Daily mortality and air pollutants: findings from Köln, Germany

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Abstract

Study objective and design – For the APHEA study, the short term effects of air pollutants on human health were investigated in a comparable way in various European cities. Daily mortality was used as one of the health effects indicators. This report aims to demonstrate the steps in epidemiological model building in this type of time series analysis aimed at detecting short term effects under a poisson distribution assumption and shows the tools for decision making. In addition, it assesses the impact of these steps on the pollution effect estimates.

Setting – Köln, Germany, is a city of one million inhabitants. It is densely populated with a warm, humid, unfavourable climate and a high traffic density. In previous studies, smog episodes were found to increase mortality and higher sulphur dioxide (SO₂) levels were connected with increases in the number of episodes of croup.

Participants, materials and methods – Daily total mortality was obtained for 1975–85. SO₂, total suspended particulates, and nitrogen dioxide (NO₂) data were available from two to five stations for the city area, and size fractionated PM₁₀ data from a neighbouring city. The main tools were time series plots of the raw data, predicted and residual data, the partial autocorrelation function and periodogram of the residuals, cross correlations of pre-filtered series, plots of categorised influences, χ^2 statistics of influences and sensitivity analyses taking overdispersion and autocorrelation into account.

Results and conclusions – With regard to model building, it is concluded that seasonal and epidemic correction are the most important steps. The actual model chosen depends very much on the properties of the data set. For the pollution effect estimates, trend, season, and epidemic corrections are important to avoid overestimation of the effect, while an appropriate short term meteorology influence correction model may actually prevent underestimation. When the model leaves very little overdispersion and autocorrelation in the residuals, which indicates a good fit, correction for them has consequently little impact. Given the model, most of the range of SO₂ values (5th centile to 95th centile) led to a 3–4% increase in mortality (significant), particulates led to a 2% increase

(borderline significant, less data than for SO₂), and NO₂ had no relationship with mortality (measurements possibly not representative of actual exposure). Effects were usually delayed by a day.

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Köln was included as the German contribution to the APHEA project because it is relatively large and because experience the short term health effects of air pollution are available from earlier studies. In December 1962, a smog episode was observed in North-Rhine Westphalia. Daily means of total suspended particulates (TSP) of up to 2400 µg/m³ and sulphur dioxide (SO₂) values of 5000 µg/m³ were observed, though values were probably smaller in Köln itself. During this episode a 25% increased mortality was found.¹² In January 1985 another smog episode covered the area. In Köln TSP values reached about 400 µg/m³ and SO₂ values about 500 µg/m³. The mortality increase observed was 17%, and was more in the densely populated and badly ventilated inner city which has a high proportion of older people.²³

In 1984–87 Köln was one of the cities participating in a multicentre study of croup. Significant increases in the daily attack counts reported by paediatricians and hospitals were seen to be associated with high levels of TSP, nitrogen dioxide (NO₂), and SO₂. The multicentre study showed a stronger influence of TSP and NO₂, while in Köln in particular the relationship seemed to be driven by SO₂.⁴

In addition to giving the results, this paper focusses on the steps of model building needed to obtain the results. It documents the use of various diagnostic plots and the decisions made at the different stages. The sensitivity of the results to different steps of modelling will also be demonstrated.

Methods

STUDY AREA

Köln is the largest city in the state of North Rhine Westphalia with almost one million inhabitants. It is situated on the Rhine in the western part of the Federal Republic of Germany inside the Kölner Bucht, a bay situation, with higher land surrounding it except for the north. The microclimate is generally warmer and more humid than elsewhere north and west

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in Germany. It is unfavourable, with frequent trappings of moisture or fog by inversions. Köln is a major traffic knot and has a high density of chemical industry.

AIR POLLUTION AND METEOROLOGY

For temperature and relative humidity the Eifelwall station was picked because of data completeness (1976–85) and its position on the outer rim of the inner city. Less than 5% of the data are missing. Dew point temperature is an alternative measure of the humidity content of the air and can be calculated from temperature and relative humidity. Only daily means are being used, as this is available to everybody in the APHEA collaborative project.

SO₂ values were available for the whole period at five stations – three just on the outside of the inner city and two rather more in the suburbs. The stations are run by the city of Köln and the method used is mostly fluorescence with one exception, where they use a conductometric device. The inlet is 3–7 m from the ground and the stations are mostly placed in schoolyards. Forty eight daily half hour values were sampled, daily means or maxima for this study were only accepted when 75% of the values were available.

TSP values are available for 1975–84 from five stations in a state run network, which was dismantled in the early 1980s and gradually replaced by a modern telemetric network. Very little data would have been available for the study period from the latter network and these data were therefore disregarded. The method was semiautomated gravimetric and did not allow for continuous running, so samples were taken three days a week, namely Tuesday, Thursday, and Saturday. No size cut off was done, but a stochastic cut off can be assumed for practical reasons at around 30–35 µm, whereas modern TSP β-attenuation measurements cut off stochastically at around 15 µm. The system provided only daily means, and around 17% were missing. Two of the five stations are within the urban ring; three in the suburbs.

Because of the large fraction of coarse particles to be expected in these data, efforts were also made to obtain size fractionated data. In Düsseldorf, 40 km directly north of Köln, a research institute had been running a PM₇ device continuously since 1965. The method gave only daily means. The size was cut off at 7.1 µm volume equivalent diameter (for a short description of the device see⁵). For practical purposes, especially in a time series study, this can be compared with PM₁₀. Data were available for 1975–85, with around 12% missing. Except for the later years, every eighth day was missing for recalibration.

NO₂ values were available for 1977–85 from two background stations. The stations are run by the city, and the method used was chemiluminescence. The inlets are about 7 m from the ground. The method gave half hour data, the criteria for daily means and maxima were the same as for SO₂, and fewer than 10% were missing. The daily mean across stations was

formed by a regression method, which avoided problems with level differences and missing values.⁶

MORTALITY AND INFLUENZA

Daily total mortality data for 1975–85 were obtained from the state authorities. This included all causes of death and assignment to Köln was by last place of residence. There is evidence that in some places and some years, 1 January was associated with artificially high numbers, because “forgotten” death certificates from previous years were assigned to that day to avoid contradictions between published summarised data and the data base.⁷ In the FRG no systematic collection of data on influenza incidence is undertaken. A research paper on influenza viruses in Germany covering the study period gives some indications of when to expect higher values.⁸ The Dutch group within the APHEA project had weekly count data available for The Netherlands, the southern data fitted best and were thus used.

STATISTICAL ANALYSIS

The details and rationales for the poisson regression used here are described elsewhere.^{6,9} Here a logistic regression modelling tool was used for the model building step by assuming a large base population for the cases every day. When repeating these analyses with proper Poisson regression assuming no overdispersion and independent errors, the results are identical. It is thus appropriate for model building. χ^2 statistics are available for each model component and allow comparison of fit and contribution of parts of the model. The final models were then repeated using Poisson regression allowing for overdispersion and autocorrelated errors, where possible.

Analytical and especially graphical methods for decision making at the modelling steps are periodograms; autocorrelation function (ACF), and especially partial autocorrelation function (PACF) diagrams; cross correlations; time series plots of observed, predicted, and residual values; and plots of categorised influence data. If the first x values of a PACF diagram of appropriately detrended data are clearly different from 0, this points to an AR(x) model – that is a model where the value of a given day is (linearly) dependent on the values of the last x days. Although we do not estimate parameters from models that are thus pre-whitened, cross correlations are useful for checking lags.^{9–11}

Results

DESCRIPTIVE RESULTS

The data are summarised in table 1. The pollutants are basically “winter type” pollutants, although seasonality is not very pronounced for NO₂ and TSP. The pollution levels in Köln are rather on the low side when compared with the other APHEA cities, though the town is more polluted than the Dutch cities and Helsinki.¹²

Table 1 Data description, Köln 1975–85

	No of days with data	Time period	All year Median	Dec–Feb*	
				Median	Maximum
Mortality (cases per d)	4018	1975–85	29	31	56
Temperature (daily mean °C)	3486	1976–85	11	4	30
Relative humidity (daily mean %)	3589	1976–85	76	82	98
SO ₂ (daily mean µg/m ³)	4011	1975–85	44	66	401
SO ₂ (daily max µg/m ³)	4011	1975–85	91	120	832
NO ₂ (daily mean µg/m ³)	3248	1977–85	45	46	176
NO ₂ (daily max µg/m ³)	3248	1977–85	72	67	316
TSP† (daily mean µg/m ³)	1296	1975–84	68	69	304
PM ₁₀ ‡ (daily mean µg/m ³)	3522	1975–85	34	39	239

* Winter; † only Tuesday, Thursday, and Saturday; ‡ for most of the time every 8th day is missing.

Table 2 Regression results in relation to confounder model

Model	SO ₂ daily mean 1 day lag			PM ₁₀ daily mean log 1 day lag		
	Parameter	(SE)	χ ² (1 df)	Parameter	(SE)	χ ² (1 df)
No confounders	0.001060	(0.000074)*	205.3	0.0459	(0.0055)*	70.6
Trend	0.000953	(0.000080)*	141.4	0.0403	(0.0057)*	50.9
Season	0.000465	(0.000091)*	25.9	0.0291	(0.0058)*	25.6
Influenza	0.000327	(0.000094)*	12.2	0.0244	(0.0058)*	17.6
Day of week + holidays	0.000314	(0.000094)*	11.0	0.0235	(0.0058)*	16.2
Temperature only	0.000231	(0.000104)†	4.9	0.0083	(0.0064) ¹⁾	1.7
Meteorologic interactions (= full meteorology)	0.000271	(0.000104)*	6.8	0.0211	(0.0065)**	3.6

* Significant at the 5% level; ** significant at the 10% level; † Temperature and humidity introduce approximately 170 missing values, hence the larger SE.

Correlations between the five SO₂ stations are quite high, between 0.76 and 0.83 (daily mean). They are even higher between the five TSP stations, 0.90–0.95. There is much less correlation between the two NO₂ stations – 0.33 (daily mean) only – which sheds some doubt on the extent to which they are representative of the whole city. PM₁₀ and TSP are highly correlated – 0.78. On average, without much seasonal difference, PM₁₀ comprise 50% of the TSP. The SO₂ daily mean is also highly correlated with PM₁₀ (0.68) and TSP (0.60). NO₂ is correlated with TSP (0.56) and some with SO₂ (0.44). Those correlations are on the same day, cross correlations were checked but did not show stronger relationships with shifts of days.

The pollution data are highly autocorrelated, between 0.77 (SO₂ daily mean) and 0.62 (NO₂ daily max) with 1 day lag.

REGRESSION RESULTS

Potential confounders

The model was fitted in a “bottom up” fashion. First a long term trend, then seasonality, then epidemics were fitted, next short term systematic effects (calendar effects), short term unsystematic potential confounders (meteorology), and finally air pollution were included. In each step, we tried to find an optimal compromise between model fit, parsimony with respect to number of variables, and comparability with the other APHEA group members. The effects the various steps have on the fitted values and the residuals, the periodicity of the residuals, and the (partial) autocorrelation of the residuals can be inspected graphically. The effects they have on pollution estimates are demonstrated in table 2.

When analysing the periodogram and the partial autocorrelation function of the raw mor-

tality data, all that could be seen was a trend spike and an AR(10) process at least, which here means insufficient detrending.

An indicator for 1 January with artificially high values in four years was always included in the model. When fitting the long term trend by a time polynomial, a 3rd order cubic model fitted best, the residual periodogram now showed a large spike at 1 year. This explained why an attempt at further correction by including a biannual cycle led to nothing. The trend was further explained by including annual dummies, to ensure comparability within the APHEA collaboration.

Including a simple seasonal model, a sine and cosine term with period 1 year, smoothed the predicted line. The periodogram now showed a few spikes, mostly between 1 year and around 2 months, a 7 day cycle and random noise. The residual partial autocorrelation now indicated an AR(8) model. Overlaying this with half and third year cycles showed a characteristic pattern with an extra hump in the second half of winter, which was due to the influenza epidemics then. Leaving it at that would have led to an underestimation of the effects of actual influenza epidemics and an overestimation in years, when there was no epidemic. The periodogram did not show an advantage over the simple seasonal model, nor did the partial autocorrelations. The predicted value plot was required to see the difference.

The influenza epidemics were fitted by identifying plausible periods and fitting piecewise harmonic waves in each of those periods, and, where appropriate, including The Netherlands case count day allowing for slightly different time lags between morbidity and mortality for each epidemic. In the time series plot, they showed up as strong increases early in some years. The residual periodogram spikes at periods below approximately 2 months were

Table 3 Regression results

Pollutant	Lag*	Range† (µg/m³)	Model building step‡			Final analysis¶		
			Parameter	(SE)	RR§	Parameter	(SE)	RR§
SO ₂ (daily mean)	1	122 v 20	0.000271	(0.000104)**	1.03	0.000281	(0.000106)**	1.03
SO ₂ (daily max)	1	231 v 42	0.000140	(0.000053)**	1.03	0.000139	(0.000054)**	1.03
NO ₂ (daily mean)	1	82 v 24	0.000153	(0.000197)	1.01	0.000190	(0.000202)	1.01
NO ₂ (daily max)	1	141 v 44	0.000066	(0.000111)	1.01	0.000094	(0.000114)	1.01
TSP (daily mean log)	1	146 v 30	0.0145	(0.0122)	1.02	0.0145	(0.0123)	1.02
PM ₇ (daily mean log)	1	82 v 20	0.0122	(0.0065)***	1.02	0.0122	(0.0066)***	1.02

* The model fitted best, when the pollution effect was lagged by “lag” days.
† Range for which the relative risk (RR) will be given. 95th centile of the data compared with the 5th centile of the data, at least 20 µg/m³
‡ Poisson regression using PROC LOGIST, see text.
§ RR for a pollution increase of the range given.
¶ Poisson regression with correction for overdispersion and autocorrelated errors, the latter is technically impossible (because of missing values) for the particle models.
** Significant at the 5% level; *** Significant at the 10% level.

Table 4 Regression results for the average effect of several days including the same day (final models*)

Pollutant	lag†	Range (µg/m³)‡	Parameter	SE	RR§
SO ₂ (daily mean log)	0–3	118 v 23	0.0221	(0.0099)**	1.04
SO ₂ (daily max log)	0–3	209 v 51	0.0257	(0.0100)**	1.04
NO ₂ (daily mean)	0–1	80 v 25	0.000140	(0.000222)	1.01
NO ₂ (daily max)	0–1	132 v 46	0.000040	(0.000129)	1.00
TSP (daily mean log)	0–2	140 v 30	0.0105	(0.0094)	1.02
PM ₇ (daily mean log)	0–1	81 v 20	0.0120	(0.0067)***	1.02

* Poisson regression with correction for overdispersion and autocorrelated errors, the latter is technically impossible (because of missing values) for the PM₇ model.
† The model fitted best when the pollution effect was lagged by the average over “lag” days.
‡ Range for which the relative risk (RR) will be given. 95th centile of the data compared with the 5th centile at least 20 µg/m³.
§ RR for a pollution increase of the range given.
** Significant at the 5% level; *** Significant at the 10% level.

now of a similar size as the weekly period and some random shorter periods. The residuals were now more or less down to an AR(3) process. The residual time series began to look mostly like random noise (fig 1A).

Including day of week dummies added a “fuzzyness” to the predicted values. Mondays were about 5% above weekends, and this pattern is consistently observed for mortality data. The 7 day period in the residual periodogram went, as did the 7 day partial autocorrelation, very little else changed. For completeness, some holidays were included by extra indicators after checking all of them and 3 days to either side. Holidays with an increasing effect (New Year, 1 November), a decreasing effect (Good Friday, Ascension, Christmas), and the days following the latter with an increasing effect were summarised.

Temperature showed a U shaped effect – that is, days which were too hot and too cold had negative health effects. This was seen in a quintile plot that yielded a parabolic shape. Temperature clearly fitted best on the same day. In 1976 a heatwave of a few weeks’ duration had an obviously strong effect on mortality. The meteorology model was also assessed by its ability to explain this phase. The heatwave effect was insufficiently explained by temperature alone. Relative humidity was included with temperature on the same day and this had a much better explanatory value than relative humidity alone. Using dew point temperature as a measure of humidity instead fitted almost as well. The heatwave was still not adequately modelled, however. Interactions of the meteorology terms were included next. The residuals were now very close to random noise. The heatwave was almost perfectly described. Including the interaction terms in the model did not change overall fit considerably, because

the heat wave, where they make a difference, lasted only a few weeks. The periodogram now looked very random, with spikes of similar, low height all over the spectrum. The partial autocorrelations of the residuals still pointed to an AR(3), but with smaller coefficients than previously (fig 1B). This model including all important risk factors and potential confounders were termed the “core model” within the APHEA project.¹

Air pollution

The APHEA group decided to search for the best relationship of each pollutant with mortality with a lag of up to 3 days and the best cumulative effect of several days including the same day and up to 3 previous days. Transformations of the dose response curve could be applied as necessary.

Table 3 presents the results of the best fitting model per pollutant and the final model, correcting for overdispersion (usually about 1.01 to 1.03) and autocorrelated errors (AR(3) models, parameters usually around 0.02, 0.04, 0.02). Because of the missing value patterns, no correction for autocorrelated errors was possible with the particle data. All models fitted best with 1 day lag – which was observed in other studies too. The same decision would have been reached, for example for the SO₂ daily mean and PM₇ not on the basis of model fit but by pre-whitened cross correlations (see fig 2).

The differences between the error corrected and the uncorrected models were negligible in terms of parameter size and standard error. This was to be expected as the overdispersion and the autocorrelation were very small themselves (table 3).

Figure 1 The effects of some selected steps of the model building process for the potential confounders. Each box consists of the first three time series beneath each other, namely the observed, predicted, and residual series, then the residual periodogram and the residual PACF. (A) Shows the situation after including trend, season, and influenza epidemics. (B) Shows the situation after adding day of week, holidays, temperature, and humidity and interaction terms.

Figure 2 Cross correlations of residuals of mortality and sulphur dioxide (SO₂) and particulates (PM₇) corrected for the “core model”. While the right side is irrelevant and only included for comparison, the left side clearly points at a 1 day lag relationship between both pollutants and mortality. The relationship is not very strong.

For SO₂ and NO₂, the daily mean fitted better than the daily maximum; an often observed phenomenon as there is more random noise in the daily maximum data. In view of their naturally high correlation, both daily level indicators described the same dose response relationship. SO₂ fitted best untransformed and showed a small but significant relationship with mortality. NO₂ had no influence on mortality, which may be seen in connection with the doubts about the validity of the measurements for personal exposure. The particulates showed a small influence on mortality with some flattening towards the higher values. PM₇ fitted better because there were more data points; otherwise the results were quite similar, in agreement with the strong correlation of the two particulate measurements. Figure 3 shows the relative risks determined from including indicators for quantile classes in the model. Open shapes stand for smaller

Figure 3 Relative risk of PM₇ beyond the “core model” in relation to quintiles (closed triangles) and deciles (open triangles). The latter are used for the high end and are necessary because of the skewed pollutant distribution. The decile estimators have more variability and are indicated by open shapes. The baseline category is the lowest quintile. The relationship is not very strong. The effect of the high levels is below the middle levels. A flattening curve obviously fits better in this case. * In quantile classes with confidence intervals corrected for all other non-pollutant variables.

classes. This is necessary because of the skewed pollution distribution. The results seem unstable and lower for the high values than at the middle level, which is presumably why the log model fits better. Expressing the regression coefficients as relative risks for a range of the “influence” makes the results comparable when ranges are comparable. Here the range between the 5th and 95th centile was chosen because it covered most of the measurements without exceptional days. SO₂ predicted a 3% increase, particulates a 2% increase, and NO₂ a 1% increase. The models fitting cumulative values basically confirmed the above results. SO₂ fitted best averaged over 4 days, perhaps because of its high autocorrelation. The effect as given by the relative risk was about the same as for 1 day lag. The relationship now flattened out slightly towards the high values; but then, taking the means may increase misclassification at those levels. NO₂ over 2 days still had no explanatory value. TSP fitted best averaged over 3 days, given the missing value pattern this now made use of the full mortality data set but meant a different number of actual values on each day of the week contributing to the lagged mean – it was a 1 day lag on average. The effect size decreased somewhat, possibly because of increased misclassification. For PM₇ the mean of two consecutive days gave practically the same result as the 1 day lag. For the inner 90% range of pollutants averaged over the appropriate number of days, SO₂ predicted a 4% increase, particulates a 2% increase, and NO₂ a 0–1% mortality increase. The analyses by season showed somewhat stronger effects for all pollutants in summer. SO₂ in relation to particle categories gave no indication of a synergism. In fact SO₂ effects were stronger when TSP was below 100 µg/m³ or PM₇ was below 60 µg/m³, which of course occurs in summer. In general particle effects also tended to be stronger at an SO₂ daily mean below 100 µg/m³, but this was less consistent. Results in relation to NO₂ levels did not vary consistently. As much larger effects have been observed elsewhere, especially for particulates, we speculated that in Köln SO₂ measurements were best correlated with the actual local active agent, but still with a large degree of misclassification. The particulate measurements available (one containing a large fraction of coarse particles and one measured in a neighbouring city) were correlated with this second best.¹³

DISCUSSION AND SENSITIVITY ANALYSIS

Table 2 demonstrates the changes in coefficient estimates in relation to modelling steps. SO₂ and PM₇ are chosen as examples. The parameter χ^2 values are not quite comparable because PM₇ has more missing values and thus the data base is different, but the orders of magnitude are comparable. SO₂ and PM₇ had rather large coefficients when correcting only for trend. SO₂ showed the better fit then because of its stronger seasonal pattern, which picked up the seasonality in the mortality data.

Next, including seasonality reduced the parameters dramatically. This demonstrated, that not correcting for season would have led to serious overestimation of the pollution effect. The next large drop was provided by correcting for the influenza epidemics. The importance of this depends on how serious the influenza epidemics are in a given data set and whether they are correlated with high pollution levels. Here they were important because of their strong effect and their occurrence usually in winter. Day of week and holidays made little difference. Including meteorology beyond what was already explained by season led to some further correction. Interestingly, it seemed that insufficient correcting for meteorology (temperature only) led to an underestimate of the pollution effects, especially here where the refined model tracked the heat wave effects.

We should be aware, that even though some relationships with air pollution are significant or of borderline significance, the actual effect size was very small.

The purpose of this paper is not to give a recipe for how a final “core” model should be fitted but to demonstrate the steps to take and the use of easily accessible tools for decision making. The actual decisions made by other researchers have to be driven by the properties of their data set – there may be no or more complicated seasonal patterns, perhaps a bi-annual pattern or one that varies from year to year, epidemics may be of less importance, and the short term relationship with meteorology may be different under different climatic or housing conditions.

As to general model fit considerations, linear regression thinking is not applicable here. By including more and more variables in the model, the variance in normally distributed data can theoretically be reduced further and further, as the variance is independent of the mean. In this case we had reason to assume that the data were approximately poisson distributed and we cannot reduce variance below Poissonian variance, as it is linked to the mean. The degree to which this is achieved can be expressed by the residual overdispersion. For this model we came very close to 1, (1.01 to 1.03, depending on the pollutant), which means that the

model included almost all the important sources of extra-Poissonian variation.

Another feature are the assumptions made with regard to autocorrelation. There is no reason why the number of deaths on a given day should positively influence the number of deaths on the following day. The autocorrelation we see comes from influencing processes such as season, epidemics, weather, and to a small extent air pollution, which are themselves strongly intrinsically positively autocorrelated. Coming close to explaining this via the model again indicates a good fit. We have not achieved this goal fully here, but came sufficiently close.

A complete set of diagnostic plots at each step of the model building process is available from the author on request.

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