

Assessment of neighbourhood-level socioeconomic status as a modifier of air pollution–asthma associations among children in Atlanta

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ABSTRACT

Background A broad literature base provides evidence of association between air pollution and paediatric asthma. Socioeconomic status (SES) may modify these associations; however, previous studies have found inconsistent evidence regarding the role of SES.

Methods Effect modification of air pollution–paediatric asthma morbidity by multiple indicators of neighbourhood SES was examined in Atlanta, Georgia. Emergency department (ED) visit data were obtained for 5–18 years old with a diagnosis of asthma in 20-county Atlanta during 2002–2008. Daily ZIP Code Tabulation Area (ZCTA)-level concentrations of ozone, nitrogen dioxide, fine particulate matter and elemental carbon were estimated using ambient monitoring data and emissions-based chemical transport model simulations. Pollutant–asthma associations were estimated using a case-crossover approach, controlling for temporal trends and meteorology. Effect modification by ZCTA-level (neighbourhood) SES was examined via stratification.

Results We observed stronger air pollution–paediatric asthma associations in 'deprivation areas' (eg, $\geq 20\%$ of the ZCTA population living in poverty) compared with 'non-deprivation areas'. When stratifying analyses by quartiles of neighbourhood SES, ORs indicated stronger associations in the highest and lowest SES quartiles and weaker associations among the middle quartiles.

Conclusions Our results suggest that neighbourhood-level SES is a factor contributing vulnerability to air pollution-related paediatric asthma morbidity in Atlanta. Children living in low SES environments appear to be especially vulnerable given positive ORs and high underlying asthma ED rates. Inconsistent findings of effect modification among previous studies may be partially explained by choice of SES stratification criteria, and the use of multiplicative models combined with differing baseline risk across SES populations.

INTRODUCTION

Ambient air pollutants are well-documented causes of respiratory morbidity.^{1–2} A broad literature base provides evidence of association between asthma morbidity and diverse classes of air pollutants including ozone (O₃), nitrogen oxides, nitrogen dioxide (NO₂) and fine particulate matter <2.5 μm in diameter (PM_{2.5}); children are especially sensitive to the respiratory effects of air pollution due to physiological and behavior-related risk factors.^{3–4} Increasing evidence suggests that socioeconomic factors may further influence vulnerability to the health effects of air pollution among children.^{5–9}

Pathways through which low socioeconomic status (SES) may potentiate susceptibility to air pollution-related childhood asthma include higher exposures to outdoor and indoor air pollutants, greater psychosocial stress associated with the social environment (eg, neighbourhood poverty, neighbourhood crime levels, parental unemployment), and reduced access to local resources (eg, healthy food options, green space, healthcare access).^{10–12} However, toxicological studies focusing on such mechanisms are limited,^{13–15} and epidemiological research has provided inconsistent findings on whether individual factors and/or neighbourhood-level indicators of SES modify short-term air pollution–asthma associations. Notably, among population-based studies that have specifically examined modification of air pollution–asthma associations by neighbourhood SES, seven reported no evidence of effect modification,^{16–22} eight reported results suggesting stronger associations in lower SES populations^{23–30} and two reported stronger associations in high SES populations.^{29–31}

Differences in analytical choices by investigators may partially explain these inconsistent findings.³² While of similar study design, these studies assessed associations at different scales (region, county, ZIP code, census block and census block group), considered different indicators of SES and used different cut-points to stratify populations by neighbourhood SES (eg, median,^{25–31} tertile,²⁴ quartile²⁰ or quintile^{16–18–30} values of neighbourhood SES indicators). Among these studies, education, household income and poverty were most commonly used as indicators of neighbourhood SES; however, reported conclusions about effect modification by SES were contradictory between studies using similar indicators^{16–30–31–33} as well as between different SES indicators within the same study.^{28–31}

Previous work in Atlanta has identified strong associations between air pollution and paediatric asthma emergency department (ED) visits.^{34–37} Here, we present a comprehensive assessment of neighbourhood SES as a modifier of air pollution–paediatric asthma ED visit associations in Atlanta with a specific focus on the influence of SES indicator choice and stratification criteria on observed associations and interpretations.

METHODS

Asthma ED visit data

Patient-level ED visit data from 1 January 2002 to 31 December 2008 were acquired from hospitals

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located within the 20-county metropolitan area of Atlanta; ED visit data were acquired directly from hospitals (2002–2004 period) and the Georgia Hospital Association (2005–2008 period). Relevant data elements included admission date, International Classification of Diseases Ninth Revision (ICD-9) diagnosis codes, age and ZIP code of patient residence. ED visits for asthma were identified using primary and secondary ICD-9 diagnosis codes for asthma (493.0–493.9) or wheeze (786.07). We restricted our analyses to the paediatric population (5–18 years old) and to patients with a residential ZIP code (defined as US Postal Service delivery areas) located wholly or partially in 20-county Atlanta (232 ZIP codes).

To facilitate merging with air quality and census-based SES data, which were estimated for all Atlanta ZIP Code Tabulation Areas (ZCTAs, 2010 Census Bureau boundaries, created from census blocks to approximate ZIP codes), each ZIP code in the ED visit data set was assigned to one of 191 ZCTAs. Assignments were accomplished by matching ZIP-to-ZCTA ID numbers and verifying locations of ZIP code centroids via ZCTA map shapefiles in ArcGIS. ZIP code change reports facilitated ZCTA assignments for 31 ZIP codes that were altered or eliminated within the study period. ED data were excluded from 10 ZCTAs with no SES data (eg, businesses, university campuses).

Air quality data

Daily concentrations of ambient air pollutants for each ZCTA in 20-county Atlanta were estimated from 1 January 2002 to 31 December 2008. Pollutant concentration estimates were obtained by fusing observational data from available network monitors with pollutant concentration simulations from the Community Multi-Scale Air Quality (CMAQ) emissions-based chemical transport model at 12×12 km grids over Atlanta.³⁸ Pollution concentrations were estimated for each ZCTA by determining the fraction of a ZCTA's area within each 12×12 km grid cell and area weighting the observation-simulation data fusion estimates to get the ZCTA-specific value. Online supplementary figure S1 illustrates the Atlanta study area with 12×12 km pollution estimate grid cells overlaid onto ZCTAs. The following pollutants and daily temporal metrics were evaluated: 1-hour maximum NO₂; 8-hour maximum O₃; 24-hour average PM_{2.5} and 24-hour average major PM_{2.5} component, elemental carbon (EC). Daily meteorological data measured at the Atlanta Hartsfield International Airport were acquired from the National Climatic Data Center.

Neighbourhood-level socioeconomic data

Estimates of ZCTA-level SES were obtained from the 2000 US Census long form and the American Community Survey (ACS) 5-year (2007–2011) summary file, all normalised to 2010 ZCTA borders ('The Time-Series Research Package', GeoLytics, East Brunswick, New Jersey, USA 2013). To examine the influence of SES indicator choice on air pollution health associations, we evaluated six single indicators that included education, household type, income, poverty, transportation and unemployment socioeconomic domains (table 1). In addition, to capture the multifaceted nature of neighbourhood SES, we included two composite indices of material and social deprivation, the Neighborhood Deprivation Index (NDI)³⁹ and the Townsend Index⁴⁰ (table 1). We used linear interpolation (by year) between Census 2000 and ACS (2007–2011) to obtain yearly SES indicators and account for possible changes in neighbourhood-level SES over the 2002–2008 study period.

To examine the influence of SES stratification criteria on observed effect modification, we categorised ZCTAs based on 'deprivation area' status (ie, 'poverty areas' were defined as ≥20% of the population living below the federal poverty line, and 'under-educated areas' were defined as ≥25% of the adult population (≥25 years old) with less than a 12th grade education)^{12 39} and also based on several a priori cut-points of continuous ZCTA-level SES data (above/below the 90th centile, above/below the median and quartiles).

Statistical analyses

Associations between 3-day moving average (lag days 0–2) pollutant concentrations and paediatric asthma ED visits were assessed using conditional logistic regression in single-pollutant case-crossover models, matching on ZCTA of patient residence, year, month and day of week of the ED visit. By design, the case-crossover approach controls for individual-level time-invariant confounders since case and control days are compared for the same person. Models included additional control for time-varying factors: indicator variables for season (four levels); periods of hospital participation and holidays; cubic polynomials for 3-day moving average (lags 0–2) maximum temperature and mean dew point; interaction terms between season and maximum temperature; and a cubic spline on day of year (5° of freedom) to control smoothly for recurrent within-window seasonal trends. See online supplementary appendix 1 for the full conditional logistic regression equation.

To evaluate effect measure modification, models were stratified by SES categories. ORs and 95% CIs are presented for associations between air pollution and paediatric asthma ED visits for each SES stratum, scaled to each pollutant's approximate IQR. Difference between strata-specific ORs was tested in pairwise comparisons. To evaluate the robustness of results to different model specifications, we performed a series of sensitivity analyses, described in more detail in online supplementary appendix 2. All analyses were performed using SAS V9.4 (SAS Institute, Cary, North Carolina, USA).

RESULTS

Descriptive analysis results: ED visits and air pollution data

Our ED visit database included 1 624 572 total ED visits of children aged 5–18 years, with 128 758 ED visits for asthma during the years 2002–2008 in 20-county Atlanta (191 ZCTAs). Online supplementary table S1 presents descriptive statistics for the ED visit database, and online supplementary table S2 presents descriptive statistics and Spearman correlations for air pollutants.

Epidemiological results: air pollution–asthma associations

Overall associations (per IQR) between short-term exposure to ambient air pollutants and paediatric asthma are reported in table 2. Ozone exhibited the highest overall association with paediatric asthma, followed by PM_{2.5}, and EC.

Descriptive analysis results: socioeconomic subpopulation characterisation

Table 1 presents summary statistics for each SES indicator, and online supplementary table S3 presents Spearman correlations between indicators. In summary, we found that socioeconomic composition varied widely across the 191 Atlanta ZCTAs (eg, per cent living below the poverty line varied from 1.66% to 45.9%) and we observed moderate-to-high correlations between most SES indicators (see online supplementary table S3), suggesting these indicators describe similar SES constructs and have

Table 1 Indicators of neighbourhood socioeconomic status, indicator descriptions and summary statistics across Atlanta metropolitan area neighbourhoods* (n=191 ZCTAs), Atlanta, Georgia, 2002–2008

SES domain	SES indicator description	Census/ACS variable code†	Frequency of ZCTA days‡	Min	p25‡	p50‡	p75‡	Max
1. Education	1a. Per cent <12th grade: percentage (%) of adult population (≥25 years) with <12th grade education	P37/B15		0.08	9.4	14.8	21.5	39.1
	1b. Undereducated area (yes/no): ZCTA with ≥25% of the adult population (≥25 years) with <12th grade education	P37/B15	Yes: 15.1% No: 84.9%					
2. Household	2a. Median home value (\$)	H76/B25		76 153	127 548	157 541	208 800	774 900
	2b. Per cent renter occupied HH	H07/B25		5.27	17.7	25.4	42.8	92.1
	2c. Per cent female headed HH	P01/B11		0.69	9.1	12.9	18.5	45.0
	2d. Per cent HH living in crowding	H02/B25		0	1.5	2.5	4.0	17.5
3. Income	3a. Median income	P53/B19		20 397	44 186	53 663	66 846	130 270
	3b. Per cent HH on public assistance	P06/B19		0	1.0	1.5	2.3	9.13
4. Poverty	4a. Per cent HH living below the federal poverty line	P87/B17		1.66	7.6	11.4	16.2	45.9
	4b. Poverty area (yes/no): ZCTA with ≥20% of HH living below the federal poverty line	P87/B17	Yes: 15.6% No: 84.4%					
5. Transportation	5a. Per cent HH that do not own or lease a car	H44/B25		0.09	2.5	4.2	7.4	43.8
6. Unemployment	6a. Per cent civilian population (≥16 years) unemployed	P43/B23		0.84	5.8	8.0	10.9	50.6
7. Composite indices	7a. NDI: principle component analysis of 8 indicators: per cent HH low income (<\$30 000), per cent males not in management, and indicators 1a, 2c, 2d, 3b, 4a, 6a (above). Z-score standardised			−2.00	−0.8	−0.1	0.6	3.41
	7b. Townsend Index: summary metric that combines data on indicators 2b, 2d, 5a, 6a (above). Z-score standardised			−4.41	−2.3	−0.8	1.3	16.6

Bold typeface indicates variables evaluated for effect modification in stratified models.

*Neighbourhoods are identified by ZCTA boundaries.

†Census/ACS variable codes identify which variable groups were used to create indicators of neighbourhood SES within Census 2000 and ACS 2007–2011 data tables.

‡SES frequencies and percentiles based on distribution of the yearly values (2002–2008) across 191 ZCTAs in Atlanta (n=488 387 ZCTA days).

ACS, American Community Survey (2007–2011); Census, Census 2000; HH, households; Max, maximum value; Min, minimum value; NDI, Neighborhood Deprivation Index; p25, 25th percentile; p50, 50th percentile; p75, 75th percentile; SES, socioeconomic status; ZCTA, Zip Code Tabulation Area.

Table 2 ORs from case-crossover analyses between 3-day moving average ZCTA-level pollutant concentrations (per IQR increase) and asthma-related emergency department visits in Atlanta, Georgia, 2002–2008

Air pollutant	IQR	OR	95% CI	p Value*
O ₃	25 ppb	1.073	1.043 to 1.104	<0.001
NO ₂	15 ppb	1.012	0.994 to 1.030	0.18
PM _{2.5}	10 µg/m ³	1.027	1.012 to 1.043	<0.001
EC	0.5 µg/m ³	1.013	1.005 to 1.022	0.002

*Two-sided p value.

EC, elemental carbon fraction of PM_{2.5}; NO₂, nitrogen dioxide; O₃, ozone; PM_{2.5}, particulate matter <2.5 µm in diameter (fine particulate matter); ZCTA, Zip Code Tabulation Area.

similar spatial patterning. Online supplementary appendix 3 and appendix table A1 provide further characterisation of air quality and ED visits by neighbourhood SES. Online supplementary appendix figures A1–A3 illustrate observed spatial patterning between pollutant concentrations and neighbourhood SES.

Epidemiological results: effect measure modification

Analyses stratified by deprivation area status (areas of extremely low SES were characterised as ‘poverty areas’ or ‘undereducated areas’) suggested stronger magnitudes of association in deprivation areas compared with areas of higher SES (non-deprivation areas). Differences in observed associations by deprivation area

status were more apparent for ozone and the traffic-related pollutants (NO₂ and EC) than for PM_{2.5} (table 3). As an alternative definition of extremely low SES, we stratified neighbourhoods using the 90th centiles of continuous SES variables (or 10th centiles for median income and median home value) as the categorical cut-points. In general, results from the 90th/10th centile analysis were similar to the deprivation area results, as we observed stronger effect estimates in extremely low SES neighbourhoods compared with areas of higher SES (table 3). However, this pattern of effect modification was only consistent for NO₂, across all SES indicators. In most analyses, differences in ORs between strata were not statistically significant due to the wide CIs in the low SES strata resulting from low ED visit counts.

To assess the influence of SES stratification criteria on observed effect modification, we compared results of analyses stratified by deprivation area and 90th/10th centiles (table 3) to results of analyses stratified using the median (see online supplementary table S4) or quartiles as cut-points (see online supplementary table S5). Figure 1 presents representative findings from our cut-point comparison for per cent <12th grade education and per cent below the poverty line for NO₂ and PM_{2.5}.

As figure 1A shows, when using per cent <12th grade education to indicate neighbourhood SES, patterns of effect modification differed by pollutant (NO₂ and PM_{2.5}), but patterns were similar across the different stratification criteria (undereducated area, or using cut-points based on the 90th/10th centile, median or quartiles). Specifically, we observed stronger associations between NO₂ and asthma ED visits in low SES compared with

Table 3 ORs from case-crossover models stratified by deprivation area and 90th/10th centiles for IQR increases in 3-day moving average ZCTA-level pollutant concentrations and asthma emergency department visits in Atlanta, Georgia, 2002–2008

SES indicator	Stratification criteria	SES strata*	#Asthma ED visits	O ₃ (per 25 ppb)		NO ₂ (per 15 ppb)		PM _{2.5} (per 10 µg/m ³)		EC (per 0.5 µg/m ³)	
				OR	95% CI	OR	95% CI	OR	95% CI	OR	95% CI
Stratification by deprivation area											
UA	<25% <12th gradet	High†	111 446	1.067	1.035 to 1.099	1.008	0.989 to 1.028	1.027	1.011 to 1.044	1.012	1.003 to 1.021
	≥25% <12th grade	Low	17 312	1.116	1.033 to 1.207	1.038	0.990 to 1.088	1.023	0.983 to 1.066	1.020	0.999 to 1.042
PA	<20% below poverty†	High†	99 069	1.067	1.034 to 1.102	0.999	0.979 to 1.022	1.020	1.003 to 1.038	1.010	0.999 to 1.021
	≥20% below poverty	Low	29 689	1.099	1.034 to 1.168	1.038‡	1.003 to 1.074	1.048	1.017 to 1.081	1.018	1.004 to 1.033
Stratification by 90th (or 10th) centile											
Per cent <12th grade	≤90th centile (27.3%)†	High†	117 765	1.067	1.036 to 1.099	1.010	0.991 to 1.029	1.028	1.012 to 1.044	1.013	1.004 to 1.022
	>90th centile (27.3%)	Low	10 993	1.134	1.030 to 1.248	1.029	0.969 to 1.093	1.020	0.969 to 1.074	1.015	0.990 to 1.041
Median home value	≥10th centile (\$109 011)†	High†	118 110	1.074	1.042 to 1.106	1.009	0.990 to 1.028	1.028	1.012 to 1.044	1.012	1.003 to 1.021
	<10th centile (\$109 011)	Low	10 617	1.068	0.970 to 1.175	1.038	0.980 to 1.100	1.011	0.960 to 1.065	1.023	0.997 to 1.050
Median income	≥10th centile (\$36 680)†	High†	109 786	1.074	1.042 to 1.107	1.002	0.982 to 1.023	1.023	1.007 to 1.040	1.010	1.001 to 1.020
	<10th centile (\$36 680)†	Low	18 972	1.070	0.993 to 1.152	1.050‡	1.006 to 1.095	1.049	1.010 to 1.090	1.023	1.005 to 1.041
Per cent living in poverty	≤90th centile (22.5%)†	High†	107 547	1.069	1.037 to 1.102	1.005	0.984 to 1.025	1.023	1.006 to 1.040	1.013	1.003 to 1.022
	>90th centile (22.5%)	Low	21 211	1.103	1.026 to 1.187	1.032	0.992 to 1.074	1.048	1.011 to 1.086	1.014	0.998 to 1.031
Per cent HH no vehicle	≤90th centile (14.1%)†	High†	104 255	1.086	1.052 to 1.120	1.004	0.983 to 1.026	1.023	1.006 to 1.040	1.011	1.001 to 1.021
	>90th centile (14.1%)	Low	24 503	1.022	0.956 to 1.091	1.028	0.991 to 1.067	1.044	1.010 to 1.079	1.018	1.002 to 1.034
Per cent unemployed	≤90th centile (14.1%)†	High†	104 594	1.078	1.045 to 1.112	1.008	0.988 to 1.029	1.026	1.009 to 1.043	1.016	1.006 to 1.026
	>90th centile (14.1%)	Low	24 158	1.057	0.987 to 1.132	1.018	0.980 to 1.058	1.035	1.000 to 1.071	1.004	0.988 to 1.021
NDI	≤90th centile (1.3)†	High†	105 329	1.073	1.040 to 1.106	1.001	0.980 to 1.022	1.023	1.006 to 1.040	1.012	1.002 to 1.022
	>90th centile (1.3)	Low	23 429	1.076	1.006 to 1.151	1.037	0.999 to 1.077	1.043	1.008 to 1.079	1.016	1.000 to 1.032
Townsend Index	≤90th centile (4.4)†	High†	105 873	1.077	1.044 to 1.111	1.003	0.982 to 1.024	1.025	1.009 to 1.042	1.013	1.003 to 1.023
	>90th centile (4.4)	Low	22 885	1.057	0.987 to 1.131	1.038	1.000 to 1.079	1.033	0.998 to 1.069	1.014	0.998 to 1.030

Bold typeface indicates stratum specific CIs that do not include the null value.

*Column denotes which stratum was designated as 'high (SES)' and 'low (SES)'.

†Indicates referent group used in assessment of heterogeneity of stratum-specific ORs (ie, referent strata is 'high (SES)').

‡Indicates significant difference (one-sided $p < 0.05$) from referent group. Heterogeneity between stratum-specific ORs was tested in pairwise comparisons by dividing the difference in log OR by the square root of the sum of the variances and computing a Z-statistic.

EC, elemental carbon fraction of PM_{2.5}; ED, emergency department; HH, households; NDI, Neighborhood Deprivation Index; NO₂, nitrogen dioxide; O₃, ozone; PA, poverty area; PM_{2.5}, particulate matter <2.5 µm in diameter (fine particulate matter); SES, socioeconomic status; UA, undereducated area; ZCTA, Zip Code Tabulation Area.

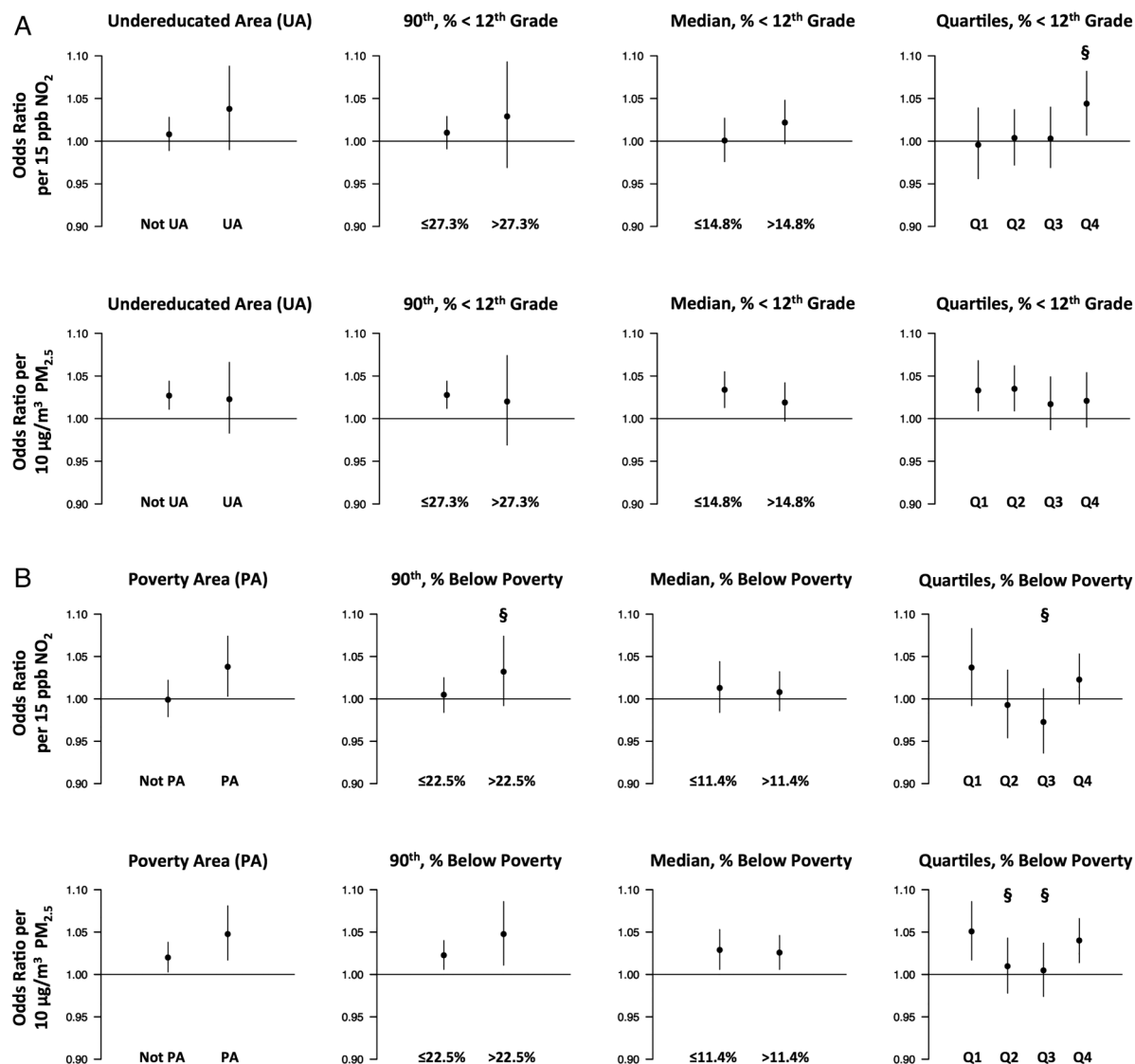


Figure 1 Comparison of alternative stratification criteria in relation to observed effect modification of associations between asthma ED visits and 3-day moving average ZCTA-level pollutant concentrations in Atlanta, Georgia (2002–2008). ORs and 95% CIs per IQR increase are shown for (A) associations between asthma ED visits, NO_2 and $\text{PM}_{2.5}$, stratified by undereducated area, or by categories defined by cut-points based on the 90th centile, median and quartile values of per cent <12th grade education; (B) associations between asthma ED visits, NO_2 and $\text{PM}_{2.5}$, stratified by poverty area, or by categories defined by cut-points based on the 90th centile, median and quartile values of per cent below poverty. IQR values are as follows: $\text{NO}_2=15$ ppb and $\text{PM}_{2.5}=10$ $\mu\text{g}/\text{m}^3$. Quartile values of per cent <12th grade education: Q1<9.4%; Q2 $\geq$ 9.4% to <14.8%; Q3 $\geq$ 14.8% to <21.5%; Q4 $\geq$ 21.5%. Quartile values of per cent below poverty: Q1<7.6%; Q2 $\geq$ 7.6% to <11.4%; Q3 $\geq$ 11.4% to <16.2%; Q4 $\geq$ 16.2%. § Indicates significant difference (one-sided $p<0.05$) from referent group. Heterogeneity between strata-specific ORs was tested in pairwise comparisons by dividing the difference in log OR by the square root of the sum of the variances and computing a Z-statistic. ED, emergency department; NO_2 , nitrogen dioxide; per cent <12th grade, per cent of persons (25 and older) with <12th grade education; per cent below poverty, per cent of households living below the federal poverty line; $\text{PM}_{2.5}$, particulate matter <2.5 μm in diameter (fine particulate matter); ZCTA, Zip Code Tabulation Area.

high SES strata for all stratification criteria based on per cent <12th grade education; however, significant differences between strata-specific ORs were only observed in the quartile analysis (figure 1A). In contrast, for $\text{PM}_{2.5}$, slightly weaker associations with asthma ED visits were observed in low SES strata compared with high SES strata; differences between observed ORs across strata were not significant (figure 1A). Similar patterns of effect modification (and differences between pollutants) were found when stratifying by median home value (see online supplementary table S5).

When using per cent below the poverty line to indicate neighbourhood SES, patterns of effect modification differed across the different stratification criteria, but were generally consistent

across pollutants (figure 1B). In particular, we observed less pronounced patterns of effect modification when stratifying at the median compared with deprivation area or 90th centile stratification criteria for NO_2 and $\text{PM}_{2.5}$ (figure 1B). Stratifying by quartile values of per cent below poverty provided insight into these findings, as ORs across strata followed a U-shaped pattern, indicating stronger magnitudes of air pollution–paediatric asthma associations in the highest and lowest SES quartiles (figure 1B). Similar U-shaped effect modification was consistently observed for all pollutants for several other indicators (median income, NDI, Townsend Index) when stratifying by quartiles (see online supplementary table S5). In sensitivity analyses, patterns of effect modification were similar by SES indicator,

stratification criterion and pollutant to those observed in main analyses (see online supplementary appendix 2).

DISCUSSION

In this analysis of over 128 000 ED visits for paediatric asthma, we assessed neighbourhood SES as a potential effect modifier of acute air pollution–paediatric asthma associations over a 7-year period. Our comprehensive assessment considered multiple indicators of SES as well as multiple ways to categorise socioeconomic strata.

In overall models, we observed statistically significant associations between air pollutants and paediatric asthma, particularly for 3-day average concentrations of O_3 . When assessing the impact of living in a neighbourhood characterised by extremely low SES, we generally observed stronger associations between air pollution and paediatric asthma in extremely low SES neighbourhoods compared with areas of higher SES. Our results were particularly consistent across SES indicators when evaluating NO_2 , a traffic-related pollutant; these findings support similar results in the literature and a common hypothesis in the health disparities field that low SES environments confer vulnerability to a variety of health outcomes, including traffic pollution-related paediatric asthma morbidity.^{6 8}

Patterns of effect modification varied with the modelling operationalisation of SES. In some cases, effect modification of air pollution–asthma associations differed depending on our SES indicator choice and stratification approach. Notably, when indicating SES by per cent <12th grade education and median home value, we consistently observed stronger associations between asthma and traffic-related pollutants (NO_2 and EC) in low SES strata, for all cut-point definitions. Conversely, for other SES indicators (eg, per cent below poverty), results from analyses stratified by median cut-points contradicted results from deprivation area analyses (figure 1B). Defining strata more finely through quartile values of neighbourhood SES provided some insight into the differences observed. In particular, for several SES indicators (median income, per cent below poverty, NDI, Townsend Index) we observed a distinct U-shaped pattern in OR estimates across quartiles, with stronger associations in high and low SES quartiles and weaker associations in the middle quartiles (figure 1B, online supplementary table S5). This pattern of effect modification could be responsible for the null and unanticipated patterns observed with median cut-points. Complex spatial patterning of neighbourhood SES (eg, location being an important determinant of home value), as well as the possibility that single measures of SES are poor proxies for nuanced socioeconomic environments, may partially account for the different patterns of effect modification observed by SES indicator and pollutants. In our assessment, SES indicators based on per cent below poverty and the NDI provided the most consistent results across pollutants for the stratification criteria we examined.

Although a U-shaped pattern of effect modification was consistently observed across multiple SES indicators and pollutants, it is important to consider the interpretation of our findings with respect to the mathematical scale of effect measures. Modelling of air pollution health effects on a multiplicative scale is common;^{41 42} however, the true nature of the effect of air pollution on asthma ED visits may be additive. In this scenario, it is possible that low baseline risk in the highest SES strata could explain apparent stronger relative effects of air pollution. If air pollution increases the risk of ED visits on an absolute (ie, additive) scale, and the highest SES strata has lower baseline risk compared with the lowest SES strata (an assumption supported

by the literature⁴³ and our data (figure 2)), we would expect an OR from a multiplicative model to appear larger for the population with the lowest baseline risk (ie, the highest SES strata). However, assuming strict additivity, we would expect the high baseline risk in the lowest SES strata to result in weaker apparent effects on a multiplicative scale compared with the highest SES strata. Instead, in many analyses, we consistently observed strong, positive associations in the highest and lowest SES strata. It is therefore possible that higher ORs in high SES strata reflect their lower baseline risk, whereas higher ORs in low SES strata reflect supra-additive effects of SES and air pollution.

Synthesising the results from our deprivation area and quartile analyses, and taking into account the high baseline risk in Atlanta's lowest SES populations (figure 2), we believe the data support our main conclusion that children living in low SES environments in Atlanta suffer from a higher burden of asthma due to air pollution compared with their counterparts living in wealthier SES environments.

Our study had several limitations that should be acknowledged. First, differences in ORs across strata were small for some analyses (eg, ORs for EC stratified by increasing quartile of per cent below poverty: 1.029, 1.004, 1.001, 1.016); while statistically different, these small ORs indicate that the contribution of air pollution to asthma ED visits may be small relative to other risk factors. Second, by assessing neighbourhood SES effects at the ZCTA level, we assumed that ZCTA boundaries are relevant socioeconomic environments with regard to air pollution vulnerability. However, other scales may also be relevant, and the relevance of specific scales may vary by geographical location due to regional patterns of urban development.⁴⁴ Third, our study used 12×12 km pollution grids (the spatial resolution at which CMAQ was run) to estimate daily ZCTA-level air pollution concentrations. A 12×12 km grid is a relatively large area to assess exposure to air pollutants, especially for spatiotemporally variable primary pollutants (NO_2 and EC). For these pollutants, concentrations vary over small scales due to influences of local traffic sources. The possibility of differential exposure error between SES strata could affect observed patterns of effect modification. Our exposure assignment approach, based on modelled ZCTA-specific pollution estimates, was chosen to minimise the possibility of such differential error compared with common approaches in time-series studies which typically assign daily pollution values to an entire study area based on central monitor estimates. Finally, although we had large numbers of daily ED visits overall, we had low power to detect associations with air pollution in some socioeconomic strata.

Overall, our findings suggest that neighbourhood-level SES is a factor contributing vulnerability to air pollution-related paediatric asthma morbidity in Atlanta, and this study provides important insights on how the choice of neighbourhood SES indicator and stratification criteria influences results. Published studies investigating SES effect modification of air pollution–health associations commonly define strata based on median cut-points of continuous SES.^{25 27 30 31} Given our current findings, it is possible that stratifying at the median may be partially responsible for the inconsistent reports in the literature of effect modification by neighbourhood SES on air pollution–health associations. Inconsistent findings of effect modification may also be due to the use of multiplicative models and differing baseline risk across SES populations. We recommend evaluating multiple indicators of SES, using multiple stratification criteria including consideration of strata indicating extremely low SES environments, and estimating baseline risks across diverse

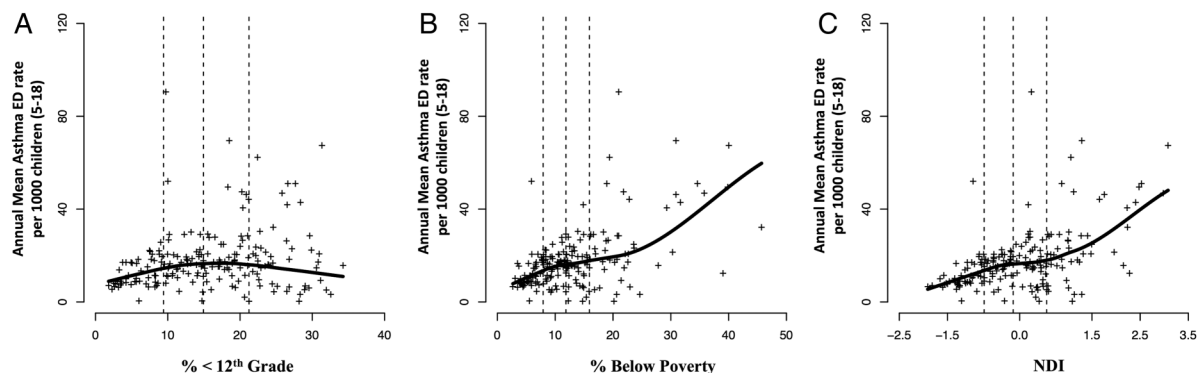


Figure 2 Annual mean ED visit rates of paediatric asthma by neighbourhood SES for each ZCTA in Atlanta, Georgia (2002–2008). Asthma ED rates are reported per 1000 children (5–18 years old) and were calculated for each ZCTA by dividing the annual total number of asthma ED visits by annual estimates of the 5–18 years old population. Annual ED rates were then averaged over the entire study period (2002–2008). ED visit rates for each ZCTA are represented by the '+' symbol and shown in (A) by percentage (%) of the adult population (≥ 25 years old) with less than a 12th grade education (% <12th grade), in (B) by per cent of households living below the federal poverty line (% below poverty), and in (C) by the NDI. The solid black line represents local polynomial regression using weighted least squares to fit a line through the data. The dotted grey lines represent the first, second and third quartile values of each SES indicator. In each panel, neighbourhood SES decreases from left to right. ED, emergency department; NDI, Neighborhood Deprivation Index; SES, socioeconomic status; ZCTA, Zip Code Tabulation Area.

What is already known on this subject

- Ambient air pollutants are well-documented causes of respiratory morbidity.
- Studies investigating effect modification of acute air pollution–health associations by neighbourhood socioeconomic status have reported contradictory results.
- The underlying reasons for contradictory findings regarding modification of air pollution–health associations by neighbourhood socioeconomic status are not well understood, and comprehensive investigations are needed to determine the impact of analytical choices on results and interpretations.

What this study adds

- We conducted a comprehensive examination of effect modification of associations between air pollution and paediatric asthma morbidity by six single and two composite indicators of neighbourhood socioeconomic status with a specific focus on the influence of socioeconomic status indicator choice and stratification criteria on observed associations.
- In multiplicative models, we consistently observed a U-shaped pattern of effect modification when stratifying our analyses by quartile values of neighbourhood socioeconomic status (ie, positive associations observed in the highest and lowest socioeconomic strata and null associations in the middle strata).
- Method of socioeconomic status categorisation (eg, above/below the median vs quartiles) and differences in baseline risk of asthma events across socioeconomic subpopulations combined with the traditional use of multiplicative models may partially explain inconsistent reports of effect modification of air pollution–health associations by neighbourhood socioeconomic status in the literature.

socioeconomic populations. Going forward, it will be critical to explore additive interaction models and whether diverse study areas have similar patterns of effect modification across multiple SES indicators and categorisation criteria.

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Data sharing statement Data used in this study include data on emergency department visits, air pollution concentrations and socioeconomic data at the ZIP code level in Atlanta. Data use agreements with participating hospitals and the Georgia Hospital Association prevent sharing of the emergency department visit data outside the research team. Air pollution data were generated by the Georgia Institute of Technology research team using a fusion of publicly available air monitoring data and modelled air pollution estimates; the outputs are not currently publicly available. Finally, we used socioeconomic data from Census 2000 and the American Community Survey, which are already publicly available through various forums.

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