Ambient pollution and respiratory outcomes among schoolchildren in Durban, South Africa

R N Naidoo,[1] MB ChB, PhD; **T G Robins**,[2] MD, MPH; **S Batterman**,[2] PhD; **G Mentz**,[2] PhD; **C Jack**,[1] MSc

[1] *Discipline of Occupational and Environmental Health, School of Nursing and Public Health, College of Health Sciences, University of KwaZulu-Natal, Durban, South Africa*
[2] *Department of Environmental Health Sciences, School of Public Health, University of Michigan, Ann Arbor, Michigan, USA*

Corresponding author: *R N Naidoo (naidoon@ukzn.ac.za)*

Objective. To examine associations between ambient air pollutants and respiratory outcomes among schoolchildren in Durban, South Africa.
Methods. Primary schools from within each of seven communities in two regions of Durban (the highly industrialised south compared with the non-industrial north) were selected. Children from randomly selected grade 4 classrooms were invited to participate. Standardised interviews, spirometry, methacholine challenge testing and skin-prick testing were conducted. Particulate matter (PM), sulphur dioxide (SO_2) and carbon monoxide were monitored at each school, while nitrogen oxides (NO_x) and other pollutants were monitored at other sites.
Results. SO_2 was significantly higher in the south than in the north, while PM concentrations were similar across the city. The prevalence of symptoms consistent with asthma of any severity was 32.1%. Covariate-adjusted prevalences were higher among children from schools in the south than among those from the north for persistent asthma (12.2% v. 9.6 %) and for marked airway hyperreactivity (AHR) (8.1% v. 2.8%), while SO_2 resulted in a twofold increased risk of marked AHR (95% confidence interval 0.98 - 4.66; p=0.056).
Conclusions. Schoolchildren from industrially exposed communities experienced higher covariate-adjusted prevalences of persistent asthma and marked AHR than children from communities distant from industrial sources. Our findings are strongly suggestive of industrial pollution-related adverse respiratory health effects among these children.

S Afr J CH 2013;7(4):127-134. DOI:10.7196/SAJCH.598

A substantial body of literature provides evidence for the adverse effects of ambient pollution on respiratory health, particularly among children with pre-existing respiratory disease.[1] Increased ambient air pollution levels have been reported to precipitate symptoms of asthma.[2] Against the reported background of a worldwide increasing prevalence of childhood asthma,[3] environmental pollution has received scrutiny as a cause of increased respiratory morbidity.

The study area, south Durban, South Africa, is recognised as one of the most highly industrialised and heavily polluted areas in southern Africa.[4] Residential and industrial areas mingle in the region, which has a population of over 400 000.[5] A previous study reported a high prevalence of asthma among children at a primary school in south Durban, with pollutants having a significant association with increased respiratory symptoms and decrements of pulmonary function in asthmatic children.[6] However, the generalisability of the findings is uncertain, given the closeness of the school to large sources of pollution. Further description of adverse respiratory health among children in communities with varying proximity to industrial pollution was necessary.

This study investigated the possible relationships between ambient pollution and respiratory health among schoolchildren in the metropolitan area of Durban, comparing covariate-adjusted prevalences of chronic respiratory symptoms and conditions of those residing in industrialised (south) and non-industrialised (north) areas.

Methods

Selection of the study communities and schools

Four communities in south Durban in close proximity to industrial areas (Merebank, Wentworth/Austerville, Bluff and Lamontville) and three communities in north Durban (Newlands East, Newlands West and KwaMashu) were selected. This study design permitted description of health outcomes among the various communities exposed to industrial pollution in the south. The northern communities were selected as comparison areas based on their similar socio-economic and race/ethnicity profiles to those of the southern communities, together with their greater distance from major industry and expected lower exposure to industrial emissions. The design increased the ability to separate effects of race/ethnicity and socio-economic position from effects of ambient air pollutant concentrations, with regard to both short-term exacerbations and prevalence of specific respiratory diagnoses and symptoms.

All primary schools in the selected communities were assessed by location, geography and potential sources of exposure. Only schools where bussing of students from surrounding communities was minimal (<15%) were eligible, to ensure that exposure measurements at the schools were reasonably representative of residential exposures of the study sample. One school was randomly chosen from each community. None was selected on the basis of the health status of children at the school.

Student recruitment

At each of the seven schools, all children in one or two randomly selected grade 4 classrooms were invited to participate in the study ('type A' classrooms). In addition, all students from all other classrooms ('type B' classrooms) in grades 3 - 6 with known or probable persistent asthma, based on parent/caregiver responses on a screening questionnaire, were invited. Inclusion of these additional students augmented statistical power to address the hypothesis that students with persistent asthma are at increased risk for adverse health effects associated with exposures to ambient air pollutants. The questionnaire was adapted from an instrument used in a study of asthma among children in Detroit, USA, and had been used previously in south Durban.[6]

The legal guardians of the children who participated gave written informed consent, and the children participated voluntarily and had the right to withdraw at any stage. Ethical approval was obtained from the Institutional Review Board of the University of Michigan and the Ethics Committee of the University of KwaZulu-Natal, Durban. The study was conducted over an 8-month period, with continuous environmental monitoring during this time.

Child and caregiver interviews

Survey instruments were written in English, then translated and back-translated into Afrikaans and isiZulu. Interviews were administered in the respondent's language of choice. Survey instruments utilised standardised and validated questions addressing presence and severity of respiratory and other relevant symptoms.[7] Participating children and caregivers were interviewed at school and at home, respectively. Caregiver responses categorised the children as having moderate to severe persistent, mild persistent, mild intermittent or no asthma based on the US National Asthma Education and Prevention Program (NAEPP) guidelines.[8] Information about the child's household, residential history, use of biomass fuels at home, smoking in the home and household income was obtained from an interview of the head of the household.

Chronic respiratory symptoms were defined on the basis of responses from the caregiver interview. Symptoms included chronic cough ('yes' to 'usual cough on most days for 3 consecutive months or more during the year'); chronic phlegm ('yes' to 'bringing up phlegm on most days for as much as 3 months each year'); chronic bronchitis ('periods or episodes of (increased) cough and phlegm lasting for 3 weeks or more each year'); wheeze ('yes' to 'chest sounding wheezy or whistling on most days and nights'); and wheezing with shortness of breath ('yes' to 'ever having an attack of wheezing that has made the child feel short of breath'). 'Doctor-diagnosed' outcomes were based on the responses from the caregiver interview.

Pulmonary function assessments

Spirometric assessments and methacholine challenge tests were conducted by experienced respiratory technicians on all participants. American Thoracic Society guidelines for conducting spirometry were followed.[9] Participants were instructed not to take any anti-asthmatic inhalants from 12 hours before the test, or oral asthma medications from 48 hours before the test, unless this was necessary (in which case testing was delayed appropriately). Participants with an obstructive pattern at baseline (the ratio of forced expiratory volume in one second/forced vital capacity (FEV_1/FVC) <0.75) were administered an inhaled bronchodilator and had testing repeated. Those without a baseline obstructive pattern underwent methacholine challenge testing according to an abbreviated protocol.[10] Precautionary measures and medical personnel were available at all times during the tests. Students were assessed during school hours. Results of the methacholine challenge tests were classified, based on PC_{20} (dose of methacholine causing a 20% fall in baseline FEV_1), as follows: marked airway hyperreactivity (AHR): PC_{20} ≤4 mg/ml; probable AHR: PC_{20} ranging from 4 to 8 mg/ml; possible AHR: PC_{20} ranging from >8 to 16 mg/ml; none: PC_{20} >16 mg/ml.

Assessment of allergic status

Students underwent skin-prick testing for allergic sensitisation at school on a different day from methacholine challenge testing. Health personnel assessed each participant immediately before skin testing, and were equipped to respond in the unlikely event that the child had a severe reaction to a skin test. Antigens tested included mixed cockroach, mixed dust mite, mould mix (*Aspergillus*, *Cladosporium* and *Penicillium*), cat, dog, mouse, rat and mixed grasses, plus histamine as a positive control and saline as a negative control. Participants were told to stop taking any antihistamines and any other reactive medication (H_2 antagonists, tricyclic antidepressants, corticosteroids, etc.) at least 24 - 48 hours before the test. Test solutions were applied to the volar surface of the forearm and read 15 - 20 minutes later. A positive test was defined as a wheal ≥2 mm greater than the saline control.

Environmental monitoring

Ambient pollutants (nitrogen dioxide (NO_2), nitric oxide (NO), sulphur dioxide (SO_2), and particulate matter ≤10 μm (PM_{10}) and ≤2.5 μm ($PM_{2.5}$) in aerodynamic diameter) were measured throughout the 8-month study period. Monitoring sites were established at all schools to monitor SO_2 and PM_{10}. Continuous data collected at eight Durban municipal-operated sites were utilised to estimate exposures to NO and NO_2. The environmental monitoring strategy is detailed elsewhere.[11]

Statistical analysis

Analyses were performed using Statistical Analysis Software (SAS) version 8.1. The primary independent variable of interest was school location (i.e. south versus north), and the primary outcome variables of interest were doctor-diagnosed respiratory diseases (e.g. asthma, chronic bronchitis), symptom-defined respiratory conditions (e.g. persistent asthma, chronic bronchitis, wheezing with shortness of breath) and AHR. Potential covariates/confounding variables examined included age, gender, race/ethnicity (as reported by the caregiver), previous history of respiratory disease, education level of primary caregiver, smoker in the household, atopy status and annual household income.

All prevalence outcomes are restricted to students in the randomly selected grade 4 classrooms (type A). Given the high participation rates (93.4%), the responses can be considered true population-based estimates, i.e. the prevalence rates obtained for the various outcomes, and therefore generalisable to this school pupil population. To increase statistical power, the regression models examining associations between pollutant levels and daily measures of pulmonary function included all participating children (type A and type B).

Covariate-adjusted prevalences of health outcomes by school and covariate-adjusted logistic regression models of associations of school location with health outcomes were constructed.

Asthma severity was categorised as a binary variable: probable (or known) persistent asthma (including mild and moderate to severe persistent cases) v. no asthma or mild intermittent asthma.

Atopy was defined as a positive reaction to the skin-prick test greater than that of the response to the histamine for any one of the tested allergens.

Results

Exposure evaluation

Annual average pollutant levels differed significantly across the study region (Table 1). SO_2 levels were much higher in the south than in the north. PM_{10} levels showed much less geographical variability. NO and NO_2 showed significant differences between north and south Durban, reflecting local sources.

Participation rates

Of the 422 students in the type A classes, 366 (86.7%) completed the screening questionnaire. Of these, 341 (93.2%) participated in the full study. The non-participants were similar to the participants in respect of age, gender, and number of adults living in their household, but were more likely to speak English at home. From the type B classes, 451 completed the questionnaire and 93 known or probable persistent asthmatics were identified based on their responses. Of these identified asthmatics, 81 (87.1%) participated in the full study.

Table 1. School and geographical averages for the pollutants measured in the study

	Schools in the south				Average schools		Schools in the north		
	Nizam	Enthu	Assegai	Dirkie Uys	South	North	Briardale	Ferndale	Ngazana
PM_{10} (μg/m^3)									
Mean (±SD)	50.1 (±25.2)	51.6 (±26.3)	57.9 (±34.6)	45.6 (±24.2)	51.3 (±28.0)	48.5 (±35.4)	40.9 (±23.8)	45.3 (±30.0)	59.0 (±45.9)
Range	14.0 - 179.4	9.6 - 173.8	1.2 - 208.0	1.4 - 170.6	1.2 - 208.0	0.7 - 266.6	1.9 - 133.8	4.5 - 178.7	0.7 - 266.6
$PM_{2.5}$ (μg/m^3)									
Mean (±SD)	-	-	-	-	20.7 (±15)	20.0 (±23.6)	-	-	-
Range	-	-	-	-	3.6 - 78.6	4.4 - 131.4	-	-	-
SO_2 (ppb)*									
Mean (±SD)	8.3 (±8.4)	6.7 (±8.0)	11.9 (±10.1)	7.0 (±5.5)	8.7 (±8.2)	1.9 (±2.0)	1.6 (±2.6)	2.5 (±2.2)	1.2 (±1.2)
Range	0.01 - 61.9	0.05 - 46.8	0.43 - 73.4	0.17 - 32.2	0 - 73.4	0 - 16.8	0 - 24.1	0 - 16.3	0 - 6.0
NO_2 (ppb)†									
Mean (±SD)	-	-	-	-	17.2 (±8.8)	10.9 (±6.2)	-	-	-
Range	-	-	-	-	3.7 (±63.8)	0 - 47.5	-	-	-
NO (ppb)*,†									
Mean (±SD)	-	-	-	-	40.9 (±30.5)	22.1 (±22.2)	-	-	-
Range	-	-	-	-	3.2 - 192.2	0 - 115.7	-	-	-

PM_{10} and $PM_{2.5}$ = particulate matter ≤10 μm and ≤2.5 μm in aerodynamic diameter, respectively; SD = standard deviation; SO_2 = sulphur dioxide; ppb = parts per billion; NO_2 = nitrogen dioxide; NO = nitric oxide.
*p<0.05 (t-test comparing north v. south).
†These pollutants were monitored only at single sites in the north and south respectively, and the table reflects data from the municipal monitoring sites.

Demographic data

The mean age of the students (± standard deviation) was 10.5 (±0.9) years, with 58.2% being female (Table 2). Most (40.9%) of the participants were black. English was reported as being the first language by 50.3% of the participants.

Only 44.0% of caregivers had matriculated from high school. A wide wage gap existed within the study population. Approximately 37% of households had annual incomes exceeding US$9 375 (US$1=R8), in contrast to 19.5% with incomes under US$1 250 (Table 2).

Reported symptoms and doctor-diagnosed diseases

Prevalences of doctor-diagnosed asthma among schoolchildren were higher in the schools in the north (16.5%) than in the south (13.0%) (Table 3). This contrasts with asthma severity reporting. Students attending schools in the south were more likely to report symptoms consistent with moderate to severe persistent asthma (5.3% v. 2.9%), persistent asthma of any severity (15.3% v. 9.1%), and any asthma (35.4% v. 29.1%) than those at schools in the north (Table 4).

Among children diagnosed with asthma (n=45), the reported age of onset for a substantial proportion (39.8%) was before the age of 2, while 25.3% were diagnosed after the age of 5. Of these diagnosed asthmatics, 62.9% were reported to have current asthma. The interpretation of school-stratified data must be done with caution, because of the small numbers of children with asthma in the various schools. Of note is the relatively high prevalence of doctor-diagnosed chronic bronchitis (4.1%) in this young population. The prevalence of symptom-based chronic bronchitis was considerably lower, 1.5% of caregivers reporting their child to have symptoms of both chronic cough and chronic phlegm (Table 3). This contradictory finding may reflect a poor understanding of the diagnosis made by the doctor. Over 24% of children were reported to have wheezing symptoms, 41.5% reporting attacks of wheezing with dyspnoea. Children in the south had their first attack of wheezing at an average age of 3.5 years, compared with 6.8 years in the north. However, more children in the north than in the south were likely to have repeated episodes of wheezing, and more had experienced attacks requiring treatment (Table 3).

Lung function outcomes

Age-, height- and gender-adjusted mean FEV_1 was not statistically different between the north and the south (data not shown).

Differences in respiratory health between children at the northern and southern schools were highlighted by AHR testing: an 11.9% prevalence of marked AHR was found in the south, compared with 4.1% in the north. Over 32% of the children in the south presented with some degree of AHR (possible to marked grades), compared with 21.9% in the north (Table 4).

Allergy and atopy

Prevalences of atopy in north (36.1%) and south Durban (36.7%) were very similar, although the prevalence at one school (Enthuthukweni Primary in the south) was much higher (54.6%) than at the other schools. The overall prevalence of sensitisation to house-dust mite allergen was very high (31.0%). Enthuthukweni and Briardale (in the north) showed much higher prevalences of sensitisation than the other schools, particularly for house-dust mite and cockroach allergens (Table 4). Among children reporting hay fever, 71.1% had atopy. There was no association between the doctor-diagnosed outcomes or AHR and atopy: 48.7% of doctor-diagnosed asthmatics were atopic, compared with 42.9% of those with marked AHR (data not shown).

Table 2. Demographic variables for participating children (type A classrooms)

		Schools in the south				Average schools		Schools in the north		
	Grand total	Nizam	Enthu	Assegai	Dirkie Uys	South	North	Briardale	Ferndale	Ngazana
Age (years), mean (±SD)	10.5 (±0.9)	10.5 (±0.7)	10.9 (±1.9)	10.6 (±0.5)	10.3 (±0.6)	10.6	10.4	10.3 (±0.5)	10.5 (±0.6)	10.5 (±0.9)
Females, %	58.2	50.0	63.2	60.5	57.1	57.4	58.8	51.9	55.9	69.8
Race/ethnicity, %										
Black	40.9	15.2	100.0	30.6	-	32.2	48.7	12.0	38.5	100.0
Coloured	22.4	-	-	66.7	-	21.0	23.7	-	61.5	-
Indian	25.6	84.8	-	2.8	-	23.4	27.5	88.0	-	-
White	11.1	-	-	-	100.0	23.5	-	-	-	-
Language, %										-
English	50.3	85.7	2.7	67.7	3.7	45.4	54.6	88.9	69.6	-
Zulu	35.0	14.3	81.1	32.4	-	29.0	40.3	11.1	26.1	88.9
Xhosa	3.4	-	16.2	-	-	3.0	3.8	-	2.9	8.9
Afrikaans	11.4	-	-	-	96.3	22.6	1.2	-	1.5	2.2
Caregiver education, %										
≤Grade 11	38.4	40.0	46.7	40.6	40.0	41.4	35.6	39.5	30.2	38.5
Matric	44.0	35.0	33.3	31.3	60.0	39.4	48.3	51.2	49.1	44.2
Some tertiary	17.6	25.0	20.0	28.1	-	19.2	16.1	9.3	20.8	17.3
Annual household income, %										
≤R10 000	17.9	18.9	34.5	19.1	-	17.4	18.4	14.3	26.2	12.8
R10 000 - R30 000	19.4	18.9	27.6	23.8	10.0	20.0	18.8	17.1	16.7	23.4
R30 001 - R75 000	21.8	29.7	13.8	14.3	10.0	17.3	26.0	22.9	23.8	31.9
≥R75 001	40.8	32.4	24.1	42.9	80.0	45.3	36.8	45.7	33.3	31.9
Body mass index, mean (±SD)	18.3 (±3.7)	16.7 (±4.5)	18.0 (±3.1)	19.2 (±3.3)	19.2 (±3.6)	18.3	18.5	18.1 (±3.8)	18.6 (±3.6)	18.7 (±3.0)

Covariate-adjusted predicted prevalences and risk of respiratory health outcomes

The adjusted prevalences of respiratory health outcomes show substantial variability across schools, often exceeding the variability when comparing the average across schools in the south and north regions (Table 5). All the doctor-diagnosed conditions and chronic respiratory symptoms were more common in the north than in the south, although these differences were not statistically significant. However, the prevalence of persistent asthma was higher among schools in the south (12.2% v. 9.6%), as was the objective measure of marked AHR (8.1% in the south compared with 2.8% in the north).

The adjusted odds ratios (AORs) from logistic regression models contrasting students attending schools in north and south Durban were elevated ($p<0.05$) for children in the south (from types A and B classrooms) for 5 of the 13 outcomes investigated: doctor-diagnosed chronic bronchitis (AOR 3.5, 95% confidence interval (CI) 1.6 - 7.7) (not shown in tables), as well as bronchitis by symptom definitions; watery/itchy eyes; wheezing with shortness of breath; and marked AHR (Table 6). In addition, marked AHR was associated with SO_2 exposure. While several of the other outcomes showed an increased risk for both PM_{10} and SO_2 (i.e. ORs >1), these were not statistically significant (Table 6).

Discussion and conclusions

This study compared Durban children exposed to industrial pollution with those who had less exposure, and documented prevalences of symptom-defined asthma and nonspecific AHR that are at the higher end of the ranges described in the published literature. Among the population-based sample, 32.1% presented with some grade of asthma, 12.0% with persistent asthma, of which 4.0% was marked to moderate, and 7.8% with marked AHR. The prevalence of doctor-diagnosed asthma was much lower (14.8%). These prevalences fall within the range found in previous reports of paediatric populations in other countries that are likely to be at relatively high risk or in populations with lower socio-economic status, and that use similar and well-validated instruments such as those from the International Study of Allergy and Asthma in Children (ISAAC) projects. South American studies show asthma prevalences from 3.9% to 33.1%,[12] while prevalences among children from lower socio-economic communities in the USA ranged from 6.2% to 15.2%.[13]

Schoolchildren aged 7 - 8 years from Cape Town, South Africa, had a relatively high prevalence of wheeze in the past 12 months (26.8%) and asthma diagnosis (10.8%), as reported by parents.[14] In south Durban children aged under 17 years, parents reported that 16.3% had experienced attacks of shortness of breath with wheeze during the last 12 months, and that 10% had ever been diagnosed with asthma.[15] The ISAAC-based prevalences show wide variation between countries in Africa, prevalences of wheeze symptoms ranging from 4.0% to 21.5%.[7] Our rates of 14.8% for doctor-diagnosed asthma and 24.5% for ever wheezing reported by the caregivers are within the range of other South African and international studies.

A striking finding in the present study is the substantial differences between respiratory health indicators among children in

Table 3. Respiratory and related outcomes for participating children as reported by caregivers

		Schools in the south				Average schools		Schools in the north		
	Grand total	Nizam	Enthu	Assegai	Dirkie Uys	South	North	Briardale	Ferndale	Ngazana
Range of *N*s across the variables presented	246 - 313	40 - 48	18 - 32	25 - 36	12 - 19			41 - 61	44 - 63	46 - 54
Doctor-diagnosed asthma, %	14.8	12.8	15.6	5.6	21.1	13.0	16.5	18.6	23.3	5.6
Among children diagnosed with asthma (*N*=45)										
Age of child (years) when first diagnosed with asthma, %										
<2	39.8	-	-	100.0	-	31.5	47.2	18.2	55.6	66.7
2 - 5	35.0	100.0	50.0	-	33.3	43.6	27.1	27.3	22.2	33.3
>5	25.3	-	50.0	-	66.7	24.9	25.6	54.6	22.2	-
Current asthma, %	62.9	60.0	100.0	50.0	75.0	67.8	58.6	75.0	38.9	66.7
Ever treated for asthma, %	89.3	100.0	80.0	100.0	75.0	90.4	88.3	91.7	76.5	100.0
Doctor-diagnosed chronic bronchitis, %	4.1	6.8	-	-	10.5	4.3	4.0	8.5	3.4	-
Doctor-diagnosed hayfever, %	11.5	11.1	3.1	2.9	26.3	10.6	12.4	18.6	17.0	-
Chronic cough, %	5.2	6.3	6.3	2.8	5.3	4.9	5.5	8.2	4.8	3.7
Chronic phlegm, %	3.0	-	-	-	10.5	2.5	3.5	1.6	6.4	1.9
Symptom-based chronic bronchitis, %	1.5	-	-	-	5.3	1.2	1.8	-	3.2	1.9
Ever had ear infection, %	37.1	38.1	26.3	22.6	62.5	36.8	37.4	45.5	30.2	38.2
Ever sound wheezy, %	24.5	19.2	56.3	2.9	31.6	23.8	25.2	25.4	23.0	27.8
Among those who ever sound wheezy (*N*=78)										
Ever had an attack of wheezing with SOB, %	41.5	55.6	17.6	-	100.0	41.5	47.9	64.3	46.1	33.3
Stuffy, itchy, runny nose during past 12 months, %	41.5	42.6	28.1	28.6	68.4	41.5	46.4	59.3	41.7	38.9
Watery, itchy eyes during past 12 months, %	28.1	36.2	18.8	22.9	33.3	28.1	30.1	33.9	28.8	27.8
Among those reporting attack of wheezing with SOB (*N*=32)										
Age (years) at first wheezing attack, mean (±SD)	6.5 (3.5)	4.8 (2.7)	3.6 (3.7)	-	8.0 (1.6)	3.5	6.8	8.4 (4.1)	7.6 (2.8)	4.2 (2.3)
≥2 such episodes, %	57.9	60.0	100.0	-	100.0	57.9	73.3	77.8	80.0	60.0
Required treatment for attacks, %	50.6	100.0	66.7	-	50.0	50.6	96.5	88.9	100.0	100.0
Breathing normal between attacks, %	47.3	20.0	100.0	-	100.0	47.3	38.7	22.2	66.7	20.0

SOB = shortness of breath.

communities affected by ambient industrial pollution compared with those without such exposures. While the prevalences of symptoms and AHR varied across the schools, sometimes with higher prevalences in the north (for example, a 20.5% prevalence of probable AHR in the northern school Ferndale), AORs comparing children in the south and north of Durban were 1.33 and 3.53 for doctor-diagnosed asthma and chronic bronchitis, respectively. The AORs of having symptoms defined as persistent asthma or AHR were 1.14 and 2.49, respectively. These results imply a greater risk for the children exposed to ambient pollution. There was a suggestion of a twofold SO_2-associated increased risk for marked AHR, but this was not statistically significant (p=0.056; 95% CI 0.98 - 4.66).

Similar intra-city findings have been reported in several studies in the USA[16] and elsewhere.[17] These differences have largely been explained by socio-economic and ethnic differences between communities. In the present study, comparison communities had similar socio-economic profiles, but differed in ambient pollutant exposure.

There were several limitations to this study. To ensure community representivity,

Table 4. Smoking, atopy and asthma measures

		Schools in the south				Average schools		Schools in the north		
	Grand total	Nizam	Enthu	Assegai	Dirkie Uys	South	North	Briardale	Ferndale	Ngazana
Any smoker in the household (*N*=287), %	26.4	19.4	12.5	20.9	29.0	20.8	31.3	15.2	26.8	53.9
Allergic status, skin-prick test (*N*=312), %										
House-dust mite	31.0	16.0	54.6	38.5	25.8	32.5	29.6	47.5	28.6	12.2
Cockroach	15.0	4.0	45.5	15.4	6.5	15.8	14.2	20.0	14.3	8.2
Cat	7.3	4.0	9.1	12.8	-	6.8	7.7	10.0	10.2	2.0
Dog	4.7	-	-	-	3.2	0.8	8.3	10.0	10.2	4.1
Mould	4.0	-	9.1	5.1	6.5	4.8	3.2	-	2.0	8.2
Cladosporium	2.2	-	9.1	-	-	1.7	2.6	-	2.0	6.1
Grass	0.7	-	-	-	-	-	1.4	-	2.0	2.0
Atopy*	36.4	20.0	54.6	43.6	32.3	36.7	36.1	47.5	32.7	28.6
AHR† (*N*=315), %										
Marked	7.8	13.0	14.3	5.6	17.4	11.9	4.1	2.6	6.8	2.2
Probable	8.4	13.0	7.1	8.3	-	7.4	9.2	-	20.5	4.4
Possible	10.6	8.7	7.1	16.7	17.4	13.0	8.6	13.2	4.6	8.9
None	73.2	65.2	71.4	69.4	65.2	67.7	78.1	84.2	68.2	84.4
Caregiver's report of asthma severity (*N*=301), %										
Moderate to severe	4.0	-	-	7.9	12.0	5.3	2.9	2.2	4.1	2.0
Mild persistent	8.0	-	11.1	13.2	16.0	10.0	6.2	8.9	4.1	6.0
Mild intermittent	20.1	20.0	22.2	13.2	28.0	20.1	20.0	17.8	26.5	14.0
None	67.9	80.0	66.7	65.8	44.0	64.6	71.0	71.1	65.3	78.0

AHR = airway hyperreactivity.
*Allergic to any of the listed allergens.
†Marked = PC_{20} ≤4 mg/ml; Probable = PC_{20} ranging from 4 to 8 mg/ml; Possible = PC_{20} ranging from >8 to 16 mg/ml; None = PC_{20} >16 mg/ml.

we had to select study participants from multiple communities. Resources limited us to randomly selecting a single school in each community. Although we have no reason to believe that the schools selected were not representative of the communities themselves, the generalisability of the findings must be treated with caution. Our study includes reporting symptoms from caregivers and child participants. We used instruments that have been well standardised, both internationally and in South Africa, to ensure comparison and limitation of bias. Despite the apparent differences in reporting of these symptoms, our findings are not due to over-reporting by residents living close to the polluting industries. Prevalences of respiratory outcomes reported by the caregivers were supported by the findings of objective lung function assessments, the methacholine challenge: 12.0% had some grade of persistent asthma, and 16.2% had either marked or probable AHR (Table 4). As an objective marker of airway disease, the overall rate of any grade of AHR found, a rate of 26.8%, is strikingly high, and at the high end of the range reported in other population samples in the international literature.[17] Differing protocols, definitions and population selection across studies make such comparisons difficult. Population-based studies of children of a similar age show rates of positive responses to methacholine challenge tests (defined as ≤8 mg/ml methacholine) that range from 14% to 32%.[17]

In conclusion, this population-based sample of children attending schools in north and south Durban showed substantial differences in the prevalences of key respiratory outcomes, particularly grades of asthma, persistent asthma and AHR. Children living in the industrially exposed communities had higher risks of these outcomes than those living in non-exposed communities. These findings are consistent with a negative impact of industrial pollution on the respiratory health of schoolchildren.

Acknowledgements. This project was supported by grants from the eThekwini Municipality, the South African Medical Research Council, and the US National Institutes of Health/Fogarty International Center (grant D43 TW000812). The authors are grateful for support given by the Pollution Control Unit of the eThekwini Department of Health and the Durban University of Technology. We express our appreciation to Yogan Gounden, Thabang Molefi, Pamela Nasirumbi, Mary Lou Thompson, and the staff and students of all the participating schools. We also thank the research fieldworkers, our research administrator Jenny Pillay, and the staff of the Department of Occupational and Environmental Health at the University of

KwaZulu-Natal.
The funders played no role in the study design, collection, analysis or interpretation of the data, the writing of the reports, or the decision to submit for publication.

Table 5. Covariate-adjusted prevalences* of children's health outcomes by school

	Grand total (*N*=341)	Schools in the south				Average schools		Schools in the north		
		Nizam (*n*=51)	Enthu (*n*=38)	Assegai (*n*=43)	Dirkie Uys (*n*=30)	South (*n*=162)	North (*n*=179)	Briardale (*n*=56)	Ferndale (*n*=69)	Ngazana (*n*=54)
Reported doctor diagnosed										
Doctor-diagnosed asthma†	13.7 (±9.9)	13.2 (±5.4)	15.8 (±8.4)	4.7 (±2.5)	10.3 (±9.8)	11.0	16.3	22.2 (±8.4)	20.0 (±10.7)	5.5 (±2.8)
Symptom-based chronic bronchitis	3.5 (±4.9)	5.7 (±4.3)	-	-	6.9 (±5.0)	3.1	4.0	9.3 (±5.8)	2.9 (±2.9)	-
Doctor-diagnosed hayfever‡	9.1 (±10.5)	9.4 (±7.1)	2.6 (±2.7)	2.3 (±2.2)	17.2 (±9.8)	7.4	10.8	18.5 (±12.4)	12.9 (±10.6)	-
Ever had ear infection‡	25.2 (±14.8)	28.3 (±14.3)	13.2 (±10.3)	16.3 (±9.9)	34.5 (±10.7)	22.7	27.6	40.7 (±14.1)	21.4 (±12.1)	21.8 (±9.9)
Past year symptom-defined outcomes										
Persistent asthma‡	10.8 (±8.27)	17.0 (±8.2)	21.1 (±8.5)	0.0 (±0.0)	10.3 (±3.8)	12.2	9.6	13.0 (±6.6)	8.6 (±4.6)	7.3 (±3.4)
Chronic cough†	5.3 (±5.0)	5.7 (±3.8)	5.3 (±4.6)	2.3 (±2.1)	3.5 (±6.3)	4.3	6.2	9.3 (±5.7)	4.3 (±4.9)	5.5 (±3.9)
Chronic phlegm†	2.3 (±4.2)	-	-	-	6.9 (±7.1)	1.3	3.3	1.9 (±2.0)	5.7 (±5.6)	1.8 (±1.8)
Chronic bronchitis‡	1.2 (±3.7)	-	-	-	3.5 (±8.5)	0.6	1.7	-	2.9 (±4.3)	1.8 (±3.9)
Ever sound wheezy	26.2 (±16.0)	19.5 (±7.2)	56.1 (±13.8)	2.7 (±1.5)	32.0 (±7.0)	25.9	26.5	26.7 (±8.6)	24.4 (±9.6)	29.1 (±8.8)
Ever had an attach of wheezing with SOB†	9.4 (±5.9)	9.4 (±2.8)	7.9 (±2.8)	-	13.8 (±6.6)	7.4	11.3	16.7 (±5.1)	8.6 (±3.5)	9.1 (±3.0)
Stuffy, itchy, runny nose‡	39.2 (±15.3)	50.9 (±13.1)	23.7 (±7.8)	25.6 (±7.9)	41.4 (±8.7)	36	42.2	57.4 (±11.7)	34.3 (±9.8)	36.4 (±9.7)
Watery, itchy eyes‡	25.2 (±12.6)	32.1 (±15.7)	15.8 (±7.6)	18.6 (±10.2)	20.7 (±5.8)	22.6	27.5	33.3 (±14.6)	22.9 (±9.8)	27.3 (±7.8)
Test-based outcomes										
Marked AHR†	5.3 (±5.0)	3.9 (±2.1)	10.5 (±6.0)	9.3 (±4.4)	10.3 (±7.4)	8.1	2.8	1.9 (±1.1)	4.3 (±2.6)	1.8 (±0.9)

SD = standard deviation; SOB = shortness of breath; AHR = airway hyperreactivity.
*Prevalences (±SD) have been adjusted for the following covariates: age, gender, race, education and annual household income.
†$p<0.0001$ (*F*-test for differences between north and south).
‡$0.0001 \leq p \leq 0.05$ (*F*-test for differences between north and south).

Human subjects declaration. All the legal guardians of the child participants in this study gave written informed consent. Participation was voluntary, and the children had the right to withdraw at any stage. Ethical approval was obtained from the Institutional Review Board of the University of Michigan and the Ethics Committee of the University of KwaZulu-Natal.

References

1. Epton MJ, Dawson RD, Brooks WM, et al. The effect of ambient air pollution on respiratory health of schoolchildren: A panel study. Environ Health 2008;7:16. [http://dx.doi.org/10.1186/1476-069X-7-16]
2. Strickland MJ, Darrow LA, Klein M, et al. Short-term associations between ambient air pollutants and pediatric asthma emergency department visits. Am J Respir Crit Care Med 2010;182(3):307-316. [http://dx.doi.org/10.1164/rccm.200908-1201OC]
3. D'Amato G, Liccardi G, D'Amato M, Holgatew S. Environmental risk factors and allergic bronchial asthma. Clin Exp Allergy 2005;35(9):1113-1124. [http://dx.doi.org/10.1111/j.1365-2222.2005.02328.x]
4. Matooane L, Diab RD. Air pollution carrying capacity in the South Durban industrial basin. S Afr J Sci 2000;97(Nov/Dec):450-543. http://reference.sabinet.co.za/webx/access/electronic_journals/sajsci/sajsci_v97_n11_a5.pdf (accessed 26 September 2013).
5. eThekwini Health. Air quality management plan for eThekwini Municipality. Produced by eThekwini Health and Norwegian Institute for Air Research, Durban. April 2007. http://www2.nilu.no/AirQuality/data/reports/%7BB2D475E8-BCDC-BAD1-AF03-9D183B89D4B5%7D.pdf (accessed 18 December 2012).
6. Kistnasamy EJ, Robins TG, Naidoo N, et al. The relationship between asthma and ambient air pollutants among primary school students in Durban, South Africa. International Journal of Environment and Health 2008;2(3/4):365-385. [http://dx.doi.org/10.1504/IJENVH.2008.020929]
7. Ait-Khaled N, Odhiambo J, Pearce N, et al. Prevalence of symptoms of asthma, rhinitis and eczema in 13- to 14-year-old children in Africa: The International Study of Asthma and Allergies in Childhood Phase III. Allergy 2007;62(3):247-58. [http://dx.doi.org/10.1111/j.1398-9995.2007.01325.x]
8. National Asthma Education and Prevention Program. Expert Panel Report: Guidelines for the Diagnosis and Management of Asthma. Bethesda, MD: National Institutes of Health, 1991.
9. American Thoracic Society. Standardization of spirometry – 1994 update. Am J Respir Crit Care Med 1995;152(3):1107-1136. [http://dx.doi.org/10.1164/ajrccm.152.3.7663792]
10. American Thoracic Society. Guidelines for methacholine and exercise challenge testing – 1999. Am J Respir Crit Care Med 2000;161(1):309-329. [http://dx.doi.org/10.1164/ajrccm.161.1.ats11-99]
11. Naidoo R, Gqaleni N, Batterman S, Robins T. South Durban Health Study. Final Project Report. Center for Occupational and Environmental Health, University of KwaZulu-Natal, Durban, South Africa. 2007. http://doeh.ukzn.ac.za/Libraries/Documents/SDHS_FINAL_Report_revision_February_2007.sflb.ashx (accessed 20 June 2013).
12. Mallol J, Sole D, Baeza-Bacab M, Aguirre-Camposano V, Soto-Quiros M, Baena-Cagnani C. Regional variation in asthma symptom prevalence in Latin American children. J Asthma 2010;47(6):644-650. [http://dx.doi.org/10.3109/02770901003686480]
13. Joseph SP, Borrell LN, Shapiro A. Self-reported lifetime asthma and nativity status in U.S. children and adolescents: Results from the National Health and Nutrition Examination Survey 1999-2004. J Health Care Poor Underserved 2010;21(Suppl):125-139.

Table 6. Covariate-adjusted* logistic regression models of associations of living in communities in south Durban compared with living in north Durban with child outcomes (*N*=423)

	South/north			PM_{10}†			SO_2†		
Health outcome	**OR**	**95% CI**	***p*-value**	**OR**	**95% CI**	***p*-value**	**OR**	**95% CI**	***p*-value**
Symptom-defined outcomes									
Chronic cough	0.81	0.47 - 1.40	0.45	1.03	0.41 - 2.58	0.96	1.02	0.47 - 2.19	0.97
Chronic phlegm	1.55	0.76 - 3.15	0.23	0.56	0.16 - 1.93	0.36	0.88	0.32 - 2.42	0.80
Chronic bronchitis	**3.53**	**1.30 - 9.55**	**0.01**	1.02	0.21 - 5.01	0.98	1.34	0.34 - 5.22	0.67
Wheezing	1.00	0.63 - 1.57	0.99	1.27	0.75 - 2.15	0.37	1.13	0.73 - 1.74	0.58
Wheezing with SOB	**1.12**	**1.01 - 1.24**	**0.04**	0.98	0.88 - 1.10	0.72	0.86	0.49 - 1.53	0.61
Stuffy, runny nose	1.22	0.80 - 1.87	0.36	0.91	0.58 - 1.43	0.68	0.96	0.66 - 1.40	0.85
Watery, itchy eyes	**2.29**	**1.48 - 3.55**	**0.00**	1.34	0.81 - 2.23	0.25	1.02	0.67 - 1.53	0.94
Persistent asthma	1.14	0.75 - 1.74	0.54	1.09	0.56 - 2.12	0.79	1.37	0.80 - 2.35	0.26
Test-based outcomes									
Marked AHR	**2.49**	**1.13 - 5.5**	**0.024**	1.08	0.44 - 2.66	0.867	**2.14**	**0.98 - 4.66**	**0.056**

PM_{10} = particulate matter ≤10 μm in aerodynamic diameter; SO_2 = sulphur dioxide; SOB = shortness of breath; AHR = airway hyperreactivity; OR = odds ratio; CI = confidence interval.
Bold text denotes statistically significant or borderline significance.
*Covariates included age, male gender, race (Indian, coloured, black African (reference group)), education, smoker in home, household income (<R10 000, R10 000 - R29 999, R30 000 - R74 999, ≥R75 000 (reference group)), glutathione-S-transferase M1 polymorphism (GSTM) genotype negative.
†Mean school exposure level.

14. Ehrlich RI, Du Toit D, Jordaan E, Volmink JA, Weinberg EG, Zwarenstein M. Prevalence and reliability of asthma symptoms in primary schoolchildren in Cape Town. Int J Epidemiol 1995;24(6):1138-1145. [http://dx.doi.org/10.1093/ije/24.6.1138]
15. Nriagu J, Robins T, Gary L, et al. Prevalence of asthma and respiratory symptoms in south-central Durban, South Africa. Eur J Epidemiol 1999;15(8):747-755. [http://dx.doi.org/10.1023/A:1007653709188]
16. Gupta RS, Zhang X, Sharp LK, Shannon JJ, Weiss KB. Geographic variability in childhood asthma prevalence in Chicago. J Allergy Clin Immunol 2008;121(3):639-645.e1. [http://dx.doi.org/10.1016/j.jaci.2007.11.036]
17. Jang AS, Yeum CH, Son MH. Epidemiologic evidence of a relationship between airway hyperresponsiveness and exposure to polluted air. Allergy 2003;58(7):585-588. [http://dx.doi.org/10.1034/j.1398-9995.2003.00205.x]