Proximity to two main sources of industrial outdoor air pollution and emergency department visits for childhood asthma in Edmonton, Canada

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ABSTRACT

OBJECTIVE: Children are recognized to be more susceptible than healthy adults to the effects of air pollution; however, relatively few Canadian studies of children have focused on industrial emissions. We conducted a spatial cross-sectional study to explore associations between emergency department (ED) visits for childhood asthma and residential proximity to two industrial sources of air pollution (coal-fired power plant and petrochemical industry) in Edmonton, Canada.

METHODS: Using administrative health care data for Alberta between 2004 and 2010, we conducted a spatial analysis of disease clusters of count data around these two industrial sources. The distance from children's place of residence to these industrial sources was determined by using the six-character postal code from the children's ED visit. Clusters of cases were identified at the census dissemination area. Negative binomial multivariable spatial regression was used to estimate the risks of clusters in relation to the distance to these industrial sources.

RESULTS: The relative risk of ED visits for asthma, calculated using a spatial scan test for events, was 10.4 (p value <0.01) within the power plant area when compared with the outside area. In addition, there was an inverse association of the distance to the power plant (coefficient = -0.01 per km) with asthma visits when multivariable models were used. No asthma clusters were identified around the petrochemical industrial area.

CONCLUSION: Our analyses revealed that there was a cluster of ED visits for asthma among children who lived near the coal-fired power plant just outside Edmonton.

KEY WORDS: Air pollution; asthma; disease cluster; industry; Canada

La traduction du résumé se trouve à la fin de l'article.

Can J Public Health 2017;108(5-6):e523–e529
doi: 10.17269/CJPH.108.6136

Outdoor air pollution has been associated with various health conditions, including asthma, cardiovascular diseases, respiratory infections, adverse birth outcomes, and cancer.^{1–3} Children are considered to be more susceptible than adults to the effects of air pollution because of a number of physiological and physical activity factors.⁴ The effects of outdoor air pollution on children's asthma include an increase in its incidence, prevalence, exacerbations measured by self-reported symptoms or emergency department (ED) visits, hospitalizations, and worsening of lung function measurements.^{5,6}

Most air pollution and asthma studies have focused on traffic-related air pollution, and relatively fewer studies have assessed the effect of industry-related air pollution on childhood asthma.³ In Canada, three studies have found associations between the short-term effects of exposure to oil refinery^{7,8} and aluminum smelter industrial emissions in Quebec and British Columbia,^{8,9} and an increased number of ED visits and admissions for childhood asthma.

In Edmonton, Alberta, studies conducted between 1992 and 2002 documented an increase in children's ED visits for acute asthma related to increased concentrations of nitrogen dioxide (NO₂), carbon monoxide (CO), ozone (O₃) and particulate matter (PM) with mean aerodynamic diameter of 10 µm (PM₁₀), and

2.5 µm (PM_{2.5}).^{10,11} These studies, however, did not investigate what specific local sources of air pollution contributed to these associations. The Edmonton area has multiple pollution sources, including two specific industrial sources arising from the Industrial Heartland of Alberta petrochemical industry (IHA) northeast of the

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Acknowledgements: The authors would like to thank Alberta Health Services for providing the health data for this study.

Funding: The study was supported by the Emergency Medicine Research Group from the Department of Emergency Medicine, and the Department of Pediatrics, University of Alberta. Dr. Rodriguez-Villamizar was supported by the Colombian Administrative Department for Science and Technology. Dr. Rowe's research is supported by the Canadian Institutes of Health Research (CIHR) through a Tier I Canada Research Chair in Evidence-based Emergency Medicine from the Government of Canada (Ottawa, Ontario). Dr. Osornio Vargas's research is supported by a Collaborative Health Research Program CIHR/Natural Sciences and Engineering Research Council grant. The funders do not take responsibility for the design, conduct, results, or interpretations presented here.

Conflict of Interest: Authors do not have a conflict of interest to declare.

city and the coal-fired power plants (CFPP) west of the city. Despite the presence of these important sources of industrial air emissions in the Edmonton area, the impact of the proximity of these facilities on children's asthma in this region is not well known.

The objective of the study was to explore whether there was a clustering of children's ED visits for acute asthma in relation to residential proximity to the IHA or CFPP areas.

METHODS

Study area

The study setting was the Census Metropolitan Area of Edmonton in Alberta, Canada, with a population of approximately 1.2 million, of whom 18% are children under 14 years.¹²

The two main industrial sources in the Edmonton metropolitan area are the IHA and the CFPP. The IHA is an area of approximately 530 km² (50% in the Edmonton area) where 40 major companies, including chemical, petrochemical, oil and gas facilities, are located. The IHA is Canada's largest hydrocarbon processing centre, and it emits sulphur dioxide (SO₂), oxides of nitrogen (NO_x), PM, hydrogen sulphide, volatile organic compounds (VOCs), polycyclic aromatic hydrocarbons (PAHs), and CO.¹³

The six major CFPPs in Western Canada are in Alberta, and the largest three plants are located to the west of Edmonton. These CFPPs are sources of criteria air pollutants such as NO_x, SO₂, and PM. The CFPP emitted into Alberta's atmosphere 10%, 33% and 6% of NO_x, SO₂ and PM_{2.5} respectively.¹⁴ The CFPP pollution source assessed in this study is the largest of the six plants in Alberta, located west of the Edmonton metropolitan area in Wabamum village, an area with a population of about 600 people.¹¹

Asthma data

Alberta Health Services (AHS) provided anonymous patient data. Data were obtained for all residents aged from 2 to 14 years of age whose asthma was diagnosed from April 1, 2004, to March 31, 2010, in a hospital ED facility in the Edmonton metropolitan area. Asthma data included all children's ED visits during the study period (i.e., events), and more than one visit per child (i.e., cases) was possible. The ED visits for asthma in children <2 years of age were excluded, as the diagnosis of asthma in this age group is less accurate.¹⁵ The ED visits for asthma were identified as those having the ICD-10 code J45 as the primary discharge diagnosis. Additional variables extracted from the asthma database were a unique patient identifier, date of the visit, age, sex, subsidy status, and residential postal code of the patient. Only events with a residential postal code within the boundaries of the Edmonton metropolitan area were selected.

Population and socio-economic status data

Population estimates at the dissemination area (DA) level were retrieved from the 2006 Canadian Census,¹⁶ as this was the year that occurred midway during the study period. Population data were used to estimate expected visits and rates of ED visits for asthma at the DA level. In 2006, there were 1551 DAs in the Edmonton area. We used Chan's Socio-economic Status (SES) Index¹⁷ to characterize SES at a DA level. This index was used to evaluate whether SES confounded the association between asthma ED visits and proximity to industrial sources of air pollution.

Proximity to industrial sources of air pollution

For each ED visit for asthma, we determined the distance between the patient's place of residence and the location of industrial sources by first linking the postal codes captured by the ED asthma data to the corresponding DA using a conversion file.¹⁸ We then calculated the distance from the population-weighted centroid of each DA to the IHA and CFPP spatial coordinates. For the IHA, we selected as the referent point the most centrally located emitting facility located at longitude -113.01224/latitude 53.8241219. For the CFPP Wabamum area the specific location was the plant located at longitude -114.47831/latitude 53.56186. Figure 1 shows the location of the two pollution sources and the centroids of the all the DAs in the Edmonton area. Distance (in km) and direction (in cardinal degrees) were calculated using the distance and angle calculation tools in ArcGIS® (ESRI, Redlands, US, 2014). The DA-level polygon map was obtained from Statistics Canada, and spatial data layers were created in ArcGIS® using the Edmonton Custom Azimuthal Equidistant projection and Datum WGS 1984.

Data analysis

A spatial analysis of disease clusters around pollution sources with count (ecological) data was conducted using different descriptive, hypothesis-testing and multivariable modeling techniques.¹⁹ A cluster was defined as an area with higher risk of asthma ED visits compared with the outside area having the "pollution source" as the centre of the distance analysis. For the hypothesis-testing and multivariable analyses, the air pollution exposure was the distance from each DA's centroid to the specific pollution source (IHA or CFPP), which is stable over time and therefore gives information on long-term exposure effects. Clusters were identified on the basis of cumulative rates by DA. Consequently, the cumulative ED visit rates for childhood asthma between 2004 and 2010 by DA were used as a long-term cumulative outcome.

Descriptive Analysis

Crude ED visit rates for asthma were calculated by year using, as denominators, the population of children between 2 and 14 years living in the Edmonton zone based on the yearly registry of the Alberta Health Care Insurance Plan. The cumulative age-sex directly standardized rates (DSR) by DA and their 95% confidence intervals (CI) were calculated using the Census 2006 children as the standard population. The 95% CI of the rates were adjusted for the variance of events.²⁰ The lower limit of the DSR 95% CI for each DA was used to identify areas with statistically higher rates when the overall regional rate was smaller than this limit.²¹ Crude and DSR were calculated in Stata 13 (StataCorp., College Station, US, 2013) and then mapped using ArcGIS 10.3®.

Hypothesis-Testing Analysis

The presence of clusters around the two "pollution sources" under study were assessed using three focused tests for cases: Kulldorff circular spatial scan test,²² Stone's test²³ and Lawson directional score test;²⁴ and one test for events: the Chang-Rosychuk spatial scan statistic for events.²⁵ The null hypothesis for the spatial scan tests is that the risks inside and outside the scanned area are equal; for the Stone's test, that the relative risks are constant across areas; and for the directional test, that the risks are equal in all directions.

Figure 1. Location of the Industrial Heartland Alberta, the coal-fired power plants, and the dissemination area centroids in the Census Metropolitan Area of Edmonton

The Kulldorff circular spatial scan was implemented in SaTScan[®] (SaTScan, Calverton, US, 2015) using a pure spatial analysis with a Poisson probability model. The Stone's test was calculated using R software (DCluster version 0.2-7 for R, 2015). The Lawson directional score test was calculated using the mean angle of the wind direction during the study period at the nearest air quality monitor station for each location. The Chang–Rosychuk spatial scan method used an α value of 0.05 and 999 simulations for estimating p values (Rosychuk Hyperev 5.0, 2016).

Multivariable Modeling Analysis

Multivariable models were built to assess the combination of distance and direction effects, which are of particular importance when assessing clusters around air pollution sources with contaminant dispersion patterns.¹⁹ Following Lawson's approach,²⁶ we identified the negative binomial distribution as the appropriate model function for the data. The Akaike information criterion and deviance of the potential models were used for selection of the function model, and Moran's coefficient was calculated to assess spatial autocorrelation of the model's residuals. The basic model assessed the effects of distance and direction independently on the ED visit counts as dependent variable with the log of expected visits as offset; then, multivariable models were built separately for IHA and CFPP zones, including the three spatial functions (distance in km, longitude and latitude in cardinal degrees). Then, we assessed the potential confounding effect of SES and traffic-related air pollution (using NO₂ concentrations at the DA level estimated by the national land use regression model

[NO₂LUR]²⁷). Finally, the standardized deviance residuals of the final fitted models for IHA and CFPP were calculated. The analyses were conducted in Stata 13 and ArcGIS 10.3[®].

RESULTS

Descriptive analysis results

During the 6-year study period, 10 421 ED visits for asthma were registered by the AHS for 6184 distinct children between 2 and 14 years of age living in the Edmonton area, which resulted in an average of 1.68 visits per child (median = 1; interquartile range [IQR] = 1). The overall crude rate of ED visits for asthma was 55.9/1000 children aged 2–14 years during the 6-year period, which results in a mean crude rate of 9.3/1000 children aged 2–14 years per year. Table 1 shows the total number of ED visits for asthma and the crude rate per 1000 children by fiscal year during the study period. The ED visits for asthma were more common among males (64.02%) and children between 5 and 14 years (62.13%).

The ED visits for asthma were located across the Edmonton area in 1276 of the 1550 DAs, and 10 401 visits were used in the spatial analysis. The crude visit rates by DA ranged from 0.0 to 911.1/1000 (median = 43.6; IQR = 62.9). The DSR ranged from 0.0 to 926.4/1000 (median = 44.8; IQR = 66.7). Using the lower limit of the 95% CI of the DSR, 179 DAs (14% of the total DAs with asthma visits) had significantly higher rates when the overall crude rate was smaller than this limit. Figure 2 presents the choropleth map of the DSR of ED visits for asthma during the entire study period.

Table 1. Number of emergency department (ED) visits and crude rates for acute asthma among children between 2 and 14 years of age in the Census Metropolitan Area of Edmonton between April 1, 2004 and March 31, 2010

Year	Children population 2–14 years*	No. of asthma ED visits	Crude ED visit rate per 1000
2004/2005	165 030	1931	11.7
2005/2006	167 678	2164	12.9
2006/2007	172 591	1793	10.4
2007/2008	175 733	1448	8.2
2008/2009	179 176	1603	8.9
2009/2010	182 252	1482	8.1

* Total population within the Census Metropolitan Area of Edmonton for ages 2–14 from Alberta Health Care Insurance Plan registry.

Hypothesis-testing analysis results

The Kulldorff circular spatial scan test for cases and the Chang-Rosychuk spatial scan test for events identified a statistically significant cluster of children's ED visits for asthma in the same DA (48112023) as the CFPP's location in the Wabamum area. For this area, the children population at risk was 115, the number of observed cases was 34, the number of observed events was 59, the number of expected cases was 3.8, and the expected number events was 5.7; the estimated relative risk of this DA compared with the rest of the Edmonton area was 8.2 in the spatial scan test for cases

and 10.4 for the test of events. Neither of these tests identified a cluster around the IHA area.

The Stone's test identified a statistically significant distance decline effect from both pollution sources, higher in the CFPP than in the IHA area. The Lawson directional score tests identified directional effects for both pollution sources. The results of the statistics of these tests and their *p* values are presented in Table 2.

Multivariable modeling analysis results

The negative binomial multivariable models assessing the effects of distance provided evidence of a statistically significant inverse association with distance for the CFPP models (i.e., the smaller the distance the higher the estimated SMR (standardized morbidity rate) around the CFPP); for IHA, there was a significant positive association with distance, which means the estimated ratio increased as the distance increased from the IHA. Table 3 shows the estimated coefficients and their standard errors as well as the *p* values of the estimations and the deviance of the fitted models.

The models assessing the directional effect alone showed a strong positive coefficient for the longitude and a weaker negative coefficient for the latitude function for CFPP, which suggests that the dominant associations are towards the southeast from the CFPP. For IHA there was a strong negative coefficient for the latitude and longitude function, which suggests that the dominant associations are towards the southwest from the IHA. The model assessing the association of distance and direction for CFPP suggested a significant directional and distance decline effect still

Figure 2. Directly standardized rates of emergency department visits for children with acute asthma by dissemination area (DA) in the Census Metropolitan Area of Edmonton during 2004/2005 to 2009/2010. The cumulative age-sex directly standardized rates by DA and their 95% confidence intervals were calculated using the Census 2006 children as the standard population

Table 2. Results of focused tests for detection of cluster of emergency department visits for children with acute asthma in the Census Metropolitan Area of Edmonton from April 1, 2004 to March 31, 2010

Focused test	Coal-fired power plants		Industrial Heartland Alberta	
	Statistic	p value	Statistic	p value
Kulldorff's circular spatial scan test	7.97 (DA 48112023, RR = 8.2)	<0.001	No clusters found	
Stone's test for distance decline effect	26.04	0.001	2.87	0.023
Lawson's directional score test	21.72	<0.001	34.61	<0.001
Chang-Rosychuk's spatial scan test for events	22.04 (DA 48112023, RR = 10.4)	0.001	No clusters found	

Note: DA = dissemination area; RR = relative risk.

Table 3. Negative binomial multivariable models assessing distance and directional effects of living around two industrial areas in the Census Metropolitan Area of Edmonton from April 1, 2004 to March 31, 2010

Model type	Variable*	Coal-fired power plants†				Industrial Heartland Alberta†			
		Coef	95% CI	p value	Deviance	Coef	95% CI	p value	Deviance
Distance decline	Distance	-0.01	-0.01 to -0.01	0.000	1592.6	0.01	0.00-0.01	0.002	1600.1
Directional effect	Latitude	-0.72	-1.05 to -0.39	0.000	1586.2	-2.42	-2.96 to -1.88	0.000	1517.7
	Longitude	0.93	0.37-1.49	0.001		-2.04	-2.59 to -1.49	0.000	
Distance decline plus directional effects	Distance	-0.01	-0.01 to -0.01	0.000	1560.6	0.01	0.00-0.01	0.004	1509.8
	Latitude	-0.80	-1.13 to -0.47	0.000		-2.48	-3.04 to -1.93	0.000	
	Longitude	1.29	0.71-0.15	0.000		-2.02	-2.58 to -1.45	0.000	
Distance decline plus directional effects adjusted by SES index	Distance	-0.01	-0.01 to -0.00	0.000	1202.6	0.00	-0.00 to 0.00	0.167	1200.9
	Latitude	-0.04	-0.41 to 0.32	0.815		0.27	-0.61 to 1.15	0.550	
	Longitude	0.58	0.11-1.05	0.016		-0.39	-1.09 to 0.31	0.275	

* Distance measured in km, and latitude and longitude measured in cardinal degrees.

† All models used observed cases at the dissemination area as the outcome variable and log (expected cases) as the offset term; standard errors were scaled using the square root of deviance-based dispersion.

Note: Coef = coefficient; 95% CI = 95% confidence interval; SES = socio-economic index.

with strong southeast direction. For IHA, the model confirms the absence of a distance decline effect in the presence of directional effects.

Chan's SES index was inversely associated with the children's ED visit rates for asthma at the DA level (coefficient = -0.23; $p < 0.01$). After the effect of SES had been controlled for, the distance effect of CFPP remained inverse, but the directional effects remained only for the east direction (longitude in Table 3). For the IHA, the absence of a distance effect was also confirmed after SES had been controlled for, and the directional effects were no longer statistically significant (Table 3). The models with the adjustment for SES resulted in smaller deviance values.

The traffic-related air pollution measured by the NO₂LUR was not associated with the children's ED visit rates for asthma at the DA level (coefficient = -0.0004; $p = 0.938$); therefore, multivariable models were not adjusted for this variable.

The analysis of standardized deviance residuals showed good fit of the models. There was a small spatial autocorrelation in the model's residuals, as their Moran's coefficients were 0.109 and 0.110 ($p < 0.001$) for the CFPP and IHA models respectively.

DISCUSSION

Using a large, robust, linked and population-based administrative database covering a six-year period, this study found consistent increased risk of ED visits for asthma in children around the CFPP, located at the Wabamum area in the Edmonton metropolitan area during 2004-2010. An area with higher risk of asthma

exacerbations was identified in the same DA where the main CFPP emitter is located, with a directional effect towards the east related to predominant wind direction and the location of two other major power plants. In the case of IHA, the analysis did not identify a cluster of ED visits for asthma in children near this area.

Despite the importance of CFPP as sources of major air pollutants there has never been an epidemiological study conducted in Canada examining the association of pollution from coal power plants with spatial distribution of adult or children's diseases. A study conducted in 2004 by the Wabamum and the Area Community Exposure and Health Effects Assessment Program included 196 participants (53 children) of the Wabamum area using a pseudo-randomized sample. The authors concluded that the personal exposure to selected air pollutants was low and related more to indoor air quality, and they identified an increased rate of physician visits for respiratory illnesses but none related to asthma.²⁸ In 2008, the Canadian Medical Association published a report with the results of the Illness Cost of Air Pollution (ICAP) model, which used population densities, air quality data and known impacts of air pollution to estimate health and economic damages related to air pollution in the 10 provinces.²⁹ The most recent study related to the effects of the CFPP on Albertans' health was a compilation of existing literature about the health impacts of coal using the ICAP model.¹⁴

The CFPP at Wabamum village is the largest of the six plants located in Alberta and represents the CFPP pollution source assessed in this study. The other two CFPP within the Edmonton

area are located southeast of the Wabamum plant, where high SMR of ED visits for children with acute asthma were also identified. To the best of our knowledge, ours is the first epidemiological study that has used spatial analysis to assess clustering of asthma around these two pollution sources in the Edmonton area; the study findings provide epidemiological evidence of the adverse effect of air pollution emitted from CFPP on children's asthma.

Circular spatial scan tests identified a cluster within the DA where the Wabamum CFPP is located and did not identify a cluster around IHA. These types of hypothesis tests have been demonstrated to be good tools for identifying clusters of different shapes.³⁰ Usually, the tests are designed for cases; however, we also used the Chang-Rosychuk spatial scan statistic, the only test designed to identify clusters of events.²⁵ In this analysis, the results of both spatial scan tests, for cases and events, agree, probably because most of the children presented only once to the ED during the study period (median of visits = 1 and average = 1.68 visits).

The multivariable models allowed the combined effects of distance and direction to be tested and adjusted by potential confounders. The crude multivariable model for CFPP suggests a directional effect towards the southeast in addition to the distance effect. This direction is consistent with the predominant wind blowing from WNW 289° here, and points towards two areas that were identified as presenting a high risk of ED visits for children with acute asthma at the east and southeast of the CFPP.

For the IHA analyses, after controlling for SES we found no statistically significant associations between distance and the presence of asthma clusters. A potential explanation for the absence of distance effect for the IHA is that its vast extension can dilute the air pollutant concentrations before they reach residential areas. In addition, the predominant types of chemical emitted by the IHA (e.g., VOCs, PAHs) are lighter and therefore have a faster dispersion than the predominant chemicals emitted by the CFPP (e.g., SO₂).

Strengths and limitations

The use of well-documented and robust administrative health databases is an important strength of this study. In addition to being the first study to assess the effect of important industrial outdoor pollution sources on children's asthma in the Edmonton metropolitan area, the merit of the study is the combination of descriptive, hypothesis-testing and regression modeling approaches for assessing the presence and characteristics of clusters of children's asthma visits to the ED around CFPP and IHA areas. The descriptive methods used give information of DAs with high and low asthma rates within the entire Edmonton metropolitan area but do not offer information with regard to high/low rates related to pollution sources. The hypothesis-testing methods give information about excess asthma cases or events in relation to the location (distance and direction) of the pollution sources but do not offer information about the magnitude of the distance and direction's effect. Finally, adding multivariable models allows an estimate of the magnitude of the distance and direction effect for each pollution source adjusted by potential confounders like SES. Finally, adjusting for SES controls for potential differences in children's asthma management that may be related to SES-related health care access.

An important limitation of the study is that asthma data correspond to visits to hospital EDs only, where usually more severe cases are seen, and therefore asthma exacerbations with mild to moderate symptoms are clearly under-represented.

The two pollution sources under study are located at peripheral areas within the Edmonton metropolitan area rather than in the centre. This geographic location may impose additional considerations in the interpretation of the results of the analytical tools used for detecting directional effects, as they are usually designed for testing disease risks around a central point. In addition, the ecological approach used in this study limits the conclusions to the population level and should not be applied at an individual level, at which other considerations and confounders need to be accounted for. The databases employed in the study were limited by the level of individual data available (e.g., smoking exposure and status, educational level of parents, housing). Finally, it is important to note that the use of proximity measures to industrial facilities is a proxy measure of exposure to industrial emissions, and therefore studies using improved exposure estimation methods (e.g., dispersion modelling) are recommended.

CONCLUSION

Different methods for detecting clusters of diseases consistently indicated that there is a cluster of hospital ED visits for children with acute asthma around the CFPP although not around the IHA within the Edmonton metropolitan area. These results may be explained by air pollutant type and dispersion, and by individual conditions that were not included in this ecological analysis. Asthma exacerbations are an important asthma outcome, as they can be seen as a health effect indicator in relation to acute and chronic exposure to industrial emissions. The use of different approaches to detect clusters is valuable in gaining a better understanding of the presence, shape, direction, and size of clusters of asthma exacerbations around pollution sources. This information is useful for decision-makers in order to facilitate informed decisions regarding the location and regulation of industrial emissions.

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Received: April 24, 2017
Accepted: October 2, 2017

RÉSUMÉ

OBJECTIF : Il est reconnu que les enfants sont plus sensibles aux effets de la pollution de l'air que les adultes en bonne santé, mais les études canadiennes sur les enfants portant sur les émissions industrielles sont relativement rares. Nous avons mené une étude spatiale transversale pour explorer les associations entre les visites aux services d'urgence (SU) dues à l'asthme chez les enfants et le fait de résider à proximité des deux sources industrielles de pollution de l'air (la centrale thermique au charbon et l'industrie pétrochimique) à Edmonton, au Canada.

MÉTHODE : À l'aide des données administratives sur les soins de santé de l'Alberta de 2004 à 2010, nous avons procédé à l'analyse spatiale de données chiffrées sur les grappes de cas de maladies autour de ces deux sources industrielles. La distance entre le lieu de résidence des enfants et ces sources industrielles a été déterminée à l'aide du code postal de six caractères obtenu lors des visites des enfants aux SU. Les grappes de cas ont été déterminées à l'échelle des aires de diffusion du Recensement. Une régression spatiale multivariée binomiale négative a permis d'estimer les risques de grappes par rapport à la distance des sources industrielles.

RÉSULTATS : Le risque relatif de visites aux SU dues à l'asthme, calculé à l'aide d'une analyse spatiale des événements, était de 10,4 (valeur $p < 0,01$) dans les environs de la centrale comparativement à la zone extérieure. Il y avait en outre une association inverse entre la distance de la centrale (coefficient = $-0,01$ par km) et les visites dues à l'asthme lorsque nous avons utilisé des modèles multivariés. Aucune grappe de cas d'asthme n'a été repérée dans la zone de l'industrie pétrochimique.

CONCLUSION : Nos analyses ont révélé la présence d'une grappe de visites aux SU dues à l'asthme chez les enfants vivant près de la centrale thermique au charbon située juste en dehors d'Edmonton.

MOTS CLÉS : pollution de l'air; asthme; grappe de cas de maladie; industrie; Canada