The relationship between asthma and ambient air pollutants among primary school students in Durban, South Africa

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Abstract: We examined the prevalence of asthma among students in Grades 3 and 6 at a primary school located in the highly industrialised South Durban Industrial Basin. After baseline interviews and methacholine challenge testing (MCT), students completed bihourly symptom logs during an 18-day study period. Continuous measurements of ambient contaminants at the school included sulphur dioxide (SO_2), oxides of nitrogen (NO_x), and respirable particulate matter less than 10 μm (PM_{10}). Generalised estimating equations were used to examine associations between lagged fluctuations in ambient air pollutant concentrations and daily reported symptoms. Among the 248 participants, 52% had asthma of any severity; including 11% with moderate to severe persistent asthma. On MCT, 21% of the children had marked ($PC_{20} \leq 2$ mg/ml), 29% had probable, and 19% had possible airway hyperreactivity. Concentrations of air pollutants at the school during the study period fell below international and South African standards and guidelines. Increased lower respiratory symptoms (cough, wheezing, chest tightness or heaviness, and shortness of breath) were strongly and consistently associated with prior day fluctuations in ambient levels of both SO_2 and PM_{10} in both single-pollutant and two-pollutant models. We note the important role of local stakeholders in implementing and conducting this study.

Keywords: air pollution; asthma; children; epidemiology; particulate matter; sulphur dioxide; nitrogen dioxide.

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1 Introduction

The prevalence of asthma among children has increased worldwide (Wood, 2002). In the USA, the number of asthmatic children has increased by about 150% in the past 20 years. Asthma prevalence among adolescents from the 56 countries participating in the International Study of Asthma and Allergies in Childhood (ISAAC) varies between countries, with rates ranging from 4.5% to 28% (Ehrlich, 2002). In developing countries, asthma prevalence was previously considered to be low, but recent studies have shown increases in childhood asthma (Weinberg, 2001), especially among those living in urban areas (Ng'ang'a et al., 1998; Nriagu et al., 1999). In South African studies (1979–2000), prevalence rates ranged from 0.14% to 15%, depending on the study population (Ehrlich, 2002). One study examining 455 black children from Soweto, South Africa suggested the importance of environmental factors, rather than race, in asthma causation (Luyt et al., 1995). In a separate study of 367 children from two communities in south Durban, South Africa, approximately 10% reported doctor-diagnosed asthma (Nriagu et al., 1999).

Exposure to ambient air pollutants in asthmatics triggers chemical and cellular changes in the airways, which may often require 24–48 hours to fully develop (Braga et al., 2001). Therefore, pollution-associated health effects may be more marked on subsequent days than on the day of exposure. Children, especially asthmatic, are particularly vulnerable to air pollutants (Lee et al., 2002). For example, high concentrations of particulate matter can exacerbate asthma symptoms (Lebowitz, 1996). The impact of air pollutants on children's health is further complicated by the number and types of air pollutant that may be present, and by the variety of indicators of adverse health effects (Bates, 1995). Asthmatics are susceptible to brief exposures of air pollutants.

This study, conducted among school children at a primary school located in the midst of a highly polluted industrial area in South Africa, examines prevalences of symptom-defined asthma and nonspecific Bronchial Hyperreactivity (BHR) tested using methacholine, and investigates the relationship between daily fluctuations of ambient air pollutant concentrations of sulphur dioxide (SO_2), oxides of nitrogen (NO_x), ozone (O_3), Total Reduced Sulphur (TRS), carbon monoxide (CO) and respirable particulate matter less than 10 μm in diameter (PM_{10}) and reported symptoms.

2 Methodology

2.1 Overview

The strategy of the study was to collect: (1) baseline information using a screening questionnaire, parent/caregiver baseline interview, child's baseline interview and spirometry including Methacholine Challenge Testing (MCT) and (2) daily and bihourly health status data through a combination of diaries, logs and lung function testing.

Results involving repeated measures of lung function will be reported in a separate manuscript. Health data were examined with respect to ambient air pollutant levels of SO_2, NO_x, TRS, CO and PM_{10}, which were monitored at the school during the study period for statistical associations. Informed consent was obtained from the participating children and their parents or guardians.

2.2 Study area and sample

Durban, South Africa's third largest city, is Africa's busiest port and the primary route for imported crude oil, exported refined petroleum and petrochemical products (Danmarks Naturfredningsforening (DN) and South Durban Community Environmental Alliance (SDCEA), 2002). The study area, known as the South Durban Industrial Basin (SDIB), is recognised as one of the most highly industrialised and heavily polluted areas in Southern Africa (Nriagu et al., 1999; CSIR, 2002). The SDIB contains over 120 heavy and light industries, including the country's two largest oil refineries (Butler and Hallowes, 2002), a paper mill, an airport, a sewage treatment plant, a major highway, landfill sites and many processing/manufacturing industries. The refineries and paper mill collectively emit 35–40 tons of SO_2 per day (Hurt, 2001). The prevailing meteorological conditions, topography, short emission stacks, fugitive emissions and the proximity of other smaller polluting industries also contribute to the high pollutant concentrations experienced in the area (CSIR, 1999). South Durban contains many residential areas sited among the industrial sources with a population of over 400,000 (Tonnesen, 2001). Supplemental materials, specifically the photos in Figures 1–3, show the intermingling of industry and residential areas.

Figure 1 Sapref oil refinery (back) with community residences in Merebank (front) (see online version for colours)

Figure 2 Engen refinery (middle) with community residences of Wentworth (back) and Merebank (front) (see online version for colours)

Figure 3 Community residences of Umlazi (back), Mondi paper mill and southern sewage works (middle) and community residences of Merebank (front) (see online version for colours)

This study was conducted at the Settlers Primary School situated in the Merebank community of the SDIB. This school was selected because of the anecdotal reports of high prevalence of asthma, repeated mass visits to health services and the presence of a dedicated monitoring station on the grounds of the school. The school is approximately 0.5 km from the one of the refineries, and approximately 1 km from the second (Figure 4).

Figure 4 Settler Primary School (front) with Engen refinery stacks (back) (see online version for colours)

This public school had approximately 860 students from Grades 1 to 7 in the 2001 school year when the study was conducted. Students were primarily from a low socioeconomic background and most of them lived in Merebank or Umlazi – two communities of predominantly Indian and African origin, respectively.

All students from Grades 3 to 6 were eligible for the study, representing a population-based sample. In addition, students from Grades 5 to 7 with known or probable persistent asthma (based on parent/caregiver responses on the screening questionnaire) were invited to participate. The purpose of the inclusion of these additional students was to augment 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 a similar instrument used in a study of similar design of environmental triggers of asthma among children in Detroit, MI, USA (Keeler et al., 2002). Completed screening questionnaires were categorised into asthma severity responses consistent with guidelines established by the US National Asthma and Education Program. Very similar guidelines are followed in South Africa. All students from Grades 3 to 6 returning a screening questionnaire, together with those from Grades 5 to 7 with responses consistent with persistent asthma (n = 275) were invited to participate. In the results presented below, all prevalence outcomes are restricted to Grades 3 and 6, hence with the high participation rate (90.2%), these can be considered true population-based estimates. In contradistinction, regression models examining associations between pollutant levels and daily symptom reports include all participating children. For these models, the coefficient estimates among those with persistent asthma are always reported separately from those with mild intermittent or no asthma.

2.3 Exposure data

Air pollution data were obtained from a monitoring station located on the school property in a small trailer operated by the local government (Durban Municipality), as part of the monitoring programme within the greater Durban area. A specialist environmental and occupational health consulting company (ECOSERV) was responsible for the maintenance of the instrumentation, which was run to the same standards as other stations in Durban that were accredited by the South African National Accreditation System. Continuous monitoring of O_3 was conducted at a nearby monitoring station, operated by the municipality, located 8 km north of the school at Wentworth in South Durban.

Throughout the duration of the study, SO_2, CO, PM_{10}, NO, NO_2 and TRS were measured on a continuous basis at the school. SO_2 was measured by UV absorption (Model 43b, TECO); TRS was measured after conversion to SO_2 (Model 102/100A, Advanced Pollution Instruments/API, San Diego, CA). PM_{10} was measured using a Tapered Element Oscillating Microbalance (TEOM) with a PM_{10} inlet (Model Series 1400a, Rupprecht & Patashnick, Albany, NY), and also by 24-hour (noon-to-noon) filter samples (Partisol Model 2025 Sequential Air Sampler, Rupprecht & Patashnick, Albany, NY). Filter and TEOM data showed high correlation (r = 0.95) and small biases, thus we report on only TEOM measurements. NO and NO_2 were measured by UV chemiluminescence (Model 200A, API, San Diego, CA), and NO_x was calculated as the sum of NO and NO_2. Carbon monoxide was monitored continuously using infrared absorption/correlation (Model 300, API, San Diego, CA). O_3 levels were normally measured continuously by UV fluorescence. However, due to a pump malfunction, data from 24 April to 2 May 2001 (about half of the study period) were invalid.

Generally, O_3 in Durban are low to moderate, e.g. annual averages were 17 and 24 ppb in calendar years 2000 and 2001, respectively, and O_3 levels tend to be still lower during the April/May period.

The minute-by-minute air pollutant data were processed as follows: 15-min averages were computed if at least seven 1-min observations were present in that period. Longer-term statistics were computed if at least half of the 15-min averages in that period were available. This approach ensures that exposure indicators are not unduly influenced by missing data.

Both study participants and personnel who conducted the health assessments were blinded to measured pollutant levels during the data collection period.

2.4 Questionnaires, weekly diaries and bihourly logs

Trained interviewers from the community and local tertiary institutions were recruited to conduct baseline interviews with participants and their families. Confidential parent baseline surveys were conducted either at the school or at the parent/caregiver's home. Components of this questionnaire included: demographic information; an assessment of the presence and severity of respiratory and other possibly relevant symptoms using standardised validated questions from sources such as the British Medical Research Council (BMRC) and American Thoracic Society (ATS); validated questions to specifically address the presence and severity of asthma among participants including information concerning wheezing, coughing, chest tightness or heaviness, shortness of breath, activity limitations and medication use; an assessment of the utilisation of health services for asthma; an evaluation of the caregivers' quality of life; a review of the perinatal history; information on place of birth and residential history; potential confounding factors such as exercise, viral respiratory infections, exposure to cigarette smoke and pre-existing medical conditions. A shorter child baseline survey was administered by the interviewers to the students on a confidential, individual basis at the school.

In addition, participants completed bihourly logs while at school over the 3-week period of the study (total of nine school days). On each school day, students filled out the log every 1.5–2 hours (four times per 5.5-hour school day, approximately at 08:00, 09:45, 11:30 and 13:20). As all the students, together with the teacher, did this simultaneously in each of the participating classrooms, a very high compliance rate was obtained. In addition, study personnel were assigned to the classrooms during the study period to monitor these activities and provide assistance as needed.

2.5 Spirometry and MCT

Experienced technologists conducted spirometry and MCT at the school. All guidelines for spirometry calibration and testing standardisation were followed (ATS, 1995). Spirometry was performed in a sitting position without nose clips. Participants with an obstructive pattern at baseline (FEV1/FVC < 0.73) were administered with an inhaled bronchodilator and were tested again to assess reversibility. Those without a baseline obstructive pattern underwent MCT to assess nonspecific bronchial reactivity on a separate day using an abbreviated protocol used in epidemiological surveys (European Respiratory Society, 1993). The target FEV1 was reached when there was a 20% fall from the highest post-saline baseline FEV1. At the end of the test, children were given a short acting beta 2 agonist (200 μg salbutamol) administered via a large volume spacer device. Special instructions were given to participants to ensure that tested individuals did not take any anti-asthmatic inhalers 12 hours or oral asthma medications 48 hours, prior to the test. Results were classified as: marked airway hyperreactivity (PC_{20} ≤ 2 mg/ml of methacholine), probable airway hyperreactivity (2 mg/ml < PC_{20} ≤ 8 mg/ml), possible airway hyperreactivity (8 mg/ml < PC_{20} ≤ 16 mg/ml) or no airway hyperreactivity (PC_{20} > 16 mg/ml).

2.6 Ethical issues

Voluntary informed written consent for children and parents/caregivers was obtained prior to any study procedure. Participants were free to withdraw from the study without penalty at any time or refuse to participate in any study aspect. All study protocols were approved by the ethical review boards at the University of KwaZulu-Natal, Durban, South Africa and the University of Michigan, USA.

2.7 Statistical analyses

Preliminary univariate statistical analyses included frequency tables and descriptive statistics such as means and variances of continuous variables. Bivariate analyses were used to examine the crude associations between variables of interest. For categorical dependent variables, Odds Ratios (OR) were calculated. For continuous dependent variables, correlation coefficients were calculated.

Children were classified as to asthma severity (no asthma, mild intermittent asthma, mild persistent asthma or moderate to severe persistent asthma), on the basis of symptoms and medication use reported on the parent/caregiver interview.

Generalised Estimating Equations (GEE), implemented in the SAS statistical procedure – a multivariate analogue of linear logistic regression which accounts for within participant correlation of the repeated measures (Diggle et al., 1994; Horton and Lipsitz, 1999; Edwards, 2000) – were used to examine lagged associations (1-day lag, 2-day lag and an average of 1- plus 2-day lag) between pollutant exposures of interest (PM_{10}, SO_2 and NO_2) and lower respiratory symptom reports (cough, wheeze, chest tightness or heaviness, shortness of breath). Both single-pollutant and two-pollutant models (i.e. SO_2 with PM_{10}, and SO_2 with NO_2 – PM_{10} and NO_2 were too correlated for entry in the same model) were examined. Models examining possible acute exposure effects (exposures 1–2 hours prior to symptom report) were also considered. Covariates in the final models included parent reports of other physiochemical exposures at home (presence of a smoker in the household, evidence of cockroach infestation, evidence of rodent infestation, ownership of dogs or cats), reported psychosocial stressors potentially associated with aggravation of asthma (environmental stress, financial stress, physical stress, exposure to violence, quality of life measures) and demographic variables (gender, school grade, location of home, annual family income), asthma severity (persistent asthma vs. mild or no asthma), and the interaction(s) between asthma severity and the exposure measure(s).

In the regression models, asthma severity was classified into two categories: (1) persistent asthma (combining moderate to severe persistent asthma with mild persistent asthma) and (2) mild intermittent asthma or no asthma. Effect modifications by baseline severity of underlying asthma were examined by including interaction terms between exposure measures and asthma severity in the models.

The unit of exposure measure used in the presented GEE regression models for calculating OR was the interquartile range. The interquartile range was calculated separately for each specific air pollutant being investigated and was defined as the 75th percentile minus 25th percentile of the mean daily (24-hour) exposure during the intensive study period. By using the interquartile range as the unit of exposure measure in the regression models, the effect measures such as OR, for different pollutants are directly comparable and specifically relevant to the population studied.

3 Results

3.1 Demographics

Of the total of 275 students invited, 248 (90.2%) participated in the study. This included 220 from Grades 3 to 6, and 28 from Grades 5 to 7. The gender and grade-in-school distributions of participants and nonparticipants were similar; however, nonparticipants were less likely to reside in Merebank than participants (Table 1).

Table 1 Demographic variables for participants and nonparticipants

Demographic variables	*Participants (n = 248)*	*Nonparticipants (n = 27)*
Gender (*n* = 243)[a]		
% Female	51.4	47.6
Grade (*n* = 248)		
% in Grade 3	43.2	37.0
% in Grade 6	46.1	48.1
% in Grade 5 or 7	10.7	14.8
Home location (*n* = 221)		
% in Merebank	62.9	38.9
% in Umlazi	27.6	38.9
% Elsewhere	9.5	22.2
Annual family income (*n* = 187)		
% <R5000	15.5	na[b]
% R5001–R50,000	66.8	na
% >R50,000	17.6	na
Number of smokers in household (*n* = 190)		
% of none	42.1	na
% of one or more	57.9	na

[a]Number of non-missing values for this variable among participants.

[b]Not available.

3.2 Asthma severity

Based on responses on the parent/caregiver baseline interview, among the students in Grades 3 and 6, 52% had known or probable asthma of any severity. Among these, 11% of the total had moderate to severe persistent asthma, 15% mild persistent asthma and 26% mild intermittent asthma.

Students in Grade 3 were more likely to have moderate to severe persistent asthma than students in Grade 6 (16% vs. 7%). Among those in Grades 3 and 6, students living in Merebank (where the school is located) had higher rates of persistent asthma (32%), and those living in Umlazi (17%) or other surrounding suburbs (17%). The prevalence of moderate to severe persistent asthma was highest in those with annual family incomes below R5000 (17%) (equivalent to US $625 at the then current exchange rate), intermediate in those with annual family incomes from R5000 to R50,000 (10%), and lowest in those with annual family incomes above R50,000 (4%). Asthma prevalences were quite similar in boys and girls and were not associated with the presence of cigarette smokers in the household.

3.3 Airway reactivity

Among students in Grades 3 and 6, 21% had marked airway hyperreactivity, 29% probable airway hyperreactivity and 19% possible airway hyperreactivity, with only 32% in the clearly normal range.

3.4 Predictors of asthma severity and airway hyperreactivity

Table 2 presents the results of logistic regression models investigating predictors of persistent asthma (vs. no or mild intermittent asthma), and marked BHR (PC_{20} < 2 mg/ml of methacholine), among the population-based portion of the study sample. Annual family income of <R5000 was strongly associated with both outcomes. African race/ethnicity (as compared to Indian race/ethnicity) was protective for persistent asthma, but unassociated with marked BHR. Gender, home location, grade and the presence of smokers in the household are not significantly associated with either outcome.

Table 2 OR and 95% Confidence Intervals (95% CI) for predictors of marked BHR and persistent asthma in multivariable logistic regression models among children in 3rd and 6th grades

	Marked BHR[a]		*Persistent asthma*[b]	
	OR	*95% CI*	*OR*	*95% CI*
Gender (ref: male)				
Female	0.80	(0.41, 1.58)	0.87	(0.47, 1.59)
Race/ethnicity (ref: Indian)				
African	1.02	(0.45, 2.31)	**0.34**	**(0.14, 0.84)**
Annual family income (ref: ≥R5000)				
<R5000	**4.71**	**(1.53, 14.5)**	**3.51**	**(1.12, 11.0)**
Home location (ref: Merebank)				
Umlazi	0.87	(0.30, 2.57)	1.27	(0.39, 4.13)
Grade (ref: Grade 3)				
Grade 6	0.78	(0.40, 1.52)	1.00	(0.54, 1.85)
Number of smokers in household (ref: zero)				
One or more	0.64	(0.32, 1.28)	1.13	(0.61, 2.09)

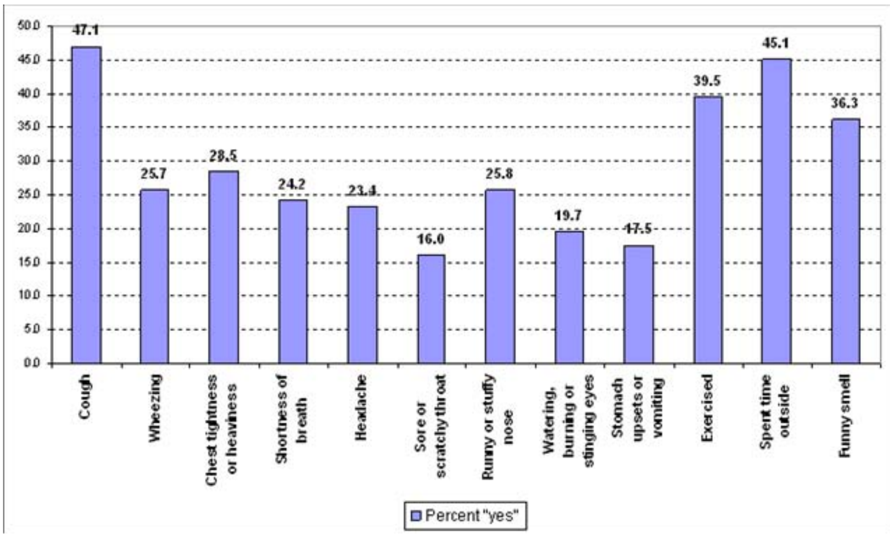
[a]BHR is defined as PC_{20} < 2 mg/ml of methacholine.

[b]Asthma classifications based on parent baseline interview; 'persistent' asthma includes both moderate to severe persistent asthma and mild persistent asthma.

3.5 Symptoms

Figure 5 presents data from the bihourly logs completed on school days. Combining information across all nine school days and four times of day (08:00, 09:45, 11:30, 13:20), cough was the most frequently reported symptom at 47%. Other symptoms frequently associated with asthma, that is shortness of breath, wheezing and chest tightness or heaviness, were reported at frequencies of 24–29%. Other symptoms queried were reported at 16% or greater, with runny or stuffy nose at 26% and headache at 23%.

Figure 5 Percent of 'yes' answers for asthma symptoms and activities on Grades 3 and 6 learners bihourly logs across all nine school days and all four times of day (08:00, 09:45, 11:30, 13:20) (average n = 185 students per asthma symptom or activity) (see online version for colours)



3.6 Air pollutant measurements

Table 3 summarises the air pollutant levels at the school during the study period. All concentrations measured at the school site during the study period for the selected pollutants fell below South African guideline values and US standards, although some concentrations exceed the recently revised 2005 WHO guidelines. For example, the 24-hour standards or guidelines for SO_2 for South Africa, the USA and WHO are, respectively, 100, 140 and 8 ppb compared to the measured average of 8.2 ppb and maximum 24-hour average of 20 ppb during the study (note that WHO also suggests targets of 19 and 48 ppb in addition to the guideline level of 8 ppb). For PM_{10}, the South African, US and WHO 24-hour standards or guidelines are 180, 150 and 50 µg/m^3 compared to the 29 µg/m^3 average and the 24-hour peak of 55 µg/m^3 monitored during the study. Over the study period, SO_2 showed significant diurnal variations, wind direction dependencies and occasional high concentrations, all reflecting strong local sources, specifically, the two refineries and a paper mill. PM_{10} levels also showed diurnal patterns, but directional effects were not as strong as SO_2, indicating that PM_{10} sources were more dispersed. NO_2 trends demonstrate a morning (07:00–09:00) and less pronounced evening (19:00–23:00) peaks. NO_2 levels were highly correlated to NO levels. NO is a short-lived and reactive pollutant, and diurnal peaks were much stronger and higher in concentration than NO_2, especially in the morning. NO more strongly shows the influence of vehicular and other nearby sources. Like NO_2, concentrations of CO peaked in the morning and evening; the morning peak is more pronounced. TRS ranged between 5 and 8 ppb, and levels were highest at night (20:00–7:00), indicating a ground-level source, specifically, uncovered digestion tanks at the nearby waste water treatment facility. Pearson correlation coefficients between daily averages of key pollutants were: PM_{10} with NO_2: 0.77; PM_{10} with SO_2: 0.63; NO_2 with SO_2: 0.52.

Table 3 Summary of air pollutant levels at Settlers School, South Durban during study period

Measure[a]	*SO_2 (ppb)*	*TRS (ppb)*	*CO (ppm)*	*NO_x (ppb)*	*PM_{10}*[b] *($\mu g/m^3$)*	*PM_{10}*[c] *($\mu g/m^3$)*
24-hour average						
Average	8.2	9.0	0.9	26.5	28.8	35.9
Median	7.3	8.3	0.9	26.6	26.5	36.0
Maximum	19.7	13.7	1.4	49.7	55.2	68.0
15-min peak						
Average	51.9	36.8	2.6	118.0	85.6	–
Median	53.5	20.8	2.5	118.6	76.1	–
Maximum	93.5	131.7	4.7	226.4	193.2	–

[a]SO_2 is sulphur dioxide, TRS is total reduced sulphur, CO is carbon monoxide, NO_x is nitrogen oxides, PM_{10} is particulate matter of 10 μm or less in aerodynamic diameter.

[b]PM_{10} from TEOM.

[c]PM_{10} from gravimetric filter (Partisol).

Meteorologic parameters showed only modest variability over the study period: average daily temperature ranged between 19.8°C and 23.1°C, and the average daily relative humidity ranged between 74% and 90%.

3.7 Relationship between exposure measures and signs and symptoms of asthma

PM_{10}, SO_2 and NO_2 showed more consistent and stronger associations with health effects than the other pollutants in preliminary models. In addition, examined preliminary models for CO and TRS generally had less stable parameter estimates (and thus were more difficult to interpret) than those for the other pollutants. Presented models are restricted to PM_{10}, SO_2 and NO_2.

The associations in children with persistent asthma of lower respiratory symptoms (cough, wheezing, chest tightness or heaviness and shortness of breath) reported on bihourly logs with previous-day (i.e. lag 1) PM_{10}, SO_2 and NO_2 in single-pollutant models are shown in Table 4.

The associations between the exposures and the symptoms are presented as OR, specifically the OR for a one interquartile increase in the particular pollutant. A substantial fraction of the OR for those with persistent asthma in these models are statistically significant. Prior day SO_2 shows a particularly strong influence on wheeze, whereas prior day PM_{10} has greater influence on chest tightness or heaviness and shortness of breath. Associations with NO_2 do not reach statistical significance. Among children without persistent asthma, these associations with PM_{10} and SO_2 are much weaker and much less consistent.

Table 4 OR[a] for presence of symptoms reported on bihourly logs for changes in measured levels of PM_{10}[b], SO_2[c] and NO_2[d] at the school grounds for the previous day (24-hour average: midnight to midnight) among all students: from logistic regression single-pollutant models using GEE[e]

		PM_{10}			SO_2			NO_2		
		OR	*95% CI*	p^f	*OR*	*95% CI*	p^f	*OR*	*95% CI*	p^f
Cough	Persistent asthma[g]	1.070	0.970–1.170	0.154	**1.160**	1.010–1.310	**0.024**	**1.082**	1.000–1.170	**0.055**
	Mild intermittent to none	1.021	0.985–1.060	0.329	1.057	1.005–1.112	0.621	1.014	0.984–1.044	0.384
Wheezing	Persistent asthma	**1.127**	1.010–1.260	**0.032**	**1.340**	1.160–1.550	**<0.0001**	1.091	1.000–1.200	0.062
	Mild intermittent to none	0.971	0.922–1.026	0.290	1.031	0.961–1.105	0.386	0.992	0.949–1.036	0.417
Chest	Persistent asthma	**1.184**	1.060–1.330	**0.003**	1.048	0.900–1.220	0.550	1.072	0.970,–0.180	0.157
	Mild intermittent to none	1.006	0.956–1.057	0.620	1.057	0.984–1.134	0.307	1.011	0.969–1.056	0.424
SOB	Persistent asthma	**1.140**	1.010–1.290	**0.035**	1.086	0.920–1.280	0.321	1.060	0.950–1.180	0.282
	Mild intermittent to none	1.016	0.960–1.077	0.564	1.064	0.985–1.148	0.161	1.018	0.968–1.070	0.257

[a]OR = odds ratio for an increase of one interquartile range in PM_{10} (11.3 μg/m³), SO_2 (5.40 ppb) or NO_2 (4.05 ppb).

[b]PM_{10} = particulate matter of 10 μm or less in aerodynamic diameter.

[c]SO_2 = sulphur dioxide.

[d]NO_2 = nitrogen dioxide.

[e]Covariates include: gender, home location, annual family income, grade in school, presence of one or more smokers in the household, having pets in the household, having a roach problem, having a rodent problem, environmental stress, financial stress, neighbourhood violence, physical stress, overall quality of life, asthma severity, interaction between asthma severity and exposure measure.

[f]p is p-value testing hypothesis OR = 1.

[g]Asthma classifications based on parent baseline interview; 'persistent' asthma includes both moderate to severe persistent asthma and mild persistent asthma.

Covariates which entered these models with a *p*-value < 0.05 included: for *cough*: with PM_{10}: gender, grade, pets; with SO_2: grade, pets, smoking; with NO_2: gender, grade, pets; for *wheezing*: with PM_{10}: grade, quality of life, smoking; with SO_2: grade, violence, smoking; with NO_2: grade, quality of life smoking; for *chest tightness*: with PM_{10}: grade, income level, quality of life; with SO_2: grade, gender, physical stress; with NO_2: grade, income level, quality of life; for *SOB*: with PM_{10}: grade, violence, physical stress; with SO_2: grade, financial stress, violence; with NO_2: grade, physical stress, violence. Models using lag 2, or the average of lag 1 plus lag 2, gave similar results as lag 1, both for those with and without persistent asthma (data not shown). Models using short-term (i.e. during the previous 1–2 hours) exposure measures failed to show statistically significant associations (at alpha = 0.05) for any of the combinations of pollutant and lower respiratory symptoms (data not shown).

In two-pollutant models (Table 5) of PM_{10} and SO_2, the associations of SO_2 with wheeze, and of PM_{10} with chest tightness or heaviness and shortness of breath, are even more marked than in the single-pollutant models. In the two-pollutant model of NO_2 and SO_2 (full data not shown), the association of SO_2 with wheeze (OR: 1.68; 95% CI: 1.30, 2.15; *p*-value < 0.0001) was more marked than in the single-pollutant models. Associations with NO_2 still did not reach statistical significance.

Table 5 OR[a] for presence of symptoms reported on bihourly logs for changes in measured levels of PM_{10}[b] and SO2[c] at the school grounds for the previous day (24-hour average) among all students: From logistic regression two-pollutant models using GEE[d]

		PM_{10}			*SO_2*		
		OR	*95% CI*	*p^e*	*OR*	*95% CI*	*p^e*
Cough	Persistent asthma[f]	1.070	0.970–1.170	0.154	**1.160**	1.010–0.310	**0.024**
	Mild intermittent to none	1.021	0.985–1.060	0.329	1.057	1.005–0.112	0.621
Wheezing	Persistent asthma	**1.127**	1.010–1.260	**0.032**	**1.340**	1.160–0.500	**<0.0001**
	Mild intermittent to none	0.971	0.922–1.026	0.290	1.031	0.961–1.105	0.386
Chest	Persistent asthma	**1.184**	1.060–1.330	**0.003**	1.048	0.900–1.220	0.550
	Mild intermittent to none	1.006	0.956–1.057	0.620	1.057	0.984–1.134	0.307
SOB	Persistent asthma	**1.140**	1.010–1.290	**0.035**	1.086	0.920–1.280	0.321
	Mild intermittent to none	1.016	0.960–0.770	0.564	1.064	0.985–1.148	0.161

[a]OR = odds ratio for an increase of one interquartile range in PM10 (11.3μg/m^3), SO_2 (5.40 ppb).

[b]PM_{10} = particulate matter of 10 μm or less in aerodynamic diameter.

[c]SO_2 = sulphur dioxide.

[d]Covariates include: gender, home location, annual family income, grade in school, presence of one or more smokers in the household, having pets in the household, having a roach problem, having a rodent problem, environmental stress, financial stress, neighbourhood violence, physical stress, overall quality of life, asthma severity, interaction between asthma severity and exposure measure.

[e]*p*-val is *p*-value testing hypothesis OR = 1.

[f]Asthma classifications based on parent baseline interview; 'persistent' asthma includes both moderate to severe persistent asthma and mild persistent asthma.

4 Discussion

In evaluating the study results, a number of limitations of the study design need be considered including:

1. the fact that, the study design, although very useful for investigating *aggravation* of pre-existing asthma, is unable to address questions concerning *causation* of asthma
2. the study health data concerns a single school with a history of high levels of concern about potential ambient air pollution-related health effects – as such, it is unknown to what extent the findings can be generalised to other populations residing in South Durban
3. this highly focused, relatively inexpensive and relatively quickly conducted study included no unexposed comparison group – however, it should be recognised that the need for such a comparison group is greatly reduced by the longitudinal, repeated measures design which essentially uses each individual as his or her own control
4. resources were not available to conduct a fuller evaluation of other potential risk factors for aggravation of childhood asthma which might include skin testing of participants to determine allergic status, and assessment of environmental exposures inside homes through methods such as measurement of allergen levels in household dust and/or measurement of indoor air pollutant levels – again, it should be recognised that the use of the child as his or her on control will tend to reduce the possible impact of these unmeasured variables on the study results
5. the relatively short period over which the intensive health data was collected
6. the fact that ambient air pollution levels were considerably lower than average levels have been over the past several years, raising the possibility that the absolute magnitude of historical health effects of air pollution may be underestimated by this study.

Despite limitations described above, many of the study findings are quite striking and reinforce certain important conclusions. First, levels of ambient air pollutants measured at the school during the intensive study period were low as compared to both international and South African standards and guidelines, and particularly for SO_2, to average exposures in South Durban over the past few years (data not shown). It is important to keep in mind that any of the associations of pollution levels with adverse effects on health status found in this study are occurring during exposures which may underrepresent the extent of such pollution-related problems during the past few years. In addition, to the extent that such found associations are accepted as validated and robust, this would suggest that current standards may not be adequate to protect the health of susceptible portions of population, such as individuals with persistent asthma.

Second, the prevalences of both asthma of any severity (52%), and of moderate to severe persistent asthma (11%), among the participating students at the Settlers Primary School are strikingly high. The results of the parent baseline survey and of the MCT are congruent in indicating high rates of asthma in the student study population. These prevalences are considerably higher than almost all those found in previous reports using quite similar, well-validated instruments (Pearce et al., 2000) among paediatric populations in other countries likely to be at relatively high risk (ISAAC Steering

Committee, 1998; Melaku and Berhane, 1999; Mallol et al., 2000; Kagawa et al., 2001; Akinbami et al., 2002; Ehrlich, 2002; Joseph et al., 2002; Anderson et al., 2004; Emeryk et al., 2004). The prevalence of asthma symptoms and diagnosis among students at Settlers School also is high as compared to other studies of South African children. In a study of Cape Town schoolchildren aged 7–8 years, Ehrlich et al. (1995) reported a relatively high prevalence of wheeze in past 12 months of 26.8% (as reported by parents). In this study, 10.8% reported an asthma diagnosis. In another study by this group, among 13–14-year-olds in Cape Town, 16.0% reported wheeze in the last 12 months and 13.3% reported ever having been diagnosed with asthma (Poyser et al., 2002). As compared to these findings, prevalence rates by parent report were substantially higher among the Settlers School students: 39.1% among the students in Grades 3 and 6 reported wheeze in the past 12 months and 24.0% reported a doctor diagnosis of asthma. Results from the only previous study reporting prevalences of asthma symptoms and diagnosis in South Durban (Nriagu et al., 1999) suggest that children at the Settlers School may be at especially increased risk: in the Nriagu study, among children less than 17 years old, parents reported that 16% had experienced attacks of shortness of breath with wheeze during the last 12 months (and 10 % had ever been diagnosed with asthma). Among those in Grades 3 and 6 at the Settlers School, by parent report, 22.4% had an attack of wheezing with shortness of breath in the past 12 months.

The results of MCT, a well-validated and objective method to assess one of the key pathological mechanisms of asthma, increased airway responsiveness to nonspecific irritants, are congruent with the high asthma prevalences based on parent baseline interview responses. Just over 20% of the students in Grades 3 and 6 had marked airway hyperresponsiveness ($PC_{20} \leq 2$ mg/ml of methacholine). Half of the students had either probable or marked airway hyperresponsiveness ($PC_{20} \leq 8$ mg/ml). The prevalences for participating students in Grade 3, and comparison figures based on population samples from the international literature, are presented in Table 6. (Forastiere et al., 1994; Joseph et al., 2002; Kurukulaaratchy et al., 2002) In all cases, prevalences were higher, and usually very markedly higher, among the Settlers School students.

Table 6 Percent of participants of current and comparative population-based studies with PC_{20} less than or equal to specified concentrations of methacholine (Forastiere et al., 1994; Joseph et al., 2002; Kurukulaaratchy et al., 2002)

	Settlers Primary School	*Isle of Wight (UK)*	*Italy*		*USA*	
	Grade 3	Age 10	Ages 7–11		Ages 6–8	
			Urban	Rural	African-American	White
n	*84*	*784*	*621*	*594*	*79*	*490*
≤2 mg/ml	20.2%					
≤4 mg/ml	39.4%		20.0%	14.8%		
≤8 mg/ml	59.4%	14.4%				
≤10 mg/ml	[a]				41.7%	22.3%

[a]Not directly measured in Settlers study.

Third, the study results provide substantial evidence that ambient air pollution exposures are associated with acute changes in health status among students with persistent asthma. Among these students, prior day exposure to SO_2 and/or PM_{10}, were associated with highly statistically significant increases in the odds for lower respiratory symptoms including cough, wheezing, chest tightness or heaviness and shortness of breath, in both single-pollutant and two-pollutant models adjusted for multiple covariates. The two-pollutant models suggest independent effects of each agent on varying measured outcomes. These findings are consistent with children with persistent asthma being an especially sensitive subpopulation who demonstrated adverse responses to ambient exposures below current international or national standards or guideline values.

Moreover, these results appear to be very unlikely to be explained by any plausible type of bias or confounding. Firstly, selection biases are unlikely to be operative to any significant extent in that all of the students in Grades 3 and 6 were invited and more than 90% participated. Secondly, a host of potential confounders were controlled by including them in the regression models. Thirdly, (over)reporting bias cannot explain the found associations in that the participants had no knowledge of what the pollution levels were at the time when they completed the bihourly logs. Fourthly, any unmeasured covariates (factors) are very unlikely to explain these associations as almost all such covariates would remain constant within a given individual over the short period of the intensive study.

The robustness of our findings are also supported in that they are in general agreement with what most other studies have reported, i.e. (1) effects on symptoms and pulmonary function in asthmatics at levels of sulphur dioxide and/or PM_{10} quite comparable to the current study and (2) that lagged exposures almost always show stronger associations than same day exposures (Van Der Zee et al., 1999; Ostro et al., 2001; Mortimer et al., 2002). In a study of all children ages 3–12 in Singapore, Chew et al. (1999) reported emergency room visits for asthma increased by 3.0 visits per day per 100,000 children for every 8 $\mu g/m^3$ increase in SO_2 lagged by 2 days ($p < 0.001$). Exposure levels were quite comparable to those in the current study: mean daily SO_2 was 3.5 ppb. In a study of all children <15 years old in Seoul, Korea, Lee et al. reported statistically significant increased risk for hospitalisation for asthma for SO_2 (OR = 1.11 (95% CI = 1.06–1.17 for interquartile range of 4.4 ppb)), PM_{10} (OR = 1.07 (95% CI = 1.04–1.11 for interquartile range of 40.4 μg/m3)) and NO_2 (OR = 1.15 (95% CI = 1.10–1.20 for interquartile range of 14.6 ppb)) (Lee et al., 2002). Van der Zee et al. (1999) studied children ages 7–11 with and without respiratory symptoms in urban areas in the Netherlands. Exposure levels were quite comparable to those in the current study: mean daily SO_2 levels ranged from 1.4 to 8.8 ppb, PM_{10} from 24 to 48 $\mu g/m^3$. In this study, PM_{10} lagged by 1 or 2 days was associated with increased symptoms, decreased peak flow and increased bronchodilator use; SO_2 lagged by 1 day was also associated with increased bronchodilator use. In a study of urban US children with asthma ages 4–9, Mortimer et al. (2002) reported an association of increased incidence of morning symptoms with increases in the preceding 2 days average of SO_2 (OR = 1.32 (1.03–1.70) per interquartile range of 53 ppb). Ostro et al. in a study of African-American children in Los Angeles, reported new episodes of cough were associated with exposure to PM_{10} (OR = 1.25 (1.12–1.39)) for interquartile range of 17 $\mu g/m^3$. The same sort of delayed or lag effects are also typically reported in studies using emergency room visits or hospital admissions or mortality as health endpoints (Ostro et al., 2001).

While the associations between fluctuations in ambient pollutant exposures and acute health status changes are quite strong and consistent, the analyses conducted do not allow the health effects to be attributed clearly to one specific measured air pollutant over all the others. Rather, at least, PM_{10} and SO_2 appear to make important and somewhat independent contributions. It should be remarked that the changes in health status observed are quite unlikely to be explained simply by changes in meteorologic parameters like temperature and humidity. Even persistent asthmatics would be unlikely to react to the relatively small changes in temperature and humidity over the study period (De Diego Damiá et al., 1999).

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References

Akinbami, L.J., LaFleur, B.J. and Schoendorf, K.C. (2002) 'Racial and income disparities in childhood asthma in United States', *Ambuatoryl Pediatrics*, Vol. 2, pp.382–387.

American Thoracic Society (ATS) (1995) 'Standardization of spirometry – 1994 update', *American Journal of Respiratory and Critical Care Medicine*, Vol. 152, pp.1107–1136.

Anderson, H.R., Ruggles, R., Strachan, D.P., Austin, J.B., Burr, M., Jeffs, D., Standring, P., Steriu, A. and Goulding, R. (2004) 'Trends in prevalence of symptoms of asthma, hay fever and eczema in 12–14 year olds in the British Isles, 1995–2003: questionnaire survey', *British Medical Journal*, Vol. 328, pp.1052–1053.

Bates, D.V. (1995) 'The effects of air pollution on children', *Environmental Health Perspectives*, Vol. 103, No. 6, pp.49–53.

Braga, A.L.F., Saldiva, P.H.N., Pereira, L.A.A., Menezes, J.J.C., Conceicao, G.M.S., Lin, C.A., Zanobetti, A., Schwartz, J. and Dockery, D.W. (2001) 'Health effects of air pollution on children and adolescents in Sao Paulo, Brazil', *Pediatric Pulmonology,* Vol. 31, pp.106–113.

Butler, M. and Hallowes, D. (Eds) (2002) *The groundWork Report 2002: Corporate Accountability in South Africa*, groundWork, Pietermaritzburg.

Chew, F.T., Goh, D.Y.T., Ooib, C., Saharom, R., Hui, J.K.S. and Lee, B.K.W. (1999) 'Association of ambient air-pollution with acute asthma exacerbation among children in Singapore', *Allergy*, Vol. 54, pp.320–329.

CSIR (1999) *Air Quality Indications in the South Durban Area: An Analysis based on Sulphur Dioxide (SO2), Nitrogen Oxides (NOX) and Carbon Monoxide (CO)*, Ref No.: 14 ENV/P/C 97258, Environmentek, PO Box 17001, Congella 4013.

CSIR (2002) *Air Pollution and Health Effects in South Durban – A Review of Existing Data, Final Draft*, CSIR Report ENV-D-C 2002-011, Project: JX 337(020), PO Box 17001, Congella 4013.

Danmarks Naturfredningsforening (DN) and South Durban Community Environmental Alliance (SDCEA) (2002) *Comparison of Refineries in Denmark and South Durban in an Environmental and Societal Context*.

De Diego Damiá, A., León Fabregas, M., Perpiñá Tordera, M. and CompteTorreo, L. (1999) 'Effects of air pollution and weather conditions on asthma exacerbation', *Respiration*, Vol. 66, pp.52–58.

Diggle, P., Liang, K.Y. and Zeger, S. (1994) *Analysis of Longitudinal Data*, Oxford University Press.

Edwards, L.J. (2000) 'Modern statistical techniques for the analysis of longitudinal data in biomedical research', *Pediatric Pulmonology*, Vol. 30, pp.330–344.

Ehrlich, R.I. (2002) 'The prevalence of asthma in South Africa', *Current Allergy and Clinical Immunology*, Vol. 15, No. 1, pp.4–8.

Ehrlich, R.I., Du Toit, D., Jordaan, E., Volmink, J.A., Weinberg, E.G. and Zwarenstein M. (1995) 'Prevalence and reliability of asthma symptoms in primary school children in Cape Town', *International Journal of Epidemiology*, Vol. 24, pp.1138–1145.

Emeryk, A., Chojna, E., Bartkowiak-Emeryk, M. and Postepski, J. (2004) 'Prevalence of asthma and some respiratory symptoms in the years 1995 and 2001 in schoolchildren from rural regions of Poland', *Annals of Agricultural and Environmental Medicine*, Vol. 11, pp.63–66.

European Respiratory Society (1993) 'Airway responsiveness', *European Respiratory Journal*, Vol. 6, No. S16, pp.58–83.

Forastiere, F., Corbo, G.M., Pistelli, R., Michelozzi, P., Agabiti, N., Brancato, G., Ciappi, G., Perucci, C.A. (1994) 'Bronchial responsiveness in children living in areas with different air pollution levels', *Archives of Environmental Health*, Vol. 49, pp.111–118.

Horton, N.H. and Lipsitz, S.R. (1999) 'Review of software to fit generalized estimating equation regression models', *American Statistician*, Vol. 53, pp.160–169.

Hurt, Q. (2001) Personal communication to Kistnasamy, J., 28 February 2001, Managing Director: ECOSERV, (t) 031–7101864, (f) 031–7101851, e-mail: hurt@ecoserv.co.za, 10a Caversham Rd, PO Box 416, Pinetown, 3600.

Joseph, C.L.M., Ownby, D.R., Peterson, E.L. and Johnson, C.C. (2002) 'Does low birthweight help to explain the increased prevalence of asthma among African-Americans?', *Annals of Allergy, Asthma and Immunology*, Vol. 88, pp.507–512.

Kagawa, J., Nohara, M., Pan, G., Qu, C. and Yang, Z.M. (2001) 'Comparison of respiratory symptoms between schoolchildren in China and Japan', *Allergology International*, Vol. 50, pp.303–309.

Keeler, G.J., Dvonch, J.T., Yip, F.Y., Parker, E.A., Israel, B.A., Marsik, F.J., Morishita, M., Barres, J.A., Robins, T.G., Brakefield-Caldwell, W. and Sam, M. (2002) 'Assessment of personal exposures to Particulate Matter (PM) among asthmatic children in Detroit, Michigan as part of Community Action Against Asthma (CAAA)', *Environmental and Health Perspectives*, Vol. 110, Suppl. 2, pp.173–181.

Kurukulaaratchy, R.J., Fenn, M., Twiselton, R., Matthews, S. and Arshad, S.H. (2002) 'The prevalence of asthma and wheezing illnesses amongst 10-year-old schoolchildren', *Respiratory Medicine*, Vol. 96, No. 3, pp.163–169.

Lebowitz, M.D. (1996) 'Epidemiological studies of the respiratory effects of air pollution', *The European Respiratory Journal*, Vol. 9, No. 4, pp.1029–1054.

Lee, J.T., Kim, H., Song, H., Hong, Y.C., Cho, Y.S., Shin, S.Y., Hyun, Y.J. and Kim, Y.S. (2002) 'Air pollution and asthma among children in Seoul, Korea', *Epidemiology*, Vol. 13, pp.481–484.

Luyt, D.K., Davis, G., Dance, M., Simmank, K and Patel, D. (1995) 'Clinical characteristics of black asthmatic children', *South African Medical Journal*, Vol. 85, No. 10, pp.999–1001.

Mallol, J., Sole, D., Asher, I., Clayton, T., Stein, R. and Soto-Quiroz, M. (2000) 'Prevalence of asthma symptoms in Latin America: The International Study of Asthma and Allergies in Childhood (ISAAC)', *Pediatric Pulmonology*, Vol. 30, pp.439–444.

Melaku, K. and Berhane, Y. (1999) 'Prevalence of wheezing asthma related symptoms among schoolchildren in Addis Ababa, Ethiopia', *Ethiopian Medical Journal*, Vol. 37, pp.247–254.

Mortimer, K.M., Neas, L.M., Dockey, D.W., Redline, S. and Tager, I.B. (2002) 'The effect of air pollution in inner city children with asthma', *European Respiratory Journal*, Vol. 19, pp.699–705.

Ng'ang'a, L.W., Odhiambo, J.A., Mungai, M.W., Gicheha, C.M., Mderitu, P., Maingi, B., Macklem, P.T. and Becklake, M.R. (1998) 'Prevalence of exercise induced bronchospasm in Kenyan school children: an urban-rural comparison', *Thorax*, Vol. 53, pp.919–926.

Nriagu, J., Robins, T., Gary, L., Liggans, G., Davila, R., Supuwood, K. and Harvey, C. (1999) 'Prevalence of asthma and respiratory symptoms in south-central Durban, South Africa', *European Journal of Epidemiology*, Vol. 15, pp.747–755.

Ostro, B., Lipsett, M., Mann, J., Braxton-Owens, H. and White, M. (2001) 'Air pollution and exacerbation of asthma in African-American children in Los Angeles', *Epidemiology*, Vol. 2, pp.200–208.

Pearce, N., Sunyer, J., Cheng, S., Chinn, S., Björkestén, B., Burr, M., Keil, U., Anderson, H.R. and Burney, P. (2000) 'Comparison of asthma prevalence in the ISAAC and ECHRS', *European Respiratory Journal,* Vol. 16, pp.420–426.

Poyser, M.A., Nelson, H., Ehrlich, R.I., Bateman, E.D., Parnell, S., Puterman, A. and Weinberg, E.G. (2002) 'Socioeconomic deprivation and asthma prevalence and severity in young adolescents', *European Respiratory Journal*, Vol. 19, No. 5, pp.892–898.

The International Study of Asthma and Allergies in Childhood (ISAAC) Steering Committee (1998) 'Worldwide variation in prevalence of symptoms of asthma, allergic rhinoconjunctivitis, and atopic eczema: ISAAC', *Lancet*, Vol. 351, pp.1225–1232.

Tonnesen, M.R. (2001) *The Role of Environmental NGOs in South Africa*, Master's Thesis, University of Roskilde, Denmark.

Van Der Zee, S., Hoek, G., Boezen, H.M., Schouten, J.P., van Wijnen, J.H. and Brunekreef, B. (1999) 'Acute effects of urban air pollution on respiratory how the children with and without chronic respiratory symptoms', *Occupational and Environmental Medicine*, Vol. 56, pp.802–813.

Weinberg, E.G. (2001) 'Urbanisation and childhood asthma in South Africa', *Urban Health and Development Bulletin*, Vol. 4, No. 2, pp.19–26.

Wood, R.A. (2002) 'Pediatric asthma', *Journal of the American Medical Association*, Vol. 288, No. 6, pp.745–747.