smog was stronger in areas where the impact of this previous episode had been lower (*18,29*).

The same episode analysis in Erfurt shows no increase in mortality, but then, the pollution during the 2 pre-episode weeks was about 1100 μg/m^3 and about 2% is what the regression coefficient would predict for an 1100–2900 μg/m^3 increase. This predicts less than one excess death in a week, and is thus hardly observable. This is further in agreement with the logarithmic relationship between risk increase and pollution.

The study in Leipzig, which included the 1985 episode and two other 1980s episodes where East German SO_2 levels probably reached about 3500 μg/m^3, showed a mortality increase of 10–25% with 1-day lag, depending on how an episode day was defined (*23*). This may be overestimated as comparisons were made to the sum of 1 week before and 1 week after the episode. Another study (*24*) in the Potsdam area (cardiovascular deaths only) examined the episodes in 1985 and 1982. No pollution data are given and no baseline pollution data. An increase of up to 7% is observed, which may underestimate the effect as the episodes defined each cover a rather long 10- to 14-day period.

Larsen (*2*) did a meta-analysis of various episodes in London and several U.S. cities, regressing log excess deaths against log pollution. He found a strong relationship both with SO_2 and particulates and interprets the effect as a synergism. Results are not expressible as percent increases.

The London data set (winters 1959–72 or subsets thereof) was analyzed by various authors using various regression methods. Mazumdar et al. (*8*) used a kind of "prewhitened" mostly univariate regression: eliminating other sources of variation in several steps first and doing the next step with the residuals of the previous one. This procedure may lead to overcorrection and makes interpreting regression coefficients difficult. It is not quite clear whether percent increases obtained this way are comparable to those obtained by an episode approach or a multivariate regression including confounders in the model. Mazumdar and co-workers (*8*) reported a 17% increase per 1000 μg/m^3 SO_2 in a linear model. They repeated various of their regressions split up by "event/nonevent days," and their tables show mostly smaller regression coefficients for the "event" days. In 1982, Mazumdar et al. (*13*) analyzed the data among other variations separated by years; their tables show a general increase in linear regression coefficients in later years, where pollution is lower. For smoke, the relationship became flatter as pollution increased and therefore they used an additional square term and predicted values peak at about the maximum observed particle value. This does not work for SO_2, although Mazumdar et al. clearly saw the lack of fit for high SO_2 values. "The result, however, is ambiguous since the high pollution data set equation predicts a mortality excess of 185% for the peak SO_2 day of the entire data set (SO_2 = 3410 mg/m^3 and smoke 1970 mg/m^3) when the actual response is little over 30%. This value is predicted closely by dose response curves based on (smoke)^2 alone" (*13*: 218). In a similar analysis of Pittsburgh data, 1972–77, Mazumdar and Sussman (*32*) found no relationship with SO_2, some with COHs (coefficient of haze), but do not give a range.

Ostro (*15*) checked the London data set for a threshhold, which is hypothesized to lie at 150 mg/m^3 SO_2. He does not confirm this hypotheses; his tables show smaller coefficients for days with SO_2 > 150 μg/m^3 as compared to days with SO_2 ≤ 150 μg/m^3 for 10 out of the 14 study winters.

Schwartz and Marcus (*9*) analyzed the London data set again with an epidemiologic multivariate model. They did not find a threshold and found a better fit for a root transform as compared to no transformation of the pollution variables, which is similar in behavior to a log transform. BS explains more variation than SO_2, which is reduced strongly in a two-pollutant model. As far as this can be said, the regression slopes found in London are somewhat steeper for SO_2 than in Erfurt and slightly flatter for BS, which in turn is assumed to have a logarithmic relationship with TSP. A graph suggests a maximal increase in deaths of about 30% for the whole range of pollution.

Another data set which has been analyzed multiple times is from New York, 1963–76, or subsets thereof. Schimmel (*12*) and Schimmel and Greenburg (*33*), using the "prewhitened" method mentioned above, found about + 0.5% per 100 $\mu g/m^3$ SO_2, more for smoke shade (particulates), and Buechley et al. (*34*) come to mostly the same conclusion. Variations of these analyses (*35*) basically confirm these results. A later analysis (*36*) finds no relationship with SO_2, and a weak one with smoke shade.

Other analyses include slightly more than 1 year in Hannover, Germany, in 1969 (*10*), where at a generally low pollution level (no maximum given), + 8.8% per 100 $\mu g/m^3$ SO_2 was found. This paper is interesting as it is one of the few that try to model the harvesting effect. It was included via the mean of deaths of up to 7 previous days as a confounder, and the regression coefficient is small but negative, in agreement with the hypothesis.

In an overview, Lipfert (*5*) reported a relationship between log(excess deaths) and log(pollution). The regression coefficients are presented as between 0.6% and 5% increase per 100 $\mu g/m^3$ particulates. Hatzakis et al. (*11*) analyzed data from Athens, 1975–82. The range of SO_2 goes up to about 500 $\mu g/m^3$; the linear coefficient translates as + 2% per 100 $\mu g/m^3$ SO_2. Taking away more and more highly polluted days leads to a zero regression coefficient for days below 150 $\mu g/m^3$, which by the authors is interpreted as a threshold.

Schwartz and Dockery (*14,37,38*) analyzed in three papers time series in Detroit, Steubenville, Ohio, and Philadelphia. Each of these emphasizes the importance of particulates over SO_2, especially in two-pollutant models. In its role as an indicator, SO_2 alone usually shows a (often lagged) relationship with mortality. The absolute values are not very high. In Philadelphia, SO_2 and TSP go up to about 300 $\mu g/m^3$. Per 100 units, SP and SO_2 lead to mortality increases of 7% and 5%; respectively.

Most of these studies are in agreement with the results presented here. A linear relationship seems to fit the data only in studies with a relatively low range of pollution. Some analyses with a higher range report that the relationship becomes flatter as pollution increases. Many early studies show this in the tables, without the authors actually mentioning it. Practically no study shows more than a 20–30% increase of mortality in relationship to any episode or height of pollution, whereas extrapolating the linear relationships given by some authors to the amount of air pollution seen in Erfurt would predict 100% or more. If the true relationship is logarithmic, then the actual regression coefficient calculated in studies which postulate a linear relationship would depend mostly on the observed pollution range. As to the time component of the effect, there is agreement insofar as no study reports lagged effects of more than 2 days, and at least a 1-day lag was seen by several. Only a few studies claim to see a threshold for the effect. Ostro (*15*) and Schwartz and Marcus (*9*) explicitly disagree with this; most studies, including ours, do not find an indicator.

In this study, the lack of overdispersion and autocorrelation in the residuals of the final model indicate a good fit of the model. After fitting SO_2, several variations and refinements were checked. Remodeling without meteorology made little difference in the pollution parameters. Also, Table 4 gives no indication of systematic differences in pollution parameters between years, whether a meteorology correction was available or not. So meteorology may be an important covariate, but it is not an important confounder. Correcting only for annual variation slightly increased the SO_2 effect, so the parameter given here is somewhat conservative.

References

1. Brimblecombe P. The big smoke: a history of air pollution in London since medieval times. New York:Methuen, 1987.
2. Larsen RI. Relating air pollutant effects to concentration and control. Air Pollut Control Association 20:214 ff(1970).
3. Holland WW, Bennett AE, Cameron IR, Florey CV, Leeder SR, Schilling RSF, Swan AV, Waller RE. Health effects of particulate pollution: reappraising the evidence. Am J Epidemiol 110: 527–658(1979).
4. Ware J, Thibodeau LA, Speizer FE, Colome S, Ferris BG. Assessment of the health effects of sulfur oxides and particulate matter: evidence from observational studies. Environ Health Perspect 41:255–276(1981).
5. Lipfert FW. Mortality and air pollution: is there a meaningful connection? Environ Sci Technol 19:764–770(1985).
6. Lipfert FW, Morris SC, Wyzga RE. Acid aerosols: the next criteria air pollutant? Environ Sci Technol 23:1316–1322(1989).
7. Brasser LJ, Joosting PE, van Zuilen D. Sulphur dioxide—to what level is it acceptable? Report G 300. Delft, the Netherlands:Instituut voor gezondheidstechniek, 1967.
8. Mazumdar S, Schimmel H, Higgins I. Daily mortality, smoke and SO_2 in London, England 1959 to 1972. In: The proposed SO_x and particulate standard conference report. Atlanta, GA:Air Pollution Control Association, 1980.
9. Schwartz J, Marcus A. Mortality and air pollution in London: A time series analysis. Am J Epidemiol 131:185–194(1990).
10. Hecker H, Basler HD, Wolf E. Schwankungen der Mortalität in Beziehung zur Luftverschmutzung. MethInformMed 14:218–223 (1975).
11. Hatzakis A, Katsouyanni K, Kalandidi A, Day N, Trichopoulos D. Short-term effects of air pollution on mortality in Athens. Int J Epidemiol 15:73–81(1986).
12. Schimmel H. Evidence for possible acute health effects of ambient air pollution from time series analysis: methodological questions and some new results based on New York City daily mortality 1963-1976. Bull NY Acad Med 54:1052–1108(1978).
13. Mazumdar S, Schimmel H, Higgins ITT. Relation of daily mortality to air pollution: an analysis of 14 London winters, 1958–1972. Arch Environ Health 37:213–220(1982).
14. Schwartz J. Particulate air pollution and daily mortality in Detroit. Environ Res 56:204–213 (1991).
15. Ostro B. A search for a threshhold in the relationship of air pollution to mortality: a reanalysis of data on London winters. Environ Health Perspect 58:397–399(1985).
16. Steiger H, Brockhaus A. Untersuchungen über den Zusammenhang zwischen Luftverunreinigungen und Mortalität im Ruhrgebiet. Die Naturwissenschaften 53:498(1966).
17. Steiger H, Brockhaus A. Untersuchungen zur Mortalität in NRW während der Inversionswetterlage Dezember 1962. Staub-Reinhaltung der Luft 31:190–192(1971).
18. Wichmann HE, Müller W, Allhoff P, Beckmann M, Bocter N, Csicsaky MJ, Jung M, Molik B, Schöneberg G. Health effects during a smog-episode in West-Germany. Environ Health Perspect 79:89–99(1989).
19. Wichmann HE, Brockhaus A, Schlipköter HW. Smogepisoden in Nordrhein-Westfalen und ihre gesundheitlichen Auswirkungen. Öff Gesundh Wes 50:314–318(1988)
20. Schmitt OA. Smogepisoden im Ruhrgebiet seit 1980. Schr Reihe Verein WaBoLu 69:119–25 (1986).
21. Steiger H. Mortalitätsuntersuchung während der Smogwetterlage im westlichen Ruhrgebiet am 17. Zbl Bakt Hyg B 171:445–447 (1980).
22. Borgers D, Heberling R. Auswirkungen der Smog-Tage des Winters 81/82 auf die Mortalität in Berlin-West. Bundesgesundheitsblatt 25:33– 37(1982).
23. Lautenschläger D, Dörre WH, Horn K, Kowalewicz B. Mortalitätsuntersuchungen im Zusammenhang mit lufthygienisch bedenklichen Situationen. Z Gesamte Hyg 37:127–128(1991).
24. Bredel H, Herbarth O. Epidemiologische Untersuchungen zur akuten Wirkung der Luftverunreinigung. Gesundheit Umwelt 5:30–37(1989).
25. Wichmann HE, Sugiri D, Herold G, Knülle E. Atemwiderstandsmessungen bei Gesunden im Winterhalbjahr 1985/86 und im Januar/Februar 1987. Zbl Bakt Hyg B 185:509–519 (1988).
26. Höpken W, Willers H. Epidemiologie der Influenza seit 1968. Internist 26:83–88(1985).
27. Liang KY, Zeger SL. Longitudinal data analysis using generalized linear models. Biometrika 73:13–22(1986).
28. Zeger SL, Liang KY. Longitudinal data analysis for discrete and continuous outcomes. Biometrics 44:1019–1031(1986).
29. Wichmann HE, Spix C. Ergänzende Betrachtungen zu den gesundheitlichen Auswirkungen der Smogepisode 1985. Öff Gesundh Wes 52:260–266(1990).
30. WHO. Air quality guidelines for Europe. Copenhagen: World Health Organization, Regional Office for Europe, 1987.
31. Lahmann E, Laskus L, Siggelkow W, König R, Abshagen J, Buck M, Ixfeld H, Manns H. Schwefeldioxid- und Schwebstaub-Vergleichsmessungen gemäß der EG-Richtlinie 80/779. Staub-Reinhaltung der Luft 46:72–81(1986).

32. Mazumdar S, Sussman N. Relationships of air pollution to health: results from the Pittsburgh study. Arch Environ Health 38:17–24(1983).
33. Schimmel H, Greenburg LA. A study of the relationship of air pollution to mortality, New York City, 1963-68. J Air Pollut Control Assoc 22:607–616(1972).
34. Buechley RW, Riggan WB, Hasselblad V, VanBruggen JB. SO_2 levels and perturbations in mortality. A study in New York-New Jersey metropolis. Arch Environ Health 27:134 (1973).
35. Schimmel H, Murawski TJ. The relation of air pollution to mortality. J Occup Med 18:316–333(1976).
36. Shumway RH, Tai RY, Pawitan Y. Statistical analysis of daily London mortality and associated weather and pollution effects. Report of the Statistical Laboratory Division of Statistics. Davis, CA:University of California, 1983.
37. Schwartz J, Dockery DW. Particulate air pollution and daily. mortality in Steubenville, Ohio. Am J Epidemiol 135:12–29(1992).
38. Schwartz J, Dockery DW. Increased mortality in Philadelphia associated with daily air pollution concentrations. Am Rev Respir Dis 145:600–604(1992).