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Short-term associations between outdoor air pollution and visits to accident and emergency departments in London for respiratory complaints

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ABSTRACT: Many epidemiological studies have shown positive short-term associations between health and current levels of outdoor air pollution. The aim of this study was to investigate the association between air pollution and the number of visits to accident and emergency (A&E) departments in London for respiratory complaints. A&E visits include the less severe cases of acute respiratory disease and are unrestricted by bed availability.

Daily counts of visits to 12 London A&E departments for asthma, other respiratory complaints, and both combined for a number of age groups were constructed from manual registers of visits for the period 1992–1994. A Poisson regression allowing for seasonal patterns, meteorological conditions and influenza epidemics was used to assess the associations between the number of visits and six pollutants: nitrogen dioxide, ozone, sulphur dioxide, carbon monoxide, and particles measured as black smoke (BS) and particles with a median aerodynamic diameter of <10 µm (PM10).

After making an allowance for the multiplicity of tests, there remained strong associations between visits for all respiratory complaints and increases in SO_2: a 2.8% (95% confidence interval (CI) 0.7–4.9) increase in the number of visits for a 18 $\mu g \cdot m^{-3}$ increase (10th–90th percentile range) and a 3.0% (95% CI 0.8–5.2) increase for a 31 $\mu g \cdot m^{-3}$ increase in PM10. There were also significant associations between visits for asthma and SO_2, NO_2 and PM10. No significant associations between O_3 and any of the respiratory complaints investigated were found. Because of the strong correlation between pollutants, it was difficult to identify a single pollutant responsible for the associations found in the analyses.

This study suggests that the levels of air pollution currently experienced in London are linked to short-term increases in the number of people visiting accident and emergency departments with respiratory complaints.
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In the first half of this century, very high levels of sulphur dioxide and particles produced from coal burning were responsible for severe health effects [1]. Today, the air pollution mixture is substantially different, with the predominant source being motor vehicles [2]. Many epidemiological studies have shown positive short-term associations between indices of health and the relatively low levels of outdoor air pollution currently experienced in major cities in Europe and the USA [3–10]. These indices have most commonly been daily counts of deaths and emergency admissions to hospitals. In the USA, studies have tended to concentrate on particles measured as those with a median aerodynamic diameter of <10 µm (PM10) and ozone. The European and more recent American studies have investigated a wider range of air pollutants, including nitrogen dioxide, SO_2, and carbon monoxide. Studies in London for the years 1987/1988–1991/1992 have observed associations between daily mortality and black smoke (BS) and O_3, and between respiratory hospital admissions and O_3 [11, 12].

A number of studies from the USA, Spain and Finland [13–21] have examined emergency room admissions (as opposed to visits), predominantly for asthma, with no consistent results emerging. The only study of emergency room visits in the UK [17] reported associations between O_3 and SO_2 and patterns of attendance for acute childhood wheezy episodes at one hospital over 1 yr. In the UK, visits to accident and emergency (A&E) departments include some less severe cases of acute respiratory disease in addition to the more severe cases, which result in an emergency admission to hospital. Unlike hospital admissions, they are unrestricted by bed availability. The objective of this study was to assess the relationship between air pollution levels and visits to A&E departments for respiratory complaints across London. By studying a large, densely populated city like London over a substantial period of time (1992–1994) we were able to obtain sufficient data to investigate visits for asthma and for other respiratory complaints separately as well as by age group whilst retaining sufficient statistical power. London has a comprehensive air-pollution monitoring network providing daily data on several air pollutants including CO and PM10 (available from 1992) [22].

Methods

Accident and emergency visits data

All A&E departments in London were contacted to find out whether they kept manual registers of A&E attendances and whether they were willing to allow us to extract data from them. Sixteen hospitals were suitable for inclusion in the study. All sixteen were selected as they represented approximately half of the number of A&E departments in London, were geographically dispersed across London (fig. 1) and provided enough visits to perform analyses with sufficient statistical power. In each hospital, the manual registers used to record all visits to their A&E department were scanned for visits for respiratory complaints. These complaints were (in order of priority where more than one complaint was coded): asthma, wheezing, inhaler request, chest infection, chronic obstructive lung disease (COLD), difficulty in breathing, cough and finally any other respiratory complaints such as croup, pleurisy and noisy breathing. The recorded complaint was that reported by the patient and not a clinical diagnosis. For each of these visits between January 1992 and December 1994, the presenting complaint together with the patient's age and the date of attendance were extracted from the manual registers. Daily counts of visits for asthma, for all other respiratory complaints and for the two together were computed for four age groupings: children aged 0–14 yrs, adults 15–64 yrs, elderly ≥65 yrs (for other and all respiratory complaints only) and all ages.

Air pollution and meteorological data

Daily maximum and minimum temperature and 06:00 h and 15:00 h relative humidity measures at Holborn, central London, were obtained from the Meteorological Office. Daily average temperature and humidity measures were computed as the mean of the two respective values. Air pollution data were obtained from a number of monitoring stations across London according to availability and completeness during 1992–1994 and their geographical location. NO_2 and CO data were obtained from three sites, O_3 from two, and only one site provided PM10 data. BS and SO_2 were obtained from five sites. Figure 1 indicates the location of the monitoring stations and the data they supplied. Where possible, missing values were estimated using a standard procedure [23], and single daily average values for each pollutant were calculated. Further detailed information on sites and measurement methods are provided in a contemporary review of UK air quality [22].

Fig. 1. – Locations of hospitals participating in the study and air-pollution monitoring stations providing data. The continuous lines represent the boundaries of the four Regional Health Authorities in London. The numbered dots represent the pollution monitoring sites providing data. Pollution monitoring sites: 1: Bridge Place (NO_2, O_3, CO); 2: Bloomsbury (NO_2, O_3, CO, PM10); 3: West London (NO_2, CO); 4: Acton (SO_2, BS); 5: Enfield (SO_2, BS); 6: London city (SO_2, BS); 7: Ilford (SO_2, BS); 8: Croydon (SO_2, BS). BS: black smoke; PM10: particles with a median aerodynamic diameter of 10 µm.

Statistical methods

The statistical analysis was based upon the methods developed by the "Air Pollution and Health: a European Approach" (APHEA) project [24]. The long-term trend, seasonality and day of week fluctuations of a series were determined using a number of statistical tools. Spectral analysis was used to determine the periodicity of the seasonal patterns and appropriate trigonometric variables constructed to account for them in a statistical model. The suitability of the statistical model was assessed using the overdispersion parameter, model deviance and plots of Pearson residuals, and any remaining serial correlation was assessed using the partial autocorrelation function. Daily counts of hospital admissions for influenza for the age group under study were included in the model to account for any possible confounding due to influenza epidemics in the community. Any remaining association between the observed counts and temperature and humidity was determined using plots of the model residuals against various measures of temperature and humidity. Alternative methods of modelling these meteorological variables (linear, quadratic, piece-wise, spline functions) were then compared using model-fit statistics and the most appropriate measure selected for inclusion in the model. Once the explanatory variables of the "core" model had been decided upon, an air pollution indicator was added. Poisson regression, allowing for overdispersion and autocorrelation [25] was used to determine the percentage change in the mean number of visits associated with an increase in the pollution measure. The 10th–90th percentile range in the pollutant was used as it represents well the range of pollution levels experienced in London during the analysis period and facilitates meaningful comparisons with the results for other pollutants. A predetermined set of daily pollution measures were tested, in turn, in the statistical model. For SO_2, BS, CO and PM_{10} the 24-h average was used, but for NO_2 and O_3, two daily measures were used: for NO_2 the 24-h average and maximum one-hour measures, and for O_3 the maximum eight-hour running average and maximum one-hour measures. These measures on the same day and 1, 2 and 3 days prior to the day of the visit, termed single-day lags 0–3, as well as cumulative lags, calculated as the mean of lags 0 and 1, lags 0–2 and lags 0–3 were tested. This process of "core" model building and then pollutant testing was repeated for each outcome and age group studied. For each pollutant, the most significant single-day lag, irrespective of the direction of the estimate, was selected for reporting purposes and for further analysis. Possible interactions between seasons were investigated using a dummy variable to indicate the season (warm season defined as April–September, cool season, October–March), and where appropriate, models with two pollutant measures were also examined to try and determine whether one pollutant was more important than another. Because of the large number of tests and the selective reporting and further testing of the most significant results, statistical significance was defined as $p<0.01$. The usual 95% confidence limits have, however, been retained when presenting the results of the analyses in tables and graphically. For the purposes of simplifying the presentation and discussion, this paper focuses upon the results for the single day measures of pollution. The results for the cumulative lags are available on request. All statistical analyses were carried out using SAS statistical software (SAS Institute, Cary, NC, USA).

Results

The total entries scanned in the 16 hospitals numbered 2,170,941, of which 121,610 (5.6%) were for respiratory complaints. Four hospitals, one in central London and one each in the south west, north west and south east London, had incomplete manual registers and were excluded from the study leaving 98,685 visits for analysis. The remaining 12 hospitals in the study were representative of hospitals in the Greater London area in terms of both size and geographical distribution. There were 28,435 (28.8%) vists for asthma during the three-year period. The largest single category of complaint was for the nonspecific "difficulty in breathing" with 38,371 visits (38.9%), reflecting the self-reporting nature of the recorded complaint. The other categories were "wheeze" 6,228 (6.3%), inhaler requests 649 (0.7%), "chest infection" 9,697 (9.8%), COLD 1,613 (1.6%), "cough" 7,690 (7.8%) and other respiratory complaints 6,002 (6.1%). The majority of visits 42,276 (42.8%), irrespective of complaint, were by children.

Figure 2 shows the time-series plots for the number of visits for all respiratory complaints together and for asthma only. The most striking feature of these plots are the large peaks in visits associated with a major thunderstorm on June 24, 1994 [26]. The mean number of daily visits for all respiratory complaints, asthma and other respiratory complaints are given in table 1 together with a summary of the distributions for the pollutants and meteorological measures used in the study.

All respiratory complaints

Table 2 gives the results for the most significant single-day measures of the six pollutants investigated for each age group for visits for all respiratory complaints. The results for the all-ages group for each single-day lag tested of the six pollutants are shown in figure 3 and

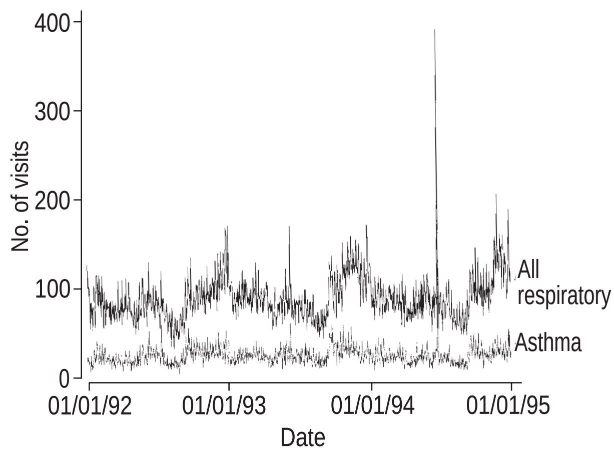

Fig. 2. – Daily number of visits to accident and emergency departments in London for all respiratory complaints and asthma between January 1992 and December 1994.

Table 1. – Summary statistics for accident and emergency (A&E) visits by complaint and age group and for pollution and meteorological variables between January 1992 and December 1994

Variable		n	Mean	SD	Min	Percentile 10th	Percentile 50th	Percentile 90th	Max
A&E complaints (daily number of visits)									
All respiratory	All ages yrs	1096	90.0	25.1	34	64	86	121	390
	0–14	1096	38.6	15.9	10	21	36	59	146
	15–64	1096	29.2	11.2	10	20	28	39	278
	≥65	1096	19.3	6.1	5	12	18.5	27	49
Asthma	All ages yrs	1096	25.9	9.4	6	16	25	38	128
	0–14	1096	12.0	5.8	1	5	11	19	37
	15–64	1096	11.4	5.3	1	6	11	17	96
Other respiratory	All ages yrs	1096	64.1	18.8	19	45	61	88	262
	0–14	1096	26.6	12.4	5	14	24	42	115
	15–64	1096	17.8	7.5	5	11	17	24	182
	≥65	1096	17.6	5.7	3	11	17	25	42
Pollutants (daily concentrations)									
NO_2 1 h ppb		1096	50.3	17.0	22.0	34.3	47.0	70.3	224.3
O_3 8 h ppb		1067	17.5	11.5	1.9	4.4	16.0	30.1	79.9
SO_2 24 h $\mu g \cdot m^{-3}$		1096	21.2	7.8	7.4	13.0	19.8	31.0	82.2
CO 24 h ppm		1096	0.8	0.4	0.2	0.5	0.7	1.3	5.6
PM_{10} 24 h $\mu g \cdot m^{-3}$		997	28.5	13.7	6.8	15.8	24.8	46.5	99.8
BS 24 h $\mu g \cdot m^{-3}$		1096	12.7	7.9	1.6	5.5	10.8	21.6	69.8
Meteorological measures									
Temperature °C		1096	11.9	5.0	-0.8	5.6	11.7	18.6	25.5
Humidity %		1090	70.4	11.0	33.0	56.0	70.0	85.0	97.0

BS: black smoke; PM_{10}: particles with a median aerodynamic diameter of <10 µm. ppb: parts per billion; ppm: parts per million.

illustrate the degree of consistency, in terms of the direction and magnitude of their associations, across the lags investigated.

Increases in visits to A&E departments for respiratory complaints were associated with increases in daily levels of the six pollutants studied. The associations with SO_2 and PM_{10} were statistically significant, small in magnitude (approximately a 3% increase in the number of visits for a 10th–90th percentile increase in the pollutant), and were slightly more consistent for SO_2 than for PM_{10}. The SO_2 associations were found to be stronger (smaller p-values and larger effect estimates) for children: lag 2 days 6.01% (95% CI 2.98–9.12), p=0.00008. In adults, there was a strong association between visits with the lag 1 day measure of PM_{10}, 5.18% (95% CI 2.06–8.39), p=0.001. There was also some evidence for a significant association with BS, again at lag 1 day but none for O_3. There were no significant seasonal differences in these results (data not shown). SO_2 and PM_{10} measures are closely correlated (Pearson correlation coefficient=0.6). Results of a two-pollutant model containing both SO_2 and PM_{10} measures suggested that it was not possible to determine whether only one of these pollutants was responsible for both observed single pollutant model associations (data not shown).

A significant association between visits for respiratory complaints and CO was found in the elderly: 4.29% (95% CI 1.15–7.54), p=0.007. This result was largely unaffected by the addition of any of the other pollutants into the model (data not shown).

Asthma

There were consistent and highly statistically significant associations between asthma visits and increases in daily levels of SO_2, NO_2 and PM_{10} and, to a lesser extent, CO and BS. Table 3 summarizes these results for all age groups investigated, and figure 4 shows the results, for the all-ages group, for each lag of the single day measures of the six pollutants investigated. Particularly strong associations with SO_2 and NO_2 were found in children: SO_2, lag 1 day, 9.92% (95% CI 4.75–15.34), p=0.0001; and NO_2, 1-h measures, lag 1 day, 8.97% (95% CI 4.39–13.74), p=0.00009. PM_{10} was associated with increases in visits for asthma in each of the three age groups studied. There was no evidence that O_3 was associated with visits for asthma. There was strong evidence of a significant seasonal difference in the association between asthma visits and NO_2 in children, p=0.009; and during the warm season, the association was very strong at 19.70% (95% CI 10.61–29.53), p=0.000008. Table 4 presents the results of the two-pollutant models for asthma in children. They show that both the magnitude and statistical significance of the single pollutant model results for NO_2, SO_2 and PM_{10} were all reduced by the addition of another of these pollutants to the statistical model. This indicates that none of these three pollutants acted independently of the others. However, a two-pollutant model by season suggested that the NO_2 association was independent of the SO_2 association in the warmer months (data not shown). Broadly similar results were obtained for adults and all ages (full details on request from the authors).

All other respiratory complaints

For respiratory complaints other than asthma, both SO_2 and PM_{10} showed significant associations with an increased number of visits. However, the pattern of results

Table 2. – Summary of single pollutant results for all respiratory complaints

Age group	Pollutant	Lag	% change in visit No. (95% CI)	p-value
All ages	NO_2	1	1.20 (-0.57–3.00)	0.2
	O_3	1	1.65 (-0.92–4.30)	0.2
	SO_2	1	2.81 (0.72–4.93)	0.008
	CO	1	0.76 (-0.83–2.38)	0.3
	PM10	1	2.97 (0.83–5.16)	0.006
	BS	1	1.63 (-0.24–3.54)	0.09
Children	NO_2	1	2.17 (-0.49–4.91)	0.1
	O_3	2	-3.28 (-7.20–0.80)	0.1
	SO_2	2	6.01 (2.98–9.12)	0.00008
	CO	1	2.92 (0.60–5.30)	0.01
	PM10	1	3.86 (0.55–7.27)	0.02
	BS	1	3.72 (0.98–6.53)	0.007
Adults	NO_2	2	1.87 (-0.69–4.49)	0.2
	O_3	0	-2.54 (-5.68–0.71)	0.1
	SO_2	2	2.72 (-0.18–5.70)	0.07
	CO	1	2.15 (-0.27–4.63)	0.08
	PM10	2	5.18 (2.06–8.39)	0.001
	BS	1	3.55 (0.81–6.36)	0.01
Elderly	NO_2	0	3.97 (0.51–7.55)	0.02
	O_3	2	6.77 (0.81–13.08)	0.03
	SO_2	1	-1.82 (-5.72–2.25)	0.4
	CO	0	4.29 (1.15–7.54)	0.007
	PM10	1	-2.85 (-6.91–1.39)	0.2
	BS	1	-3.70 (-7.25– -0.02)	0.05

Associations are expressed as the percentage change (95% confidence interval (CI)) in the number of accident and emergency visits for a 10th to a 90th percentile change in each pollutant presented at its most significant single-day lag. All p-values have been rounded to one significant digit. BS: black smoke; PM10: particles with a median aerodynamic diameter of <10 µm.

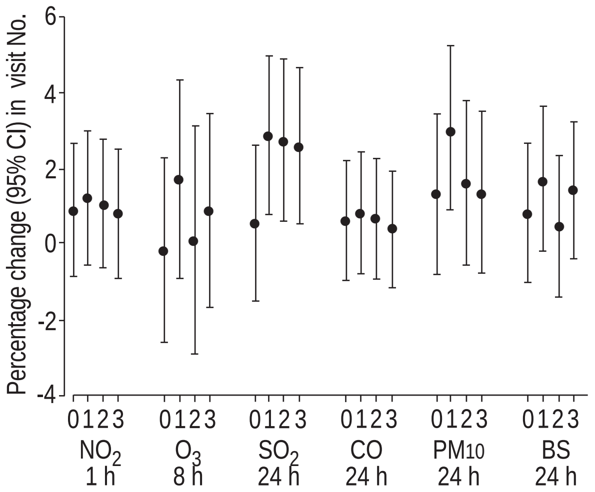

Fig. 3. – Single pollutant model results for all respiratory complaints. Associations are expressed as a percentage change (95% confidence interval (CI)) in number of accident and emergency visits for a 10th to a 90th percentile change in each pollutant. Results for each lag tested, lags 0–3, for each pollutant are shown. BS: black smoke; PM10: particles with a median aerodynamic diameter of <10 µm.

across the different measures and lags and the levels of statistical significance obtained gave a less convincing message than for asthma (full details on request from the authors).

Discussion

This study found significant associations between the number of daily visits to A&E departments and measures of outdoor air pollutants such as SO_2, NO_2, and PM10.

In evaluating the results of this study, a greater emphasis has been placed on results which are highly significant, $p<0.01$, and consistent in terms of direction, magnitude and statistical significance across the various lags of each pollutant tested. In this way, we have attempted to avoid placing too much importance on isolated significant associations amongst a large number of statistical tests.

In studies of this type, a key issue is the appropriate control for confounding variables. The statistical models were constructed following a standardized methodology and then checked to ensure that the model fit was satisfactory. Particular attention was paid to the modelling of temperature and humidity. It is unlikely, therefore, that either temperature or humidity is confounding the relationships with air pollution. The unusual environmental conditions associated with the thunderstorm in June 1994 were accounted for by including dummy variables in the statistical models.

A limitation of the present study is that the population exposure to outdoor air pollution across London is derived from only a few monitoring stations. The correlations between sites for NO_2, O_3 and CO are all positive and high, at 0.7–0.96, suggesting that whilst levels may vary between locations, the short-term temporal pattern of fluctuations

Table 3. – Summary of single pollutant results for asthma visits

Age group	Pollutant	Lag	% change in visit No. (95% CI)	p-value
All ages	NO_2	0	4.37 (1.32–7.52)	0.005
	O_3	1	2.67 (-1.66–7.21)	0.2
	SO_2	1	4.95 (1.53–8.48)	0.004
	CO	1	3.32 (0.56–6.16)	0.02
	PM10	1	5.35 (1.77–9.05)	0.003
	BS	2	2.85 (-0.21–6.01)	0.07
Children	NO_2	1	8.97 (4.39–13.74)	0.00009
	O_3	0	-5.23 (-12.07–2.15)	0.2
	SO_2	1	9.92 (4.75–15.34)	0.0001
	CO	0	4.13 (-0.11–8.54)	0.06
	PM10	2	7.41 (2.10–13.00)	0.006
	BS	2	4.57 (-0.04–9.40)	0.05
Adults	NO_2	1	4.44 (0.14–8.92)	0.04
	O_3	0	-4.11 (-10.39–2.61)	0.2
	SO_2	1	4.19 (-0.53–9.13)	0.08
	CO	1	4.41 (0.46–8.52)	0.03
	PM10	1	7.83 (2.83–13.07)	0.002
	BS	1	5.14 (0.72–9.75)	0.02

Associations are expressed as the percentage change (95% confidence interval (CI)) in the number of accident and emergency visits for a 10th to a 90th percentile change in each pollutant presented at its most significant single-day lag. All p-values have been rounded to one significant digit. BS: black smoke; PM10: particles with a median aerodynamic diameter of <10 µm.

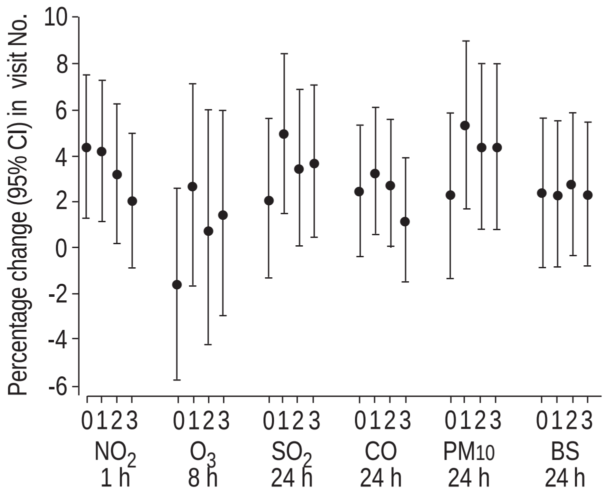

Fig. 4. – Single pollutant model results for all asthma complaints. Associations are expressed as percentage change (95% confidence interval (CI)) in number of accident and emergency visits for a 10th to a 90th percentile change in each pollutant presented at its most significant single day lag. Results for each lag tested, lags 0–3, for each pollutant are shown. BS: black smoke; PM10: particles with a median aerodynamic diameter of <10 µm.

do not. Correlations between the five sites providing SO_2 and BS data are smaller, in the range 0.5–0.8 for BS and 0.2–0.5 for four of the five SO_2 sites. The sites providing BS and SO_2 data are sampling sites, rather than continuously monitored and are geographically dispersed across London rather than co-located or in close proximity. Either of these factors may be responsible for the lower correlation between sites.

There have been a number of epidemiological studies of emergency room admissions and air pollution, and a summary of some of these studies is given in table 5. They focus mostly on asthma and address a variety of pollutants, age ranges and time periods as well as utilizing a range of statistical methods. No consistent picture emerges from their results. Statistically significant associations with visits for asthma and O_3, SO_2, NO_2, PM10 and BS are all reported. There are a number of distinct differences between these studies and the work reported here. Firstly, the size of the population at risk in London was considerably larger than in other studies. Secondly, the power of our study, determined by the mean number of events per day and the time period covered, was larger than in other studies. Finally, the complaint used in our study was that stated by the subject at presentation and did not represent the clinical diagnosis after assessment in the A&E department. This enabled us to record the full number of visits to A&E, irrespective of severity, but at the expense of a large number of nonspecific respiratory complaints such as "wheezing" and "difficulty in breathing" being recorded. STIEB *et al.* [19] recorded both the presenting complaint and the diagnosis recorded by the physician. They concluded that whilst the majority of asthma presentations were for asthma, they did not represent the true incidence of asthma. It is possible, therefore, that we have underrecorded the true incidence of asthma. If visits for asthma are associated with air pollution levels, then the effect of this underrecording is

Table 4. – Summary of results for two pollutant models for asthma visits by children

Pollutants	Single-pollutant model results	NO_2 1 h Lag 1	O_3 8 h Lag 0	SO_2 24 h Lag 1	CO 24 h Lag 0	PM10 24 h Lag 2	BS 24 h Lag 2
NO_2 1 h	8.97 (4.39–13.74)	-	9.68 (5.02–14.54)	5.75 (0.39–11.40)	8.34 (3.61–13.29)	6.95 (1.96–12.19)	8.32 (3.56–13.30)
lag 1	p=0.00009		p=0.00003	p=0.04	p=0.0004	p=0.006	p=0.0005
O_3 8 h	-5.23 (-12.07–2.15)	-5.50 (-12.22–1.73)	-	-4.17 (-11.04–3.23)	-4.00 (-10.99–3.55)	-3.70 (-10.98–4.18)	-4.97 (-11.83–2.43)
lag 0	p=0.2	p=0.1		p=0.3	p=0.3	p=0.3	p=0.2
SO_2 24 h	9.92 (4.75–15.34)	5.42 (0.18–10.93)	8.39 (3.82–13.17)	-	8.05 (3.45–12.86)	5.63 (0.53–10.98)	8.03 (3.32–12.96)
lag 1	p=0.0001	p=0.04	p=0.0002		p=0.0005	p=0.03	p=0.0007
CO 24 h	4.13 (-0.11–8.54)	2.05 (-2.25–6.54)	4.48 (0.00–9.16)	2.34 (-1.94–6.81)	-	2.93 (-1.53–7.58)	4.19 (-0.04–8.60)
lag 0	p=0.06	p=0.4	p=0.05	p=0.3		p=0.2	p=0.05
PM10 24 h	7.41 (2.10–13.00)	4.72 (-0.74–10.48)	6.28 (0.97–11.88)	4.94 (-0.66–10.85)	7.24 (1.94–12.81)	-	6.37 (-0.44–13.64)
lag 2	p=0.006	p=0.09	p=0.02	p=0.08	p=0.007		p=0.07
BS 24 h	4.57 (-0.04–9.40)	2.15 (-2.52–7.05)	3.76 (-1.14–8.91)	1.99 (-2.73–6.94)	4.64 (0.03–9.47)	1.50 (-4.84–8.27)	-
lag 2	p=0.05	p=0.4	p=0.1	p=0.4	p=0.05	p=0.7	

Associations are for the "row pollutant" in the presence of the "column pollutant" and are expressed as the percentage change (95% confidence interval (CI)) in the number of accident and emergency visits for a 10th to a 90th percentile change in each pollutant presented at its most significant single-day lag. All p-values have been rounded to one significant digit. BS: black smoke; PM10: particles with a median aerodynamic diameter of <10 µm.

Table 5. – Summary of published results for time series analyses of emergency room visits for asthma and other respiratory complaints

First author [Ref.]	Year of publication	Setting	Period covered	Outcome measure	Analysis method	Main pollutants	Main findings	Comments
BATES [13]	1990	Vancouver, Canada	1984–1986	Asthma, $9.5 \cdot day^{-1}$ All ages	Univariate correlation coefficients	O_3, SO_2, NO_2	S: adults, SO_2 lag 0 days r=0.12 p<0.01 W: elderly, SO_2 lag 1 days r=0.15 p<0.001 (lags 0 and 2 also)	Significant correlation for respiratory visits and SO_2/NO_2 also
CODY [14]	1992	New Jersey, USA	May 1988–Aug 1989	Asthma, $3.6 \cdot day^{-1}$ All ages	MLR	O_3	O_3 coefficient 20.3 (SEM 7.2) p=0.005	
WEISEL [21]	1995	New Jersey, USA	Summer 1986–1990	Asthma	MLR	O_3	O_3 associated	
SCHWARTZ [15]	1993	Seattle, USA	Sept 1989–Sept 1990	Asthma, $7.1 \cdot day^{-1}$ All ages	PR	PM_{10}	PM_{10} mean lags 0–4 30 $\mu g \cdot m^{-3}$ RR 1.12 (1.01–1.06)	Control for temperature, humidity, seasonality, serial correlation and overdispersion
CASTELLSAGUE [16]	1995	Barcelona, Spain	1985–1989	Asthma, all ages S: $2.7 \cdot day^{-1}$ W: $3.9 \cdot day^{-1}$	PR	O_3, BS, NO_2 SO_2	S: BS lag 0, 25 $\mu g \cdot m^{-3}$ RR 1.08 (1.01–1.16); NO_2 lag 0, 25 $\mu g \cdot m^{-3}$ RR 1.05 (1.01–1.08)	Similar results in winter for NO_2 only. Cumulative measures gave larger RR. Confounder control as per SCHWARTZ [15]
BUCHDAHL [17]	1996	London, UK	Mar 1992–Feb 1993	Wheeze, children 0–16 yrs (median 2)	PR	O_3, NO_2, SO_2	SO_2 and O_3 associated wheeze	"U" shape for O_3 response. No day-of-week adjustment
DELFINO [18]	1997	Montreal, Quebec	June–Sept 1992 and 1993	All respiratory $98 \cdot day^{-1}$, all ages. Other ages also	MLR	O_3, H^+, PM_{10}, $PM_{2.5}$, SO_4	O_3 and PM_{10} associated with ≥65 yrs	Results based on one summer
STIEB [19]	1996	Saint John, New Brunswick, Canada	May–Sept 1984–1992	Asthma, $1.5 \cdot day^{-1}$ All ages	PR	O_3, SO_2, NO_2, TSP, SO_4	O_3 and asthma all ages, adults, not children	Presenting complaint O_3 associated non-linear. Invariant to co-pollutants. Little PM_{10} data
ROSSI [20]	1993	Oulu, Finland	Oct 1985–Sept 1986	Asthma, adults 15–85, $<1 \cdot day^{-1}$	MLR and DA	SO_2, NO_2, TSP, H_2S	NO_2 associated with asthma, all year and cool season	Basic modelling, low counts, 1 yr

MLR: multiple linear regression; PR: Poisson regression; DA: discriminant analysis; S: summer months; W: winter months; RR: relative risk; BS: black smoke; SO_4: sulphates; TSP: total suspended particles; H+: aerosol strong acidity; PM_{10}: particles with a median aerodynamic diameter of <10 µm; $PM_{2.5}$: particles with a median aerodynamic diameter of 2.5 µm.

likely to be a bias towards the null, leading to underestimates of the effect of the air pollutants on asthma.

Statistically significant associations between air pollution and visits to A&E departments for respiratory complaints were found. The associations with NO_2 and SO_2 in children presenting with asthma are particularly strong. There have been few time-series studies of children and asthma using these more advanced statistical techniques so comparisons with other findings are difficult. The NO_2 findings in adults are comparable with those of CASTELLSAGUE *et al.* [16], but not STIEB *et al.* [19] or BUCHDAHL *et al.* [17]. There is some evidence that aeroallergens may have an enhanced effect in the presence of NO_2 and/or SO_2 [27]. To assess this possibility, daily measures of grass, birch, nettle and oak pollens were added to the children's asthma model and checked for statistical significance. None of the pollen measures was statistically significant at the 5% level. This quick assessment suggests that pollen levels do not influence the air pollution results. However, further work is required to investigate possible pollution/pollen interactions as well as the role of fungal spores. There was a significant seasonal difference in the children's NO_2 result with a very strong association in the warmer months. One possible explanation is that outdoor exposure more accurately reflects real personal exposure during the warmer months compared to the cooler months, resulting in stronger, as well as more significant, associations.

CASTELLSAGUE *et al.* [16] also reported significant associations between asthma and BS in the summer months, a result not replicated in this study. We did, however, find associations with PM10 and asthma in children, adults and the all-ages group. SCHWARTZ *et al.* [15] investigated PM10 in Seattle, USA and found significant associations with asthma visits for an all-ages group. DELFINO *et al.* [18] reported similar findings for PM10 and visits for all respiratory complaints by the elderly.

Our finding that SO_2 and A&E attendances for asthma are associated is consistent with the work of BATES *et al.* [13] and BUCHDAHL *et al.* [17], but not CASTELLSAGUE *et al.* [16] or STIEB *et al.* [19]. However, the former study, conducted in 1990, used simple statistical methods, whereas BUCHDAHL *et al.* [17] studied only wheezing episodes at a single hospital for 1 yr.

In the present study, we have been unable to separate the effects of PM10 and SO_2 on asthma visits. In two-pollutant models for asthma, the magnitude and statistical significance of the single pollutant associations were reduced by the addition of the other pollutant. It is possible that the SO_2 measures were a surrogate for exposure to fine sulphate particles, which would also have been included in the PM10 measurements. A small amount of sulphate data (for 493 days between 1992 and 1994) were available, and these were used to investigate the association between visits for asthma and fine sulphate particles. For visits for asthma by children and the all-ages group, none of the single day measures of sulphate investigated (lags 0–3) was statistically significant, even at the less stringent 5% level. This result is perhaps not so surprising given the low correlation between SO_2 and sulphate (Pearson correlation coefficient=0.4). As expected, the correlation between PM10 and sulphate is quite high, at 0.7. These results suggest that the above assumptions that the SO_2 associations with visits for asthma are surrogates for associations with fine sulphate particles are incorrect.

Ozone has been associated with visits for asthma and respiratory attendances [14, 17–19, 21] as well as for emergency hospital admissions in London [11], so it is surprising that no evidence for an association with O_3 was found in the present study. In fact, the lack of any association with O_3 was a consistent finding across all outcome measures and age groups studied. Ozone levels during our study period did not differ greatly from those of other studies in London [11, 12] so the reasons for a failing to find significant associations are not clear.

The strong association between CO and visits by the elderly for respiratory complaints may be an indicator of an association between CO and cardiovascular disease as much as an association with respiratory disease. The majority of the visits by the elderly were for the nonspecific complaint of "difficulty in breathing" (68%). Carbon monoxide has been identified as being associated with increased admissions for acute myocardial infarction and other circulatory diseases in London [28].

In conclusion, we have found highly statistically significant associations between the number of daily visits to accident and emergency departments for respiratory complaints and measures of outdoor air pollution. These associations persist after adjustment for the effects of temperature, humidity, seasonal and weekly patterns in attendances. The strongest associations were found in children and in visits for asthma in particular. The main pollutants implicated are sulphur dioxide, particles with a median aerodynamic diameter of <10 μm and specifically for asthma, nitrogen dioxide.

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References

1. Anonymous. Mortality and morbidity during the London fog of December 1952. London, HMSO, 1954; Report no. 95 on public health and medical subjects.
2. Quality of Urban Air Review Group. Urban air quality in the United Kingdom. Bradford, Department of the Environment, 1993.
3. Brunekreef B, Dockery DW, Krzyzanowski M. Epidemiologic studies on short-term effects of low levels of major ambient air pollution components. *Environ Health Perspect* 1995; 103: Suppl. 2, 3–13.
4. Touloumi G, Katsouyanni K, Zmirou D, *et al.* Short-term effects of ambient oxidant exposure on mortality: a combined analysis within the APHEA project. Air Poll-

ution and Health: a European Approach. *Am J Epidemiol* 1997; 146: 177–185.
5. Spix C, Anderson HR, Schwartz J, *et al*. Short-term effects of air pollution on hospital admissions for respiratory diseases in Europe: a quantitative summary of APHEA study results. *Arch Environ Health* 1998; 53: 54–64.
6. Schwartz J. Air pollution and daily mortality: a review and meta analysis. *Environ Res* 1994; 64: 36–52.
7. Anderson HR, Spix C, Medina S, *et al*. Air pollution and daily admissions for chronic obstructive pulmonary disease in 6 European cities: results from the APHEA project. *Eur Respir J* 1997; 10: 1064–1071.
8. Katsouyanni K, Touloumi G, Spix C, *et al*. Short-term effects of ambient sulphur dioxide and particulate matter on mortality in 12 European cities: results from time series data from the APHEA project. Air Pollution and Health: a European Approach. *BMJ* 1997; 314: 1658–1663.
9. Wordley J, Walters S, Ayres JG. Short term variations in hospital admissions and mortality and particulate air pollution. *Occup Environ Med* 1997; 54: 108–116.
10. Lebowitz MD. Epidemiological studies of the respiratory effects of air pollution. *Eur Respir J* 1996; 9: 1029–1054.
11. Ponce de Leon A, Anderson HR, Bland JM, Strachan DP, Bower J. Effects of air pollution on daily hospital admissions for respiratory disease in London between 1987–88. and 1991–92. *J Epidemiol Community Health* 1996; 50: Suppl. 1, s63–s70.
12. Anderson HR, Ponce de Leon A, Bland JM, Bower JS, Strachan DP. Air pollution and daily mortality in London: 1987–92. *BMJ* 1996; 312: 665–669.
13. Bates DV, Baker-Anderson M, Sizto R. Asthma attack periodicity: a study of hospital emergency visits in Vancouver. *Environ Res* 1990; 51: 51–70.
14. Cody RP, Weisel CP, Birnbaum G, Lioy PJ. The effect of ozone associated with summertime photochemical smog on the frequency of asthma visits to hospital emergency departments. *Environ Res* 1992; 58: 184–194.
15. Schwartz J, Slater D, Larson TV, Pierson WE, Koenig JQ. Particulate air pollution and hospital emergency room visits for asthma in Seattle. *Am Rev Respir Dis* 1993; 147: 826–831.
16. Castellsague J, Sunyer J, Saez M, Anto JM. Short-term association between air pollution and emergency room visits for asthma in Barcelona. *Thorax* 1995; 50: 1051–1056.
17. Buchdahl R, Parker A, Stebbings T, Babiker A. Association between air pollution and acute childhood wheezy episodes: prospective observational study. *BMJ* 1996; 312: 661–665.
18. Delfino RJ, Murphy-Moulton AM, Burnett RT, Brook JR, Becklake MR. Effects of air pollution on emergency room visits for respiratory illnesses in Montreal, Quebec. *Am J Respir Crit Care Med* 1997; 155: 568–576.
19. Stieb DM, Burnett RT, Beveridge RC, Brook JR. Association between ozone and asthma emergency department visits in Saint John, New Brunswick, Canada. *Environ Health Perspect* 1996; 104: 1354–1360.
20. Rossi OV, Kinnula VL, Tienari J, Huhti E. Association of severe asthma attacks with weather, pollen, and air pollutants. *Thorax* 1993; 48: 244–248.
21. Weisel CP, Cody RP, Lioy PJ. Relationship between summertime ambient ozone levels and emergency department visits for asthma in central New Jersey. *Environ Health Perspect* 1995; 103: 97–102.
22. Atomic Energy Authority Technology: National Environmental Technology Centre. Air Pollution in the UK: 1994. AEA/RAMP/200015001/1, 1997.
23. Buck SF. A method of estimation of missing values in multivariate data suitable for use with an electronic computer. *Royal Stat Soc, Services B* 1960; 22: 302–306.
24. Katsouyanni K, Schwartz J, Spix C, *et al*. Short term effects of air pollution on health: a European approach using epidemiologic time series data: the APHEA protocol. *J Epidemiol Community Health* 1996; 50: Suppl. 1, S12–S18.
25. Zeger SL. A regression model for time series of counts. *Biometrika* 1988; 75: 621–629.
26. Venables KM, Allitt U, Collier CG, *et al*. Thunderstorm-related asthma: the epidemic of 24–25th June 1994. *Clin Exp Allergy* 1997; 27: 725–736.
27. Tunnicliffe WS, Burge PS, Ayres JG. Effect of domestic concentrations of nitrogen dioxide on airway responses to inhaled allergen in asthmatic patients. *Lancet* 1994; 344: 1733–1736.
28. Poloniecki JD, Atkinson RW, Ponce de Leon A, Anderson HR. Daily time series for cardiovascular hospital admissions and previous day's air pollution in London, UK. *Occup Environ Med* 1997; 54: 535–540.