Air Pollution, Asthma Attacks, and Socioeconomic Deprivation: A Small-Area Case-Crossover Study

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With few exceptions, studies of short-term health effects of air pollution use pollutant concentrations that are averaged citywide as exposure indicators. They are thus prone to exposure misclassification and consequently to bias. Measurement of the relations between air pollution and health, generally and in specific populations, could be improved by employing more geographically precise exposure estimates. The authors investigated short-term relations between ambient air pollution estimated in small geographic areas (French census blocks) and asthma attacks in Strasbourg, France, in 2000–2005—in the general population and in populations with contrasting levels of socioeconomic deprivation. Emergency health-care networks provided data on 4,683 telephone calls made for asthma attacks. Deprivation was estimated using a block-level index constructed from census data. Hourly concentrations of particulate matter less than 10 µm in aerodynamic diameter (PM10), sulfur dioxide, nitrogen dioxide, and ozone were modeled by block with ADMS-Urban software. Adjusted case-crossover analyses showed that asthma calls were positively but not significantly associated with PM10 (for a 10-µg/m3 increase, odds ratio (OR) = 1.035, 95% confidence interval (CI): 0.997, 1.075), sulfur dioxide (OR = 1.056, 95% CI: 0.979, 1.139), and nitrogen dioxide (OR = 1.025, 95% CI: 0.990, 1.062). No association was observed for ozone (OR = 0.998, 95% CI: 0.965, 1.032). Socioeconomic deprivation had no significant influence on these relations.

The consequences of urban air pollution on human health have been clearly established (1), particularly for short-term effects such as mortality (2), cardiovascular events (3), or asthma attacks (4), which are triggered by air pollution within hours or days after exposure. Nevertheless, even for these well-established short-term effects, important questions remain. One of these questions concerns the precise characterization of the exposure-response relations, generally and in specific populations (1).

Abbreviations: CI, confidence interval; OR, odds ratio; PM10, particulate matter less than 10 µm in aerodynamic diameter; SAMU, Service d’Aide Médicale d’Urgence; SMA, Strasbourg metropolitan area.

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Most of our knowledge about the short-term effects of air pollution on health events (e.g., asthma attacks) comes from time series (5), case-crossover (6), and panel (4, 7) studies. With few exceptions (8–10), investigators in these studies average citywide ambient pollutant concentrations in order to estimate exposure, although these concentrations often vary spatially and strongly within cities (11). Failure to consider these spatial variations at the subcity level can lead to exposure misclassification and subsequent bias (12). Conversely, taking these spatial variations into account in studying the relations between air pollution and health would allow for more rigorous measurement of the magnitude of these relations (12). Jerrett et al. (11) recently labeled this topic a priority area for research.

Another such priority issue is identification of the populations most susceptible to air pollution and the precise measurement of exposure-response relations in these subsets (1, 13). Several studies show that some specific populations, such as children, the elderly, and people with chronic diseases, including people with diabetes and chronic obstructive pulmonary disease, are more susceptible to air pollution than the general population (1, 14). Some suspect that socioeconomic deprivation influences the relations between air pollution and health (15). Many investigators have tested this hypothesis with regard to mortality, and their overall results suggest the existence of larger relative risks for more deprived populations (16). Substantially fewer researchers have tested this hypothesis with regard to asthma attacks (9, 17–21), and the few that have done so have considered socioeconomic indicators measured at resolutions ranging from the individual level (18, 19) to the level of geographic residence areas of various sizes (9, 17, 19–21). Whether or not a socioeconomic indicator is an effect modifier, however, may well depend on the resolution at which it is measured (16). To our knowledge, only two studies have tested the influence of socioeconomic indicators measured at the level of small areas (Canadian enumeration areas (17) and US zip codes (9)) on the short-term relations between air pollution and asthma attacks. This topic thus merits further investigation.

Our objectives in this study were to investigate the short-term relations between air pollution estimated at the level of small subcity geographic areas and asthma attacks and to test the influence of socioeconomic deprivation, also measured at this level, on these relations.

**MATERIALS AND METHODS**

**Setting and statistical unit**

The setting of our study was the Strasbourg metropolitan area (SMA), an urban area of 450,000 inhabitants located in the Bas-Rhin district (or département, an administrative subdivision) of France. The statistical small-area unit used was the French census residential block (Ilots Regroupés pour l’Information Statistique), a submunicipal division created by the National Institute for Statistics and Economic Studies. This unit is the smallest geographic area in France for which socioeconomic information from the national census is available. The average number of inhabitants in each block is 2,000. The SMA is subdivided into 190 blocks, with areas ranging from 0.05 km² to 19.6 km² (median values of 0.45 km² for the entire SMA and 0.29 km² for the city center). Fifteen blocks covering a very small population (0.2 percent of the total population) were removed from the study because of concerns about confidentiality.

**Data**

**Asthma attacks.** The two mobile emergency and healthcare networks operating in the SMA (Service d’Aide Médicale d’Urgence (SAMU) and SOS Médecins) provided data about emergency telephone calls made to physicians for asthma attacks. The Bas-Rhin emergency medical services unit (SAMU 67) is a public service that coordinates prehospital emergency medical services. SOS Médecins of Strasbourg is a private service providing emergency general medical care.

This study included each call regarding an asthma attack that reached either SAMU or SOS Médecins from January 1, 2000, to December 31, 2005. The two databases were merged, with duplicates being excluded. Each call was geocoded to the census block where the patient was located at the time of the call, based on the postal address. Only 2 percent of the calls could not be geocoded; they were excluded from the analysis.

**Socioeconomic deprivation.** To analyze socioeconomic deprivation, we used a deprivation index constructed for the SMA census blocks by our research team. The detailed construction of this index has been described elsewhere (S. Havard, S. Deguen, J. Bodin, et al., French National School of Public Health, unpublished manuscript). Briefly, 52 socioeconomic variables covered by the National Institute for Statistics and Economic Studies 1999 census and reflecting different dimensions of deprivation (income, educational level, job, housing characteristics, ownership of basic goods, family structure, etc.) were selected. Principal-components analysis was used to synthesize information from these data. To construct a single numeric index for all of the blocks, we maximized the inertia of the first component by deleting all of the variables only weakly correlated with it and the variables with a contribution lower than the average. This allowed us to identify an axis, composed of 19 variables, that explained 66 percent of the inertia of the initial variables. This was used as a deprivation index.

**Air pollution.** Hourly ambient concentrations of particulate matter less than 10 μm in aerodynamic diameter (PM₁₀), nitrogen dioxide, sulfur dioxide, and ozone were modeled by the local air quality monitoring association (Association pour la Surveillance et l’Etude de la Pollution Atmosphérique en Alsace, Schiltigheim) for each block during the entire study period (22). Modeling was conducted with ADMS-Urban (23), a deterministic model that integrates emissions inventories, meteorologic data (supplied by Météo France, the French meteorologic service), and background pollution measurements as input parameters. Correlation coefficients for the modeled and effectively measured ambient concentrations were 0.73 for PM₁₀, 0.87 for nitrogen dioxide, 0.84 for ozone, and 0.06 for sulfur dioxide.
Confounding factors. Daily meteorologic variables (temperature, atmospheric pressure, and relative humidity) were obtained from Météo France, and daily pollen counts were obtained from the National Network of Aerobiological Surveillance (24). Weekly influenza case counts came from the Sentinelles network (25) of the National Institute of Health and Medical Research.

Statistical analyses

Associations between asthma calls and air pollution were assessed with case-crossover models (26), which are similar to case-control models, except that in the former, the subjects serve as both cases and controls, depending on when they are considered. The subject serves as a case on the day of the health event and a control on days without any health event. Control days were defined according to a monthly time-stratified design (27). For an asthma call occurring on a given weekday (e.g., Monday), control days were chosen as the same days of the week throughout the rest of the month (thus, three or four days; here, the other Mondays of the month). Conditional logistic regression was employed for analyses. The statistical significance of the odds ratios was tested by means of a two-sided \( \chi^2 \) test at the 5 percent level.

Base models. We first analyzed all calls, without differentiating them according to socioeconomic deprivation. Associations between asthma calls and ambient air pollution concentrations modeled by census block were estimated, adjusting for holidays, meteorologic variables (daily maximum temperature, maximum atmospheric pressure, and mean relative humidity), influenza epidemics, and pollen counts.

We tested the influence of air pollution indicators averaged on the day of the call (lag 0) and then averaged on the day of the call and the 1–5 previous days (lag 0–1 to 0–5). The daily air pollution indicator considered for \( \text{PM}_{10} \), nitrogen dioxide, and sulfur dioxide was the 24-hour average concentration, and for ozone it was the maximum daily value of the 8-hour moving average. The analysis for ozone considered only asthma calls made between April 1 and September 30 of each year, because of the very low concentrations of this pollutant in winter.

These associations were assessed for cases of all ages and then for groups of cases aged 0–19, 20–64, and >64 years. These groups were defined according to the guidelines of the French Data Protection Authority, to ensure the confidentiality of the health data geocoded by census blocks.

Testing the influence of deprivation. Interactions with socioeconomic deprivation were tested for the lag times for which the strongest associations were observed in the base models.

Deprivation was introduced first as a discrete variable. The SMA population was divided into five strata with contrasting deprivation levels, according to the quintiles of the distribution of the deprivation index. An odds ratio for the relation between asthma calls and pollution was estimated for each stratum. The heterogeneity of the odds ratios between these strata was assessed by means of a two-sided \( \chi^2 \) test at the 5 percent level (28). These analyses were conducted for the same age groups as in the base models.

In an alternative method, deprivation was introduced as a continuous variable. For that purpose, a case-crossover model was constructed for each of the 174 census blocks in which asthma calls occurred during the study period. The models did not converge in the census blocks with fewer than 11 asthma calls. These census blocks were treated as follows. Those adjoining neighboring census blocks of a similar deprivation level (differences of deprivation index values less than one 10th of the deprivation index scale) were merged with them. The deprivation index value attributed to each newly created geographic unit was the mean of the deprivation index values from the merged blocks, weighted by their respective population counts. Census blocks (\( n=26 \)) that bordered no neighboring census block of a similar deprivation level (differences of deprivation index values one 10th or more of the deprivation index scale) were excluded from these analyses.

The heterogeneity of the odds ratios estimated in the 136 geographic units so defined was assessed as described above (28). The influence of the deprivation level of the geographic units on the odds ratios was tested by linear regression (weighted by the inverse of the variance of these odds ratios) in both fixed- and random-effects models. These analyses were conducted for \( \text{PM}_{10} \), nitrogen dioxide, and sulfur dioxide for cases of all ages but were not feasible for ozone (April–September) and specific age groups, because of the small numbers of calls in most census blocks.

SAS software, version 9.1 (SAS Institute, Inc., Cary, North Carolina), was used to conduct these analyses.

RESULTS

Table 1 presents the distribution of asthma calls and air pollutant concentrations for the entire SMA and for the five socioeconomic deprivation strata. Overall, there were 4,677 asthma calls made during the study period. As we previously reported (29), the numbers of calls increased from the least deprived stratum to the most deprived, despite their similar population denominators. Elsewhere (22), we have published maps of ambient air pollutant concentrations averaged by census block across the SMA (for the period 2000–2005).

Table 2 presents the results of analyses by age group for these same lags. For \( \text{PM}_{10} \), as for sulfur dioxide (lag 0–1),
associations were stronger for people younger than age 20 years and older than age 64 years as compared with people of all ages. For nitrogen dioxide (lag 0), higher odds ratios were observed in people over age 64 years than in people of all ages. For ozone, positive associations were observed only in persons older than 64 years.

Testing the influence of deprivation

Deprivation as a discrete variable. Figure 2 presents the odds ratios for the five deprivation strata among people of all ages. The odds ratios show no clear trend according to deprivation level for any pollutant. We detected no

<table>
<thead>
<tr>
<th>Deprivation stratum*</th>
<th>Population (no.)</th>
<th>No. of emergency asthma calls</th>
<th>Air pollutant concentration (μm/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>All age groups</td>
<td>Age 0–19 years</td>
</tr>
<tr>
<td>Stratum 1</td>
<td>80,917</td>
<td>313</td>
<td>70</td>
</tr>
<tr>
<td>Stratum 2</td>
<td>92,534</td>
<td>784</td>
<td>159</td>
</tr>
<tr>
<td>Stratum 3</td>
<td>93,392</td>
<td>959</td>
<td>169</td>
</tr>
<tr>
<td>Stratum 4</td>
<td>105,367</td>
<td>1,243</td>
<td>226</td>
</tr>
<tr>
<td>Stratum 5</td>
<td>74,695</td>
<td>1,378</td>
<td>330</td>
</tr>
<tr>
<td>Overall</td>
<td>446,905</td>
<td>4,677</td>
<td>954</td>
</tr>
</tbody>
</table>

* Stratum 1 was the least deprived and stratum 5 the most deprived.
† PMₐ₀, particulate matter less than 10 μm in aerodynamic diameter.
‡ Concentrations were averaged for the period 2000–2005.
§ Maximum 8-hour daily concentrations, averaged for the summer months (April 1–September 30) of the period 2000–2005.

Figure 1. Log odds ratio for emergency asthma calls per 10-μg × m⁻³ increase in ambient pollutant concentrations, according to various lag times, Strasbourg, France, 2000–2005. Lag 0 is for pollutant concentrations averaged on the day of the call, lag 0–1 is for pollutant concentrations averaged for the day of the call and the previous day, and so on. A) particulate matter less than 10 μm in aerodynamic diameter; B) nitrogen dioxide; C) sulfur dioxide; D) ozone. Bars, 95% confidence interval.

heterogeneity of the odds ratios between strata. No clear trends by deprivation were observed in specific age groups (see Web figure 1, which is posted on the Journal’s website (http://aje.oxfordjournals.org/)).

Deprivation as a continuous variable. Significant heterogeneity ($p < 0.05$) was detected between the odds ratios estimated for the 136 geographic units for each of the three pollutants considered (PM$_{10}$, sulfur dioxide, and nitrogen dioxide). Heterogeneity remained significant after we discarded the highest and lowest 5 percent of the odds ratios in the distribution. Negative linear regression coefficients (table 3) suggested that the values of the odds ratios for these pollutants tended to decrease slightly from the least deprived geographic units to the most deprived (as also suggested by Web figure 2 (http://aje.oxfordjournals.org/)). The associations between the odds ratios and deprivation were not

| Lag* | PM$_{10}$ | Nitrogen dioxide | Sulfur dioxide | Ozone $|$ |
|------|----------|-----------------|---------------|---------|
| 0–1  | OR 1.035 | 1.025           | 1.056         | 0.998   |
|      | 95% CI 0.997, 1.075 | 0.990, 1.062 | 0.979, 1.139 | 0.965, 1.032 |
|      | p value 0.07 | 0.16 | 0.15 | 0.90 |

* Lag 0 is for pollutant concentrations averaged on the day of the emergency call; lag 0–1 is for averaged pollutant concentrations from the day of the call and the previous day.

† OR, odds ratio; CI, confidence interval; PM$_{10}$, particulate matter less than 10 $\mu$m in aerodynamic diameter.

‡ Odds ratio for a 10- $\mu$g $\cdot$ m$^{-3}$ increase in pollutant concentration, adjusted for temperature, relative humidity, atmospheric pressure, holidays, influenza epidemics, and pollen counts.

§ Estimated by means of a two-sided $\chi^2$ test.

Data for a study period extending from April 1 to September 30 of each year.

**TABLE 2. Odds ratios for the relation between emergency asthma calls and air pollutant concentrations, by age group and lag time, Strasbourg, France, 2000–2005**

<table>
<thead>
<tr>
<th>Lag*</th>
<th>All age groups</th>
<th>Age 0–19 years</th>
<th>Age 20–64 years</th>
<th>Age &gt;64 years</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–1</td>
<td>OR 1.047</td>
<td>1.020</td>
<td>1.049</td>
<td></td>
</tr>
<tr>
<td></td>
<td>95% CI 0.961, 1.141</td>
<td>0.964, 1.079</td>
<td>0.985, 1.116</td>
<td></td>
</tr>
<tr>
<td></td>
<td>p value 0.29</td>
<td>0.49</td>
<td>0.14</td>
<td></td>
</tr>
</tbody>
</table>

**FIGURE 2.** Log odds ratio for emergency asthma calls per 10- $\mu$g $\cdot$ m$^{-3}$ increase in ambient pollutant concentrations, according to stratum of socioeconomic deprivation, Strasbourg, France, 2000–2005. Stratum 1 was the least deprived, and stratum 5 was the most deprived. A) particulate matter less than 10 $\mu$m in aerodynamic diameter; B) nitrogen dioxide; C) sulfur dioxide; D) ozone. Bars, 95% confidence interval.
significant, however, regardless of the pollutant or the model (fixed or random effects).

**DISCUSSION**

In this study, emergency telephone calls made for asthma attacks were positively, though not significantly, associated with concentrations of PM$_{10}$, sulfur dioxide, and nitrogen dioxide as modeled by census blocks in the SMA. No association was observed for ozone. Overall, associations were higher among people younger than 20 years and older than 64 years. Socioeconomic deprivation measured by census block did not appear to influence these relations.

The daily exposure estimates we used were modeled for small areas and were geographically more precise than those usually employed to study short-term relations between air pollution and health (except for sulfur dioxide, for which spatial modeling was imprecise due to the very low concentrations observed). Compared with ambient concentrations averaged citywide, our exposure estimate probably reduced ecologic biases (12). In the present study, the exposure measurement attributed to each subject was the concentration estimated for the census block where the patient was located when the emergency network was called. However, we did not actually know whether each patient was in that same block during the hours to days preceding the call, and this obviously determines the extent to which our exposure measurement adequately reflected subjects’ true exposure.

This point matters mainly for subjects who are frequently away from the neighborhood they live in—principally the age group 20–64 years, who are globally characterized by mobility and autonomy and who usually work for a living (often outside their neighborhood of residence). Conversely, in general, the elderly rarely commute out of their neighborhoods of residence, and when they do so they generally travel shorter distances (30). Children also have more limited mobility than people aged 20–64 years (31) and generally attend the schools closest to their homes. These facts support the idea that our exposure measurement was more accurate for people younger than age 20 years and older than age 64 years. These subjects were more likely to have called the emergency networks from their neighborhood of residence (and thus have been geocoded in it). Moreover, for these subjects, the measurement of air pollution in the neighborhood of residence is more likely to provide an adequate reflection of exposure integrated over the days preceding the call than for more mobile subjects.

The ranges of the associations we found for the base models were similar to those reported in other studies of emergency telephone calls (32) and visits to hospital emergency departments (33) for asthma. Above all, the associations observed for PM$_{10}$ were very close to those reported in two meta-analyses of the associations between this pollutant and asthma symptoms (34, 35).

Small-area deprivation (introduced either as a discrete variable or as continuous variable) did not appear to influence the relations between ambient air pollution and asthma attacks. Of the six previous studies that investigated the influence of socioeconomic indicators on these relations (9, 17–21), five reported higher relative risks for populations with less advantageous socioeconomic characteristics (9, 17–19, 36). However, one of these studies found evidence of interaction according to the ecologic socioeconomic indicator considered and no interaction with the individual indicator (19). The sixth study reported slightly higher relative risks for the most deprived populations (21). Nevertheless, formal comparison of the results of these studies is difficult, as they focused on socioeconomic indicators measured at very heterogeneous resolutions (16).

Three of these studies focused on socioeconomic indicators measured at very coarse geographic resolutions. Lee et al. (36) and Kim et al. (19) focused on “gu” neighborhoods (neighborhoods of approximately 400,000 inhabitants) in the city of Seoul, South Korea, for children under age 16 years (36) and people of all ages (19), respectively. Overall, these studies reported higher relative risks for the relations between PM$_{10}$, sulfur dioxide, and nitrogen dioxide concentrations and asthma hospitalizations in the most deprived gu’s. Norris et al. (21), in Seattle, Washington, studied associations between the same pollutants and visits to emergency departments for asthma in children under age 19 years. They reported slightly lower relative risks for residents of the inner city (i.e., the most deprived areas).

Two other studies focused on individual socioeconomic indicators in people of all ages. Kim et al. (19), in Seoul, found that associations between PM$_{10}$ and visits to emergency

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**TABLE 3. Influence of socioeconomic deprivation introduced as a continuous variable (deprivation index) on the relation between air pollutant concentrations and emergency asthma calls, Strasbourg, France, 2000–2005**

<table>
<thead>
<tr>
<th></th>
<th>ORs for nitrogen dioxide</th>
<th>ORs for sulfur dioxide</th>
<th>ORs for PM$_{10}$*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>β†</td>
<td>p value‡</td>
<td>β</td>
</tr>
<tr>
<td>Fixed-effects model</td>
<td>-0.0027</td>
<td>0.49</td>
<td>-0.0103</td>
</tr>
<tr>
<td>Random-effects model</td>
<td>-0.0028</td>
<td>0.48</td>
<td>-0.0105</td>
</tr>
</tbody>
</table>

* OR, odds ratio; PM$_{10}$, particulate matter less than 10 μm in aerodynamic diameter.
† ORs for a $10\mu g\times m^{-3}$ increase in pollutant concentration, adjusted for temperature, relative humidity, atmospheric pressure, holidays, influenza epidemics, and pollen counts.
‡ Beta coefficient for regression of the OR values on the deprivation index.
§ Estimated by means of a two-sided $\chi^2$ test.
departments for asthma did not vary according to the annual amount of taxes paid to the national health insurance system. In contrast, in Los Angeles, California, Nauenberg and Basu (18) found that effects of PM$_{10}$ were greater among people with a less favorable health insurance status.

Lastly, two studies focused on socioeconomic indicators measured by small areas. Neidell (9) observed that carbon monoxide and ozone had a greater effect on asthma hospitalizations of Californian children aged 3–18 years in zip codes characterized by lower educational attainment. In that study, however, Neidell estimated associations between asthma hospitalizations and air pollutants on the basis of monthly indicators, which are inadequate for the study of short-term relations between these factors. Lin et al. (17) studied children aged 6–12 years in Vancouver, Canada (17), and reported higher associations between nitrogen dioxide, sulfur dioxide, and hospitalization for asthma in enumeration areas with lower household income levels.

The study by Lin et al. (17) was the most comparable to ours in design, but Lin et al. reported somewhat different results. The reasons for this are unclear. Pollutant concentrations were very similar in the two settings. Although the studies used different types of exposure measurements (pollutant concentrations averaged citywide in the study by Lin et al. (17) and modeled by census blocks in ours), this difference does not explain the variation in findings. Indeed, alternative analysis in the SMA with citywide average exposure measurements did not noticeably change our results regarding interactions with deprivation. Lack of statistical power appears to be a plausible explanation for the difference between our results and those of Lin et al. For comparable age groups (<20 years vs. 6–12 years), we had one quarter of the number of health events to analyze.

Another point is that findings of interaction with deprivation are not necessarily transposable from one setting to another: If small-area deprivation does exert an influence on the relations between air pollution and asthma attacks, it would most likely be mediated through “third” factors that in some (but perhaps not all) settings would be distributed unequally according to deprivation. Investigators in previous studies have reported that several factors thought to strengthen the associations between air pollution and asthma attacks are more prevalent in deprived neighborhoods than in well-off neighborhoods. Among these are smoking (both active and passive) (37), psychosocial stress (38), unhealthy eating habits (39), indoor allergens (40), inadequate compliance with instructions for use of antiinflammatory medication (41), and (plausibly a result of the above factors) a higher ratio of severe forms of asthma to moderate forms of asthma among subjects with asthma (42). Nevertheless, the distributions of these factors according to small-area deprivation may differ between study settings, because of, for example, differences in climate (affecting allergen proliferation), social and cultural characteristics of the local populations (influencing, among other things, eating and smoking habits), or the effectiveness of health systems (influencing prescription of and compliance with use of antiinflammatory medication).

Moreover, although we observed no interactions with small-area deprivation in the SMA, this does not rule out the existence here of interactions with socioeconomic factors measured at other resolutions (the individual, the household, or geographic areas more or less fine than the French census block), as the study by Kim et al. clearly illustrates (19). The use of multilevel models, which make it possible to assess more precisely the influence of factors (e.g., socioeconomic characteristics) measured at different resolutions, would be useful in studying this question further (15).

In conclusion, in the SMA, emergency calls for asthma attacks were positively (but not significantly) associated with PM$_{10}$, nitrogen dioxide, and sulfur dioxide concentrations modeled by small areas but were not associated with ozone concentrations, and small-area deprivation did not influence these associations. Nonetheless, discrepancies between these results and those of the study by Lin et al. (17) emphasize the need to investigate this question further in other study settings.

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